408

The improvement of modelled wind and wave fields with increasing resolution

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Abstract

We have simulated a number of periods using different resolutions of the ECMWF meteorological model. Then we have explored how the quality of the surface wind and wave model results varies with the resolution. The comparisons have been done separately in the oceans and in the Mediterranean Sea, also using measured data from buoys and satellite.

At the highest resolution we have used, T799 or 25 km, the biases in the oceans reduce to very small values of the order of a few percent. In enclosed seas, represented in this case by the Mediterranean, the errors decrease with increasing resolution, but a substantial underestimate still remains.

The maximum values of both the wind speeds and the wave heights increase with resolution. However, the suggestion is that even T799 fails to model properly the highest peaks of the storms.

1. Introduction

This paper focuses on the surface wind fields and the wave heights derived from the numerical models operational at the European Centre for Medium-Range Weather Forecasts (ECMWF, Reading, U.K.). In particular we want to see how the accuracy of the results depends on the resolution of the meteorological model. While, strictly speaking, our results are valid for the ECMWF model, it is expected that most of them hold for also other models at major meteorological centres.

The quality of the present results at ECMWF is good. Global-wide statistics suggests a bias of the modelled marine surface wind speeds U_{10} of about -35 cm/s (between 3 and 4%). The corresponding result for the significant wave height H_s is -10 cm or 4-5% (see Janssen et al., 1997, and Janssen et al., 2003). There is still a tendency towards underestimating the peak values characterised by strong spatial gradients. However, the situation can be considered as satisfactory. Such a conclusion holds for the oceans. In the inner basins, like the Mediterranean Sea, the situation is less favourable. We find a frequent underestimate of both the wind speeds and the wave heights, which seems to depend on fetch, i.e. the distance run by wind and waves from the closest land, and it is greater for smaller basins (see Cavaleri and Bertotti, 1997 and 2003a). On the whole we can be pleased with the results achieved during the last decade (see, e.g., Janssen et al. 2003), but substantial improvement is still possible and required, particularly in enclosed seas.

Basically a meteorological model can be improved in three different ways: 1) with more sophisticated data assimilation techniques to improve the accuracy of the analysis fields, 2) improving the physics and the numerics of the model, and 3) increasing its resolution. The first and the third possibilities imply a substantial investment of resources, and a choice has to be made. As a preliminary step, we have carried out a series of tests, hindcasting several periods with different resolutions. Based on the results described in a previous paper (Cavaleri and Bertotti, 2003b), we have extended the range of the considered resolutions, analysed new and different kinds of storms, and extended the comparisons with measured data.

The different quality of the results in open oceans and in enclosed basins are discussed separately in the following sections. In section 2 we describe the structure of the tests and the choice of the hindcast periods. We then discuss in 3 the results for the oceans. Section 4 is devoted to the corresponding results for inner basins, represented in our case by the Mediterranean Sea. In 5 we analyse one case of very high spatial gradients, namely a cyclone in the Bay of Bengal. The overall results are discussed in section 6 and summarised in 7.

2. The organisation of the tests

In principle, the tests should be done starting from a given meteorological situation (the analysis at a given date), and letting the system evolve according to the different resolutions. The runs should be extended in time, to be able to derive conclusive results. However, the rapid divergence between the different runs, and also with respect to the corresponding analysis, would make the comparison of limited significance. Data assimilation would help, but the lower resolution used in the assimilation cycle would smooth the details we are looking for. Therefore a compromise must be considered. Following Cavaleri and Bertotti (2003b), we have organised the tests as a series of short-term forecasts. The structure is shown in Figure 1. After identifying a suitable period, this is modelled with a sequence of, partially overlapping, 72-hour forecasts, each one shifted two days ahead with respect to the previous one. The data have been saved at 6-hour interval (00, 06, 12, 18 UT). With the exception of the first and the last runs, out of each run we have considered the fields from +24 until +66 hour forecast. The principle has been to allow enough time for the model to develop the characteristics associated with its resolution, and to limit at the same time the extent of the forecast to avoid too large a divergence with respect to the corresponding analysis. The dots in Figure 1 indicate the fields chosen for the later analysis. All the experiments have been done in coupled mode, i.e. with the meteorological and wave models mutually exchanging information during the integration procedure (see Janssen, 1991). This allows a proper consideration of the variability of the drag coefficients with the wave conditions. The spectral meteorological model operational at ECMWF has been used for the tests. The wave model is WAM, also operational at ECMWF. They are both state of the art models, fully described in the literature. See Simmons (1991) and Komen et al. (1994) as main references for the meteorological and wave model respectively.

