

**Submitter:** Luigi Cavaleri

**Organisation:** Istituto per lo Studio della Dinamica delle Grandi Masse – CNR  
S.Polo 1364, 30125 Venice, Italy

**European Centre for Medium-Range Weather Forecasts**

**Special Project:**

*“Testing and application of a third generation model in the Mediterranean Sea”*

## **Final Report**

The project started in 1988, and along these almost 14 years a large volume of data has been obtained. In this report we will describe the main results, and the most significant ones from the point of view of application and operational applications.

Our attention has been focused for a long time on the accuracy of the results, in particular on the wind fields produced by the meteorological model of ECMWF. In the early years of the project the operational model was T106, whose resolution was not sufficient to produce reliable results in the enclosed basins, and in particular in the Mediterranean Sea. The main characteristics of the results, both wind and waves, was a strong underestimate of their values with respect to the measured data. We were interested in exploring how much this was depending on the resolution. Therefore, together with a member of the Centre staff (Lorenzo Dell'osso), we hindcast a very severe storm that took place in the Mediterranean Sea in early December 1989 with a high resolution version of the ECMWF model (Dell'Osso et al, 1991). The results proved beyond any doubt (see Figure 1) the basic role of resolution in shaping the overall surface wind field.

In 1991 the Centre passed to the T213 version of the meteorological model, which brought a substantial improvement of the quality of the wind, hence wave, fields. We made intensive comparisons using also surface wind speeds from the UKMO and Meteo France analyses. The analysis wind of ECMWF turned out to be, in general, of better quality. However, there was still an evident underestimate of  $U_{10}$ .

Another result of interest was that quite often the one day forecast showed better results, expressed as surface wind speeds and structure of the fields, than the corresponding analysis. The suggestion was that the assimilation procedure was somehow forcing a modification of the fields, hence leading to an error, while the one day forecast was short enough to be very close to the truth, without the modifications introduced by the assimilation. Obviously this pointed to the need for a better assimilation cycle, something the Centre has been steadily improving.

The nice description of the overall fields suggested the idea of a video, where, with a 100 day simulation, we visualised the evolution of the wind and wave fields, comparing them at the same time with the corresponding forecasts.

In 1994 ECMWF was planning to increase the resolution of the Mediterranean wave model from 0.5 to 0.25 degree. The corresponding increased demand in computer resources prompted a series of tests, where, using the same input wind fields, we hindcast a series of storms using both the resolutions. The results showed that the increased resolution was providing a better description of the wave fields close to the coast, particularly when the direction of propagation was not perpendicular to the coast and the coast had a complicated geometrical shape. There was also a

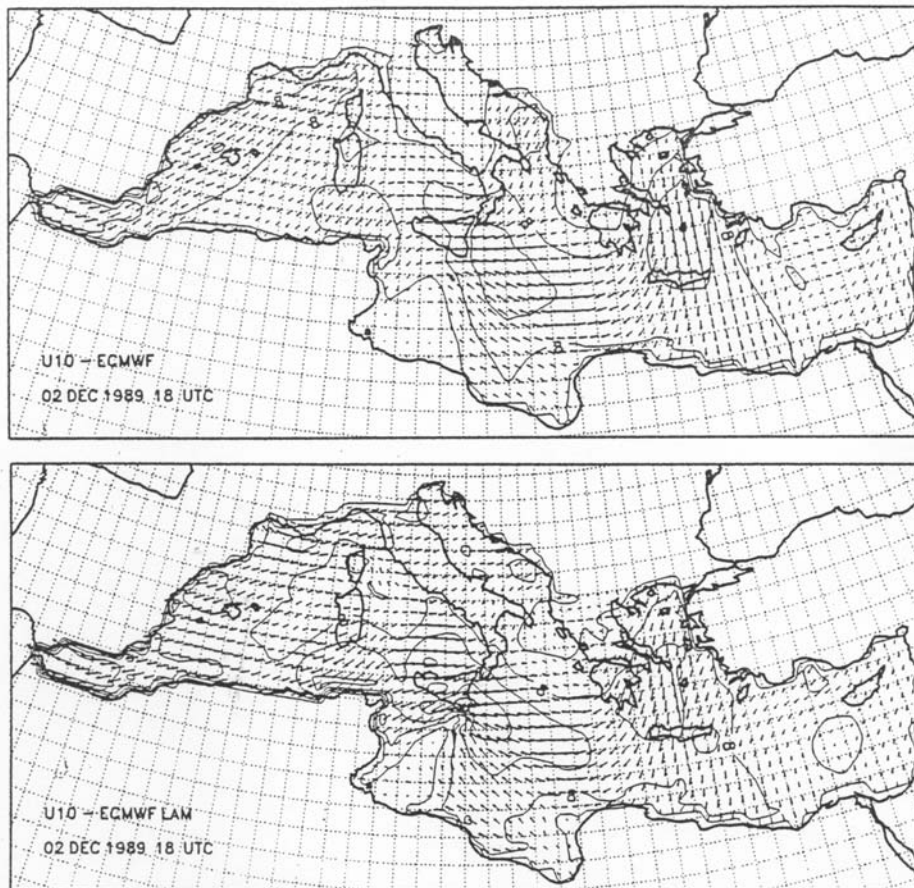


Figure 1 – Ten-metre wind from the global forecast at 1800 UTC 2 December 1989. Contours are at 4 m/s interval. (Upper panel) operational model, (lower panel) high resolution model (after Dell’Osso et al, 1991).

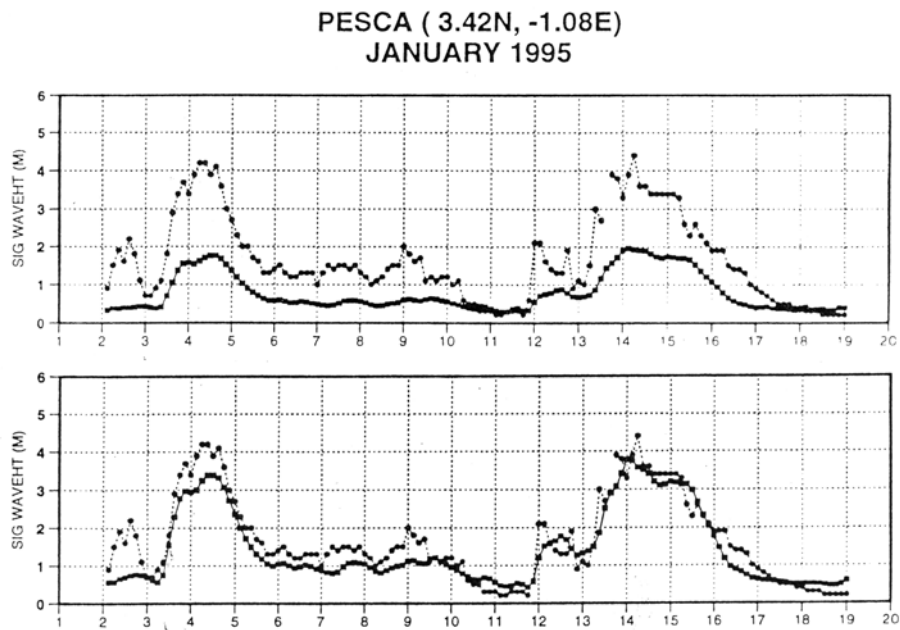
more realistic description of the evolution of the wave field in case of strong spatial gradients. In a specific case, concerning one of the most intense storms of the whole 20<sup>th</sup> century, the peak significant wave height  $H_s$  passed from 11 to 12 metre.

We found a potentially severe problem in the advection scheme used in the wave model. In case of waves moving parallel to an oblique coastline, the advection along two orthogonal directions implies a numerical dissipation of the wave energy. A solution has been found with a generalisation of the scheme, where the energy is advected along four directions (the two orthogonal ones, plus the diagonals of each element of the mesh) (Cavaleri and Sclavo, 1998).

While the shift to 0.25 degree resolution improved the performance of the wave model, the main problem still existed: the wind speeds in the Mediterranean Sea were steadily underestimated, which of course implied a similar, but enhanced, result also for the wave results. An extensive comparison was done against the measured wave data available from the network of wave measuring buoys distributed along the Italian coasts. This showed an average underestimate of 30%, which peaked at 50% in the more enclosed parts of the basin, like the Adriatic Sea. It was evident that the error was larger when the dimensions of the sub-basin were getting smaller.