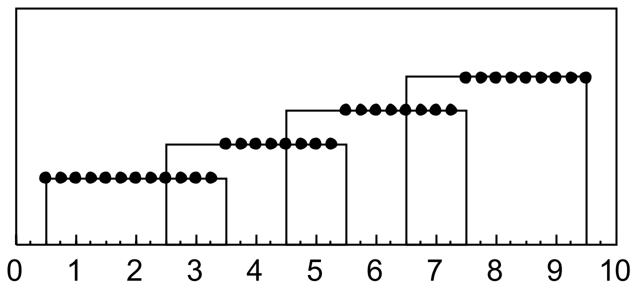

Figure 1 Selection of a continuous sequence of wind fields from a number of consecutive forecast experiments.

For a given period of interest the sequence of runs sketched in Figure 1 has been repeated for six different resolutions of the meteorological model, namely T106, T213, T319, T511, T639, T799. For each resolution the number identifies the truncation level of the two-dimensional Fourier series used to describe the horizontal fields. This corresponds to the spatial resolutions indicated in Table 1. The resolution of the wave model has been kept constant (~55 km) for all the tests. Therefore the differences between the various results depend only on the resolution of the meteorological model.

T	106	213	319	511	639	799
R (km)	188	94	63	39	31	25

Table 1 Truncation levels T considered for the meteorological model, and corresponding spatial resolutions R in kilometres.

Seven different periods of interests have been considered for the simulation and following general analysis. They are the first seven ones listed in Table 2. On the whole this provides 46 days, or 184 fields, of simulation. Modelled with the six different resolutions specified in Table 1, this provides a good database for our analysis. On top of it we have also hindcast a cyclone in the Bay of Bengal (last period in Table 2) to see how each resolution copes with the extremely high horizontal gradients there present.

1	9-12 Jan 1987
2	31 Dec 1992 - 12 Jan 1993
3	4-12 Feb 1994
4	8-17 Jan 1995
5	18-21 Mar 1995
6	26 Mar - 1 Apr 1995
7	27 Dec 2000 - 1 Jan 2001
8	14-20 May 1997

Table 2 Periods considered for the experiments

Notwithstanding its relatively large dimensions, the Mediterranean Sea experiences long periods of calm. Therefore the choice of the events listed in Table 2, with the exception of the cyclone, was based on the storms happened in this basin. At the same time the variety of situations present in the oceans ensures that the results are significant also on global scales.

The 55 km resolution, or 0.5 degree in latitude, used in the global wave model is too coarse to describe with the necessary details the wave fields in the Mediterranean Sea. Therefore in this area the hindcasts have been repeated with 0.25-degree resolution, using as input the surface wind fields derived from the experiments. These second runs were uncoupled, but this was not relevant, as the winds had already been obtained in coupled mode.

3. Results for the oceans

Our analysis has proceeded in two directions. First we have compared the results obtained with the different resolutions of the meteorological model. Then the comparison has been done against measured data. We begin with the former approach.

Starting with the coarsest resolution, T106, we compare its results (surface wind speeds U_{10} and significant wave heights H_s) with those of the next one. So we will have T106 vs T213, T213 vs T319, etc. Figure 2 shows the resulting scatter diagrams between T319 and T511 for wind speed (left panel) and wave height (right panel). As expected, we find that a higher resolution leads to higher wind speeds (by ~0.5%), hence to larger wave heights (by ~1%). The corresponding results for the five couple of resolutions are given in Table 3, where we have also distinguished between northern hemisphere (NH), tropics (TP) and southern hemispheres (SH), the limits being ±30 degrees. The Mediterranean (Med) will be discussed in the next section. These results are better seen in graphical form in the left panels of Figure 3, for wind, and of Figure 4 for waves. In the figures the data are normalised with respect to T106, the plots showing the relative increases with respect to this resolution.