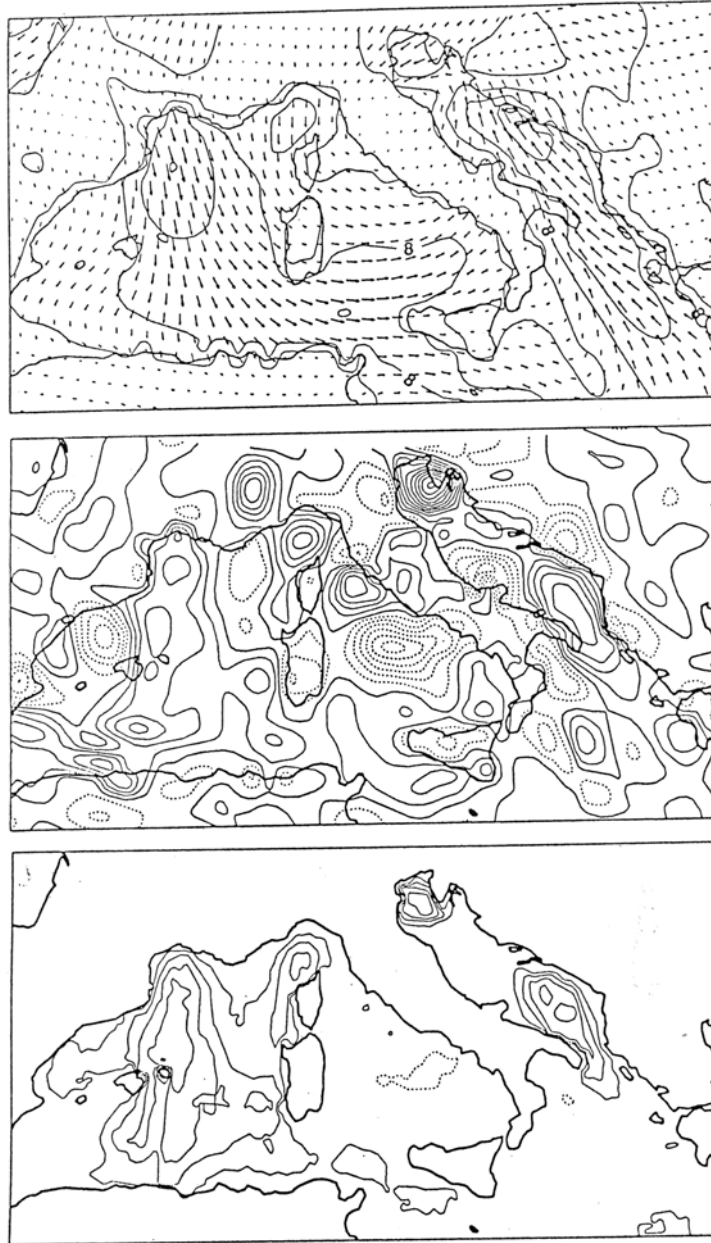
Focusing in particular on the Adriatic Sea, we made an extensive analysis of the situation. We tried a calibration of the ECMWF wind fields, with a correction (increase) of the wind moduli, while a direct comparison was showing that the structure of the fields was in general correct. After identifying a few

storms, we tried different calibration factors, the evaluation of the results being done comparing the wave results against the locally measured wave data, at two of the buoys mentioned above (Pescara and Monopoli) and at the oceanographic tower of our institute, located in the Northern Adriatic, 15 km off the coast in front of Venice, on 16 metre of depth. By trial and error we found an optimum calibration factor of 1.5 (+/-0.05). The procedure we used for the Adriatic Sea was therefore the following: we used the ECMWF surface wind fields, interpolated at the knots of a grid suitably aligned along the main axis of the basin, we corrected them multiplying the moduli times 1.5, and used the resulting wind fields to drive the Wam wave model. One example of the derived improvement is given in Figure 2, where we see the original wave results (not corrected input wind fields) and the ones derived after the calibration of the input winds. An extensive description of the calibration and of the results is given by Cavaleri and Bertotti (1997).



*Figure 2 – Time history of the modelled significant wave height at Pescara, in the Adriatic Sea. (Upper panel), results obtained using as input the ECMWF wind fields; (lower panel), after calibration of the wind speeds (after Cavaleri and Bertotti, 1997).*

Tracking the reasons for the underestimate, we focused our attention on the horizontal diffusion that is applied to the fields to increase the numerical stability during the integration procedure. While this diffusion can have limited effects in the open oceans, where most of the time the meteorological pattern is rather smooth and distributed in space, the conditions are drastically different in the enclosed basins, especially if surrounded by a complicated orography, as it is the case of the Mediterranean Sea. In this case the surface wind fields are similarly complicated, especially just off the coast where the wind is blowing from. Therefore a horizontal diffusion tends to smooth these differences, leading to an unrealistic more uniform field. Due to the nonlinear processes that relate the resulting wave field to the input wind, this leads not only to a wrong distribution of wave heights, but also to lower peak values. An example is given in Figure 3, where we show the general wind field in the Western Mediterranean. A mistral is blowing in the gulf of Lion, while sirocco is active along the main axis of the Adriatic Sea. The second panel shows the resulting differences once the horizontal diffusion is decreased in the lower layers close to the surface. Finally, the third panel shows the differences of wave height between the two runs, without and with reduced diffusion. A full description of the procedure and of the results is given by Cavaleri et al (1997).



*Figure 3 – (Upper panel): wind field in the Western Mediterranean Sea. The isotachs are at 4 m/s interval. (Middle panel): wind speed differences resulting from the use of a reduced horizontal diffusion. The isolines are at 20 cm/s interval. (Lower panel): as the middle one, but for wave height. Isolines at 5 cm interval.*

In 1998 the Centre was planning to move to a higher resolution of the meteorological model. To get an idea of the possible improvements of the surface wind fields that could be expected, we carried out a large number of experiments, something made possible by a prolonged staying at ECMWF. After identifying a number of storms in the Mediterranean Sea, we hindcast them with a series of numerical experiments. For each storm and for a given resolution, we did a sequence of three day forecasts, each shifted of two days with respect to the previous one, all starting from the available analysis. We did not make use of assimilation to avoid the smoothing effect of the lower resolution present in the procedure. To produce a continuous sequence of wind fields, we extracted from the various forecasts the fields after 24 hours from the beginning of the experiment (to allow enough time to the model to develop the characteristics of the fields associated to its resolution) up to its end (72 hours, to keep the error of the forecast within acceptable limits). The fields

were extracted at 6 hour interval, and their sequence was then used to drive a high resolution (0.25 degree) Wam wave model in the Mediterranean Sea. This run was uncoupled, i.e. there was no feed-back from the waves to the atmosphere. However, this had no consequence, because the winds had already been obtained in coupled mode.

We considered four different resolution R, namely T106, T213, T319, T639. For each one of them running all the considered storms produced a 42 day dataset (168 fields for both wind and waves), suitable for later analysis. This revealed the expected increase of the average wind speeds, hence of wave heights, with increased resolution. An example is given in Figure 4, where we show the evolution of the wind and wave conditions at Alghero, on the West coast of Sardinia during one of the considered storms. The higher values of  $U_{10}$  and  $H_s$  with increased R are evident. However, by comparing the wave results against the buoy data, it was clear that even at the highest considered resolution, both the wind speeds and the wave heights were still underestimated, the  $H_s$  values being low by 18%. A different evidence is in Figure 5, where the average increase of wind speed is shown normalised with respect to T106. For comparison, also the parallel results for the oceans are shown (northern and southern hemispheres, and tropics). It is evident that, while on the oceans the progress with increasing R is limited, and there is a tendency towards asymptotic values, no such feature is present for the Mediterranean Sea. This suggests that even the T639 resolution does not succeed in properly reproducing the fields in the basin,