	NH		TP		SH		Med	
	wind	Waves	wind	waves	wind	waves	wind	waves
T213/T106	0.962	0.956	0.966	0.960	0.964	0.958	0.910	0.848
T319/T213	0.991	0.984	0.993	0.988	0.993	0.986	0.984	0.959
T511/T319	0.994	0.988	0.996	0.991	0.995	0.989	0.974	0.952
T639/T511	0.996	0.994	0.998	0.996	0.997	0.995	0.988	0.985
T799/T639	0.997	0.995	0.999	0.997	0.998	0.996	0.993	0.988

Table 3 Best-fit slopes between the wind speeds (wave heights) obtained from experiments with different resolutions. NH = northern hemisphere, TP = tropics, SH = southern hemisphere. The limits are at ±30 degrees. Med = Mediterranean Sea.

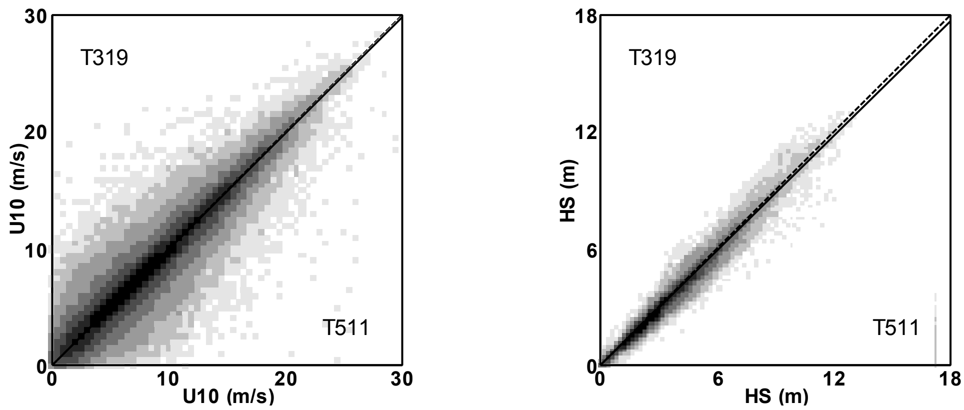

Figure 2 Comparison between the wind speeds (left panel) and the wave heights (right panel) obtained with different resolutions of the meteorological model, T319 vs T511.

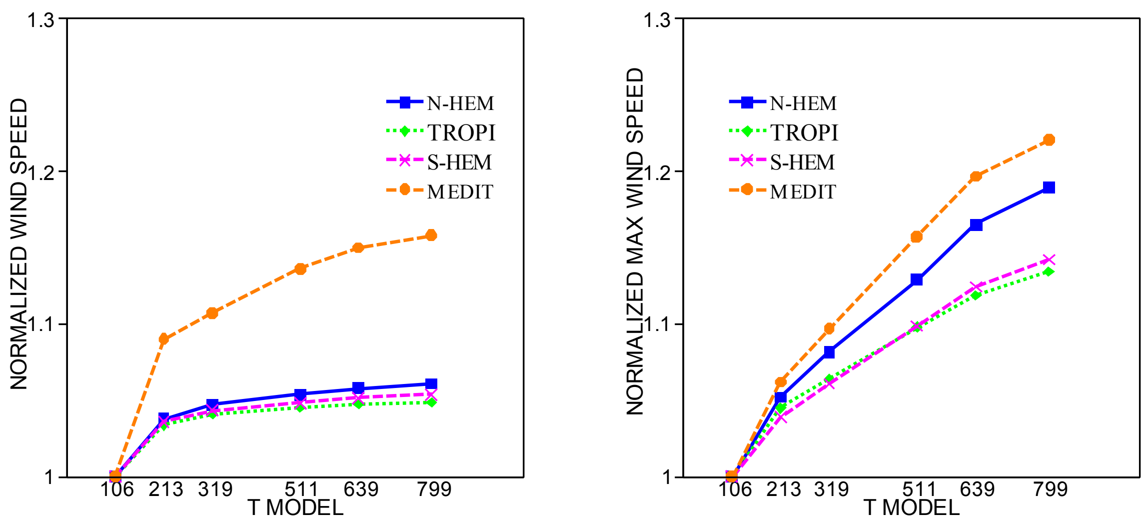

Figure 3 Left panel: relative increase of the wind speeds with the resolution of the meteorological model. Right panel: as the left diagram, but for maximum wind speeds.

We see (Figure 3) that there is a tendency towards asymptotic values in the three zones, slightly stronger in the northern hemisphere, possibly because of the local winter conditions dominant during the periods chosen for the test. There is a similar tendency also for the wave heights (Figure 4), albeit less marked because of the high sensitivity of waves to the forcing wind speeds. The implications of these results are better judged comparing the model results against measured data. For this we have used the wind and wave measurements obtained from 60 buoys in the Northern Atlantic and Pacific oceans. The full results are shown in Table 4.

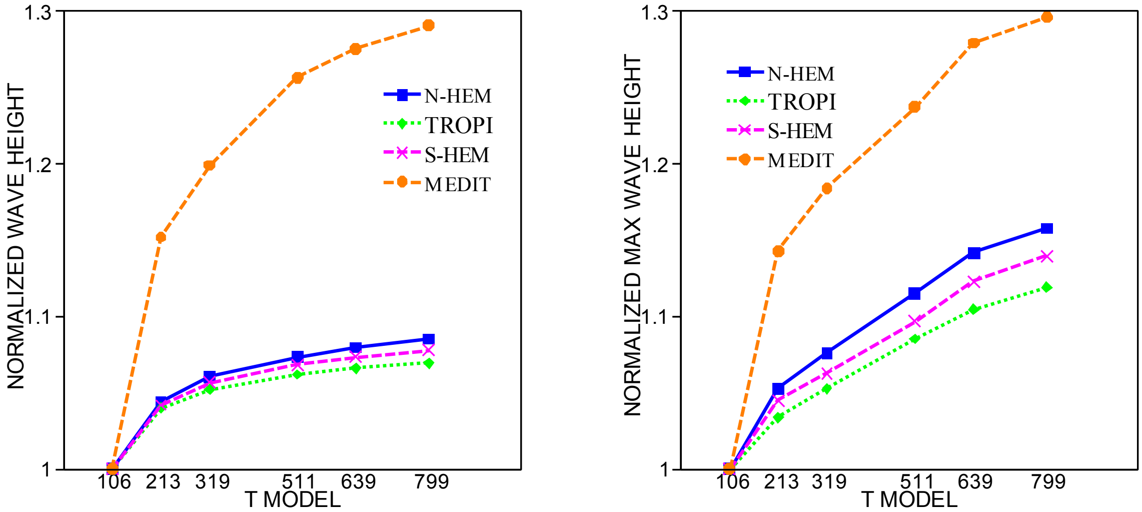

Figure 4 Left panel: relative increase of the wave heights with the resolution of the meteorological model. Right panel: as the left diagram, but for maximum wave heights.

		T106	T213	T319	T511	T639	T799
wind	bias	-0.16	-0.08	-0.03	-0.01	0.01	0.01
	SI	0.29	0.29	0.30	0.30	0.30	0.30
waves	bias	-0.28	-0.24	-0.23	-0.22	-0.21	-0.20
	SI	0.25	0.25	0.25	0.25	0.25	0.25

Table 4 Statistics (bias and scatter index SI) for wind speed (m/s) and wave height (m) model results against ocean buoy data. Different resolutions of the meteorological model have been used.

Indeed, we see that an increase of the resolution leads to a substantial decrease of the wind bias, till practically null values for the higher resolutions. Combined with the results of Figure 3 and the recent ECMWF results reported in the introduction, this suggests that a further increase of the resolution of the meteorological model presently operational at the Centre (T511) will bring the results very close to the truth. The improvement is evident also for the wave heights. However, here the tendency is towards a finite negative value, close to 20 cm, which suggests possible problems with the present set-up of the wave model.

The inspection of the scatter values SI, defined as the ratio between the rms error and the average value of the reference variable, for all the above cases tells a rather different story. Briefly summarised, the indication is that there is no improvement, i.e. no decrease of SI, either for wind as for waves, when increasing the resolution R of the meteorological model. In our experiment the scatter of the results with respect to the measured data is basically due to four reasons: a) small errors in the analysis, that rapidly increase with the extent of the forecast, b) incorrect physics and numerics of the models, c) an insufficient resolution, d) the intrinsic variability of the atmosphere. The role of a+b+c) vs d) can be quantified analysing how the scatter varies with the extent of the forecast. If the basic reason for it lies in the incorrect analysis and/or in the model, we must expect the scatter to grow with time. Conversely, a constant R or large values since the start of the experiments will point to the variability of the atmosphere as the basic reason for it. We have analysed our results in 12 hour forecast sections, i.e. analysing in the first section the analysis, in the second one all the +6 and +12 hour forecasts, and so on till +66 and +72 hours. The comparison with measured data has been repeated for each section and each resolution. The results for T639 are reported in Table 5. Those for the other resolutions we have used (see Table 1) are consistent with these ones.