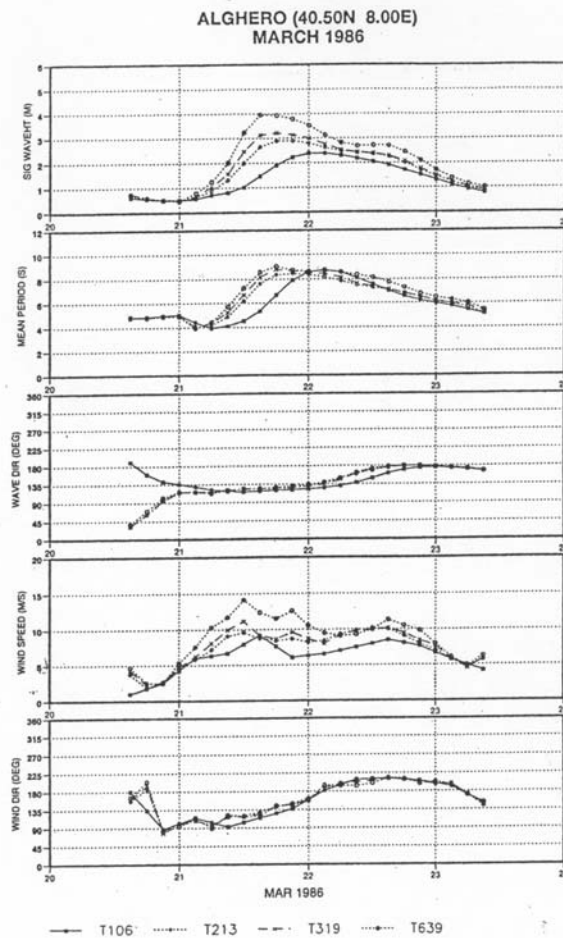


Figure 4 – Time series of wave height, period and direction, wind speed and direction at Alghero, on the West coast of Sardinia. The higher the resolution of the meteorological model (indicated below), the higher  $U_{10}$  and  $H_s$ .

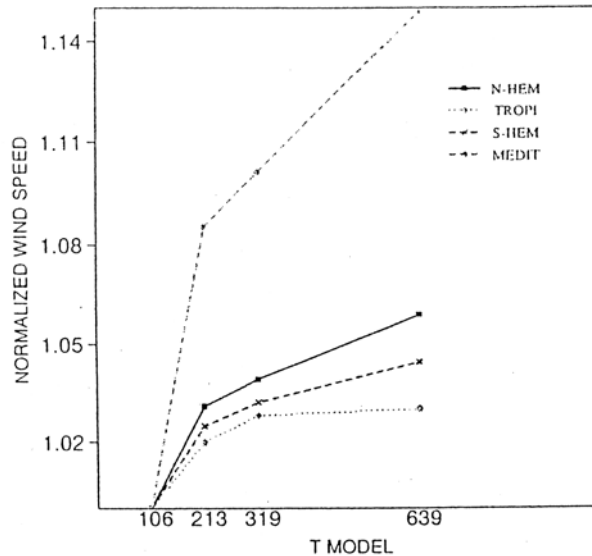


Figure 5 – Normalised increased, with respect to T106, of the average wind speeds according to resolution. The lower diagrams refer to the northern and southern hemispheres, and to the tropics. The upper one to the Mediterranean Sea.

Further exploration of the capabilities present at the different R was done studying the evolution of a cyclone in the Bay of Bengal. The purpose was to verify how the different resolutions coped with the very high gradients present in the central area of the cyclone. The results are summarised in Figure 6, representing the evolution of the pressure minimum. Expectably, the lower resolutions cannot reproduce properly the central area, up to the point that the cyclone is hardly recognisable in the evolution of the minimum. A strong deepening is found with T639, down to 964 hPa. However, also this is still far from the reported central pressure, 930 hPa, showing that even T639 fails in properly describing the evolution of the system.

When ECMWF started the 40 year reanalysis, done using T159, it was of interest to see how the quality of the products, in particular the surface wind speed, related to the previous analysis, and if, mutatis mutandis, the more sophisticated assimilation process was leading to better results. The tests was done in the early stage of the reanalysis, for the period September 1986 to August 1987. The reanalysis winds were used to drive the wave model in the Mediterranean Sea, and the comparison was done against the wave data obtained from some wave recording buoys distributed along the coasts of Italy (different from the network previously mentioned). The results indicated a steady underestimate of the wave heights of about 35%, which suggested the wind speeds to be too low by 20-25%. This figure is consistent with the values we had previously obtained for T106 and T213, indicating that, taking the resolution into account, the reanalysis was not, in the Mediterranean Sea, leading to substantially better results for wind speed and wave height.