		0	**6-12**	**18-24**	**30-36**	**42-48**	**54-60**	**66-72**
wind	bias	0.15	0.16	0.04	-0.32	-0.16	0.08	0.21
	SI	0.21	0.23	0.26	0.26	0.30	0.35	0.35
waves	bias	-0.07	-0.15	-0.15	-0.18	-0.22	-0.26	-0.23
	SI	0.19	0.21	0.21	0.23	0.27	0.28	0.29

Table 5 Variation of the results in Table 4 with the extent, in hours, of the forecast. 0 hours refers to the operational analysis. The results are given for the T639 resolution.

We focus first on the biases. The wind bias varies amply with the extent of the forecast, without an obvious trend. This hints to a certain level of randomness connected to its evaluation and to how the corresponding smooth trend in Table 4 appears only when averaging over larger quantities of data. For wave height, a parameter integrated in space and time over the driving wind fields, the randomness disappears and the increase of the model negative bias with the extent of the forecast is pretty clear. Again, this suggests possible problems with the present set-up of the wave model.

The two scatter indices, for wind and waves, tell the same story. There is an initial relatively low value of SI (0 time, i.e. analysis), and then the scatter grows steadily in time. The ones in Table 4 Statistics (bias and scatter index SI) for wind speed (m/s) and wave height (m) model results against ocean buoy data. Different resolutions of the meteorological model have been used. turn out to be just average values over the overall forecast. Therefore the suggestion is that there is indeed an initial scatter, associated to errors in the analysis and to the natural variability of the fields. Note that the SI values for wind are always larger than the ones for waves. While this is partly due to the longer memory of the wave fields, it also supports the hypothesis of the atmospheric variability as a basic reason for the scatter (Abdalla and Cavaleri, 2002). Should SI be due only to substantial errors in the meteorological pattern, this would be reflected also in the wave fields.

We now consider the maximum values. In the introduction we had mentioned how the peak values in a storm are frequently missed. There are doubts about the physics of the processes in these conditions and on the capability of the model to reproduce them. Powell et al. (2003) give a good summary of the situation. However, there are also obvious reasons in the numerics of the models. One is the resolution, the other one is the horizontal diffusion introduced for numerical stability (see Cavaleri et al., 1997). Both these tend to smooth the fields and to decrease the peak values, particularly in areas characterised by strong spatial horizontal gradients. We have explored the implications by comparing the 46 days (184 fields) of simulation available for each resolution (see section 2). One limitation of this analysis is the lack of comparison with measured data. As the maxima are isolated in space and time, only in a few rare cases is the ground truth available at the right time and position.

For each resolution and for each one of the available 184 fields, we have extracted the maximum value, for wind speed and wave height. Then, similarly to what done for the overall wind speeds (see left panel of

Figure 3, and of Figure 4 for wave height), we have determined the best-fit slope for each couple of resolutions (T106 vs T213, T213 vs T319, etc.). Normalised with respect to T106, the results are shown in the right panels of Figure 3, and of Figure 4 (the Mediterranean data will be discussed in the next section). We see that, contrarily to the overall quantities in the left panels, the maxima do not show a tendency toward an asymptotic value. This suggests that even at T799 we are not yet able to resolve properly the peaks of the distribution. This is more dramatic for the wind speeds than for the wave heights. The latter depend on the overall driving wind fields, and therefore they are less sensitive to an underestimate of the wind peaks.

4. Results for the Mediterranean Sea

As anticipated in the introduction, the quality of the model results in the Mediterranean Sea, for both wind speed and wave height, is much lower than in the oceans. We find a steady substantial underestimate for both these variables, which is greater for smaller basins. An example is given in Figure 5, where we compare model analysis data, respectively U_{10} and H_s, against the data recorded by the Topex altimeter. The period goes from January 1993 till June 1999, during which T213 (until 1998) and then T319 were the operational resolutions. With a different degree of underestimate, this is a characteristic of the whole basin (Cavaleri and Bertotti, 2003a). With some limited improvement, this is true also for the T511 model presently operational. Therefore it is of interest to determine the improvements expected with a further increase of resolution. Similarly to the oceans, Table 3, Figure 3, and Figure 4 for show the progressive relative increase of U_{10} and H_s when increasing the resolution. Table 6 reports the corresponding results of the comparison between model and Topex data.

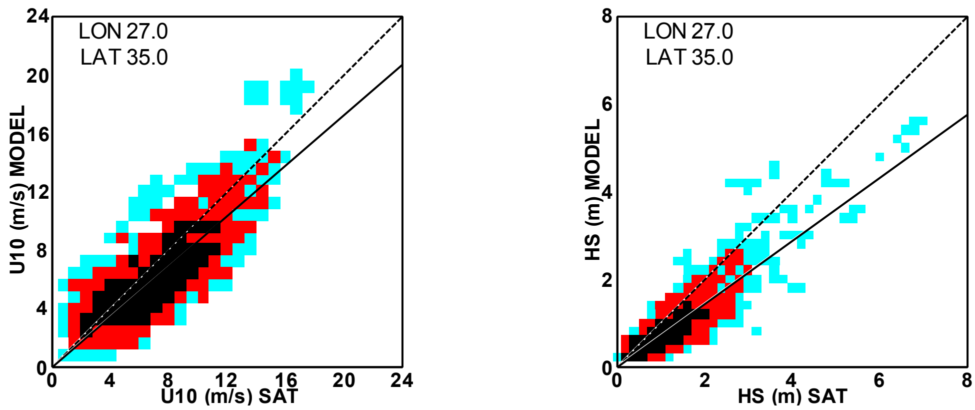

Figure 5 Scatter diagrams and best-fit lines between the ECMWF model results (surface wind speeds and significant wave heights) against Topex altimeter data at one location in the Mediterranean Sea. The considered period goes from January 1993 till June 1999. Darker pixels imply larger amounts of data.

We recognise at once the largest increase of both the wind speeds and the wave heights with increasing resolution, particularly evident in the two figures. There is some indication of a tendency towards an asymptotic behaviour for U_{10} (left panel of Figure 3). However, the corresponding diagram for H_s (left panel of Figure 4) shows a substantial increase of the wave height also when passing from T639 to T799. This suggests that also the highest resolution does not succeed in modelling properly the wind, hence the wave, fields in the Mediterranean, more in general in enclosed basins. As expected, the gain for H_s is larger than for U_{10}. In areas without or with limited swell, as it is the case in enclosed seas, the H_s dependence on U_{10} can be expressed as $H_s \propto U_{10}^{\beta}$, with β varying from 1 to 2 from fetch limited to open sea well developed conditions. In the intermediate conditions of the Mediterranean Sea, assuming β=1.5, we have ΔH_s % ≈ 1.5 ΔU_{10} %. Indeed this is what we find approximately in the statistics shown above.

The larger scatter indices for the wind speeds in the Mediterranean may point to the generally smaller scale of the features of the fields, associated to the effects of the orography and to the limited dimensions of the sub-basins. This latter characteristic is also manifest in the large scatter for H_s, because of the more "local" generation by wind with respect to the scales of the oceans. A similar argument is derived from the increase of the maximum values with resolution, in the right panel of Figure 3 (wind speed) and of Figure 4 (wave height). In face of comparable increases of maximum U_{10} in the Mediterranean and in the oceans, the maximum H_s grow much more in the smaller basin, pointing to a more direct dependence on the local winds.

		T106	T213	T319	T511	T639	T799
wind	bias	-0.83	-0.34	-0.31	-0.27	-0.24	-0.21
	SI	0.31	0.32	0.32	0.32	0.31	0.31
waves	bias	-0.64	-0.48	-0.45	-0.42	-0.37	-0.25
	SI	0.38	0.36	0.36	0.36	0.35	0.35

Table 6 Bias and scatter index SI for wind speed (m/s) and wave height (m) model results against Topex data in the Mediterranean Sea. Different resolutions of the meteorological model have been used.

5. A tropical cyclone

As an extreme example, we have analysed a tropical cyclone in the Bay of Bengal. Given the very large spatial gradients present in this kind of storm, it can be anticipated that even the maximum resolution we have used, T799, corresponding to about 25 km, is not sufficient to represent properly the fields. Nevertheless it is of interest to see how the results vary with the resolution R.