In November 2000 ECMWF moved again to a higher resolution, T511. We had not tested this specific resolution. However, we checked immediately if the results were any better in the Mediterranean Sea. This had been done two years before also for T319, operational since 1998. We had found that the shift from T213 to T319 had not produced obvious improvements of the wind in the Mediterranean Sea. On the contrary, the shift to T511 showed immediately a substantial increase of the surface wind speeds, the results being consistent with those from our numerical experiments, summarised in Figure 5. In particular we checked the most critical areas, i.e. the smaller basins, where we find the stronger underestimates. We have mentioned above that in the

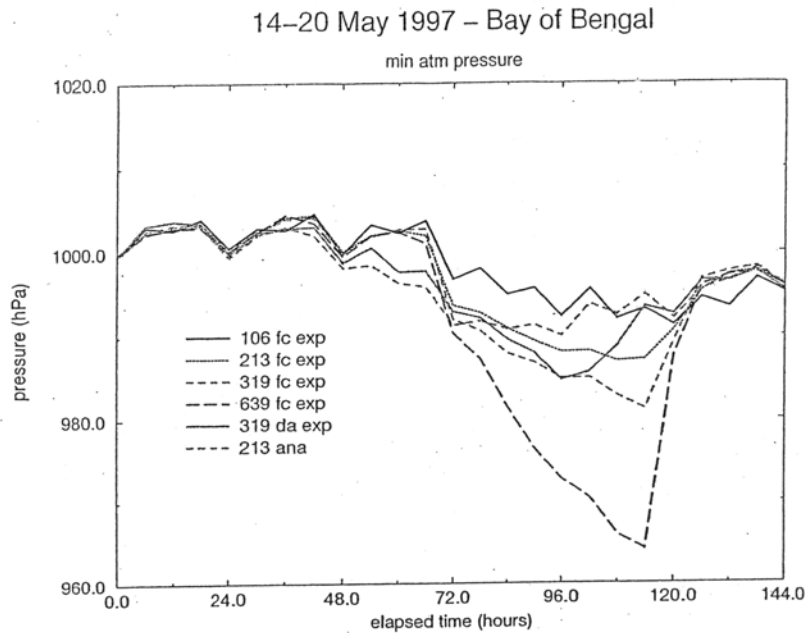


Figure 6 – Evolution in time of the minimum pressure of a cyclone in the Bay of Bengal, according to different resolutions of the meteorological model.

Adriatic Sea, to reach something comparable with the true value, the ECMWF wind moduli had to be multiplied times 1.5. Extensive tests showed that T511 was producing, on the average, wind speeds larger than T213 and T319, and the correction factor had to be accordingly reduced to 1.35.

To summarise, the main point is that the quality of the surface wind fields, hence of the associated wave results, is very good in the open oceans, but it is not good enough in the enclosed basins, or, more in general, in areas where the wind feels the influence of land. We have focused our attention in the Mediterranean Sea. In these 14 years substantial improvements have been done, and the present results provide a fair idea of the wind and wave situation in the basin. However, as to the absolute values, we still find an evident underestimate of the moduli. The meteorological patterns are well reproduced, but the fields lack strength. The average underestimate of  $U_{10}$  with the present operational model, T511, is between 10 and 15%, the value changing with the area considered. In particular, the results worsen when we consider the most enclosed areas. There is a definite tendency for an increasing underestimate when we move from the larger to the smaller areas. In the Adriatic Sea this is still 25%. Also the shift to T639 will not be sufficient to solve the problem.

## References

Cavaleri, L., and L. Bertotti, 1997, In search of the correct wind and wave fields in a minor basin, *Monthly Weather Review*, Vol. 125, No. 8, pp. 1964-1975.

Cavaleri, L., L. Bertotti, M. Hortal, and M. Miller, 1997, Effect of reduced diffusion on surface wind fields, *Monthly Weather Review*, Vol. 125, No. 11, pp. 3024-3029.

Cavaleri, L., and M. Sclavo, 1998, Characteristics of quadrant and octant advection scheme in wave models, *Coastal Engineering*, 34, pp. 221-242.

Dell'Osso, L., L. Bertotti, and L. Cavaleri, 1991, The GORBUSH storm in the Mediterranean Sea: atmospheric and wave simulation, *Monthly Weather Review*, Vol. 120, No. 1, pp. 77-90.