We have hindcast the storm from May 14 to 20, 1997, from its early beginning, along its northwards path, until its landfall on the 20th. The peak was reached on May 19, with reported wind speeds up to 50 m/s and atmospheric surface pressure as low as 930 hPa. The hindcast has been done with the technique described in section 2 and shown in Figure 1. Because of the sensitivity to the initial conditions, derived from T213, the global model operational at the time, we have used only 48-hour forecasts, considering for our analysis the +24/+48 hour sections

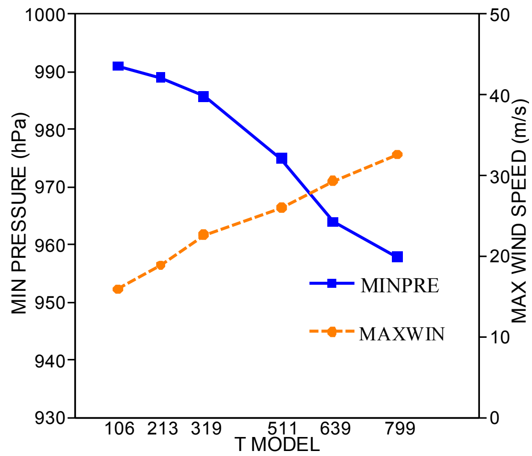

Figure 6 Minimum pressure and maximum wind speed at the peak of a cyclone in the Bay of Bengal, according to different resolutions of the meteorological model. The minimum (p) and maximum (U10) of the scales correspond to the reported extreme values.

Now we focus our attention on the peak conditions, and we explore how the results change with the resolution R. Figure 6 shows how the minimum pressure p and maximum wind speed U_{max} vary with R. As expected, there is a steady increase of the strength of the storm. However, no asymptotic behaviour is evident, and even T799 fails to reproduce the extreme values reported in the meteorological bulletins, corresponding to the lowest (p, left) and highest (U_{10}, right) values of the scales.

A more detailed view of the structure of the cyclone is obtained analysing how p and U_{10} vary along a west-to-east section across the eye of the cyclone. This is shown in Figure 7. Looking first at the p diagram, we recognise the expected reduced dimensions of the storm with increasing resolution, and the deepening at its centre. However, there is no evident real progress from T639 to T799, notwithstanding the minima are well off the 930 hPa reported value. The poor performance of the analysis (operational model) is noteworthy, much worse than the hindcast with the same resolution (T213). This can be explained by the data assimilation operational at the time, based on a very coarse resolution (T63).

In the second panel of Figure 7, showing the wind speed distributions, the structure of the cyclone is evident, with the minimum value of U_{10} at the eye position. There is no clear dependence of the minimum on resolution, although T799 does indeed provide the lowest value, about 2 m/s, which is realistic. While the higher resolutions provide also the higher wind speeds, we were surprised to find only a limited enhancement in this range, with values well below the reported 50 m/s. Also, the structure lacks the typical asymmetry of a cyclone, with higher wind speeds on its right flank (with respect to its motion, if in the northern hemisphere, hence counterclockwise rotation). This asymmetry is recognised in the analysis, possibly a feature introduced by the data assimilation.

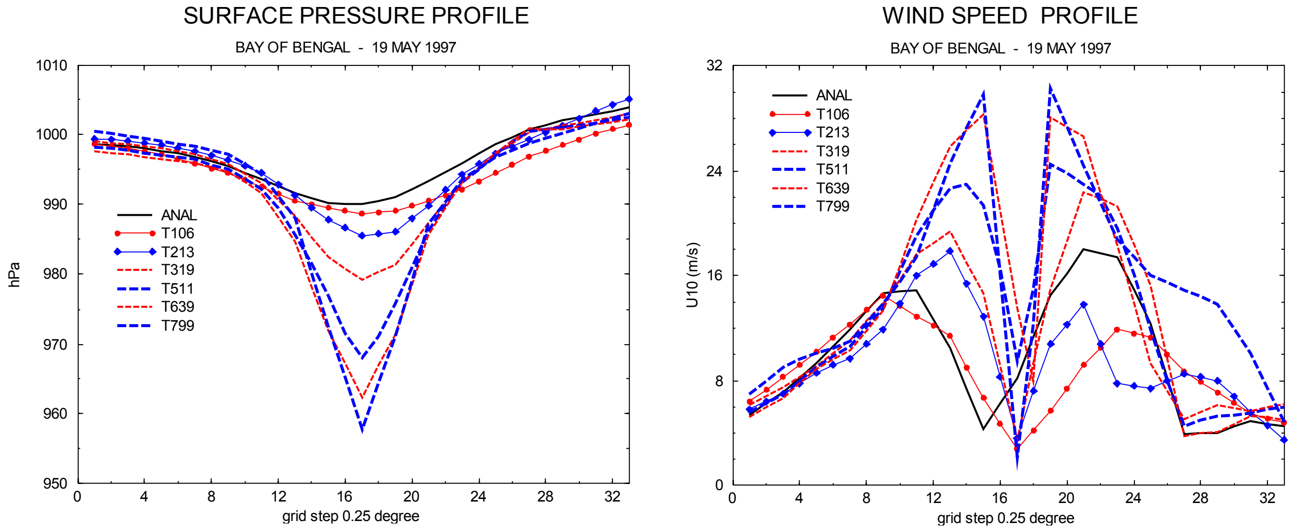

Figure 7 Upper panel: pressure distributions across a west-to-east section in a cyclone in the Bay of Bengal, according to different resolutions of the meteorological model. Lower panel: wind speed distributions along the same section.

6. Discussion

The technique we have used, a sequence of relatively short forecasts, can only be partly indicative of the performance of a corresponding operational model. However, our results provide some useful indications.

The present performance of the global operational meteorological and wave models at ECMWF, together with our results, suggest that a further enhancement of the resolution of the meteorological model will indeed bring the average results very close to the truth. The maximum values are still a problem. In this respect the model resolution and the horizontal diffusion introduced for numerical stability are obvious limiting factors. Our results indicate a substantial improvement with resolution, but we do not find the apparent asymptotic behaviour as indicative of an approach to the correct values. Many of the peaks have very reduced dimensions and are characterised by strong horizontal gradients. Even a T799 resolution, with the theoretical capability of identifying features of the order of 50 km or more, has obvious limitations.

The wave results follow accordingly, with an expected enhancement due to the sensitivity to small wind variations. This is less the case for the maxima, because of their integral properties with respect to the driving wind fields.

The results in the Mediterranean Sea, as representative of enclosed basins, are less favourable. There seems to be a basic problem, that worsens when the dimensions of the basin are smaller. The T511 model, presently operational at ECMWF, shows an evident underestimate of both the wind speeds and the wave heights, that seems to depend on fetch, i.e. the distance run by wind or waves from the closest land. The reason is still unclear, and further research in this direction is required. Increasing the resolution, as we have done, increases the values of the wind speed, hence of the wave height, but still below the measured values. The wind maxima, a more local affair, seem to depend less on the dimensions of the basin. However, in an enclosed basin, with a wind generation more limited in space and time, the maximum wave heights show a stronger correlation with the local wind peaks.

The hindcast of a cyclone had the aim of showing how well this phenomenon will be represented by a further increase of resolution with respect to the present T511. In this sense our results are disappointing, because we have not found any substantial trend towards the reported values. One obvious limitation is the horizontal resolution. The scale required for a proper representation of this kind of storm close to its centre is of the order of a few kilometres at most. Therefore in this area and with the present computer power, there is no possibility that a global model can accomplish this task. However, the lack of a tendency towards substantially higher (U_{10}) and lower (p) values when increasing the resolution may suggest that there is something else to be considered. Apart from the necessary parameterisation of the sub-grid processes, there have been arguments about the relevant physics in these extreme conditions. The suggestion is that the present formulation of the meteorological models does not include the necessary physics. This argument may also apply to the extremes in the extra-tropical storms.

7. Summary

In the oceans,

- a further increase of resolution will indeed bring the general results very close to the truth, with errors expected to be between 1 and 2% for both wind speed and wave height,
- in the range of extreme values, there is still ample margin for improvement. While we see that increasing the resolution of the meteorological model does enhance the extreme values, both the trend with resolution and the comparison with data suggest further improvements are still necessary. It is suggested this does not depend only on the resolution, but also in an incorrect representation of the physics of the processes. The problem is more manifest for the wind speeds than for the wave heights, because the latter ones do not depend only on the local wind conditions.

In enclosed basins,

- the present underestimate of both the wind speeds and the wave heights is only partially solved by an increase of resolution of the meteorological model, at least within the range we have explored. The available results suggest a strong influence of the land on the marine surface wind fields, for distances of some hundreds of kilometres,

- the failure to model peak values is similar to the oceans, somehow enhanced by possible orographic effects. However, the wave peak values are more dependent on the wind peak values than in the oceans, because of the more local generation in the enclosed basins.

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