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Impact of wind field horizontal resolution on sea waves hindcast around Calabrian coasts(*)

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Summary. — We investigated the impact of wind field enhanced horizontal resolution on sea wind-wave hindcast around the Calabrian coasts, which lie at the southernmost tip of the Italian peninsula. Simulations have been performed using WAM (WAve Model), a third-generation state of the art wave-model. In order to study this topic, we shall discuss two simulations sets. The first set forces WAM by ECMWF (European Centre for Medium-Range Weather Forecasts) surface wind field analysis, used in this paper with a resolution of 0.5°; while for the second simulation set RAMS (Regional Atmospheric Modelling System) surface wind field forces WAM. Initial and dynamic boundary conditions for RAMS simulations, which have a 20 km horizontal resolution, are derived from ECMWF analysis. To obtain a reliable statistical data set, integrations have been performed over six months from 1 October 2003 to 31 March 2004. We have evaluated performance comparing the WAM modelled wave heights and directions against data of Wave measuring Buoys (WBs) moored off Cetraro and Crotone. Statistical tests are performed to assess differences between modelled data and measurements and between modelled data sets. Results show better performance for wave height fields when RAMS forces WAM. The best results are obtained for Crotone but differences between simulated and measured wave height distributions are significant at a 99% statistical level. Simulated wave directions are generally good for the model set-up used in this paper and the differences between modelled data sets are minor.

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(*) The authors of this paper have agreed to not receive the proofs for correction.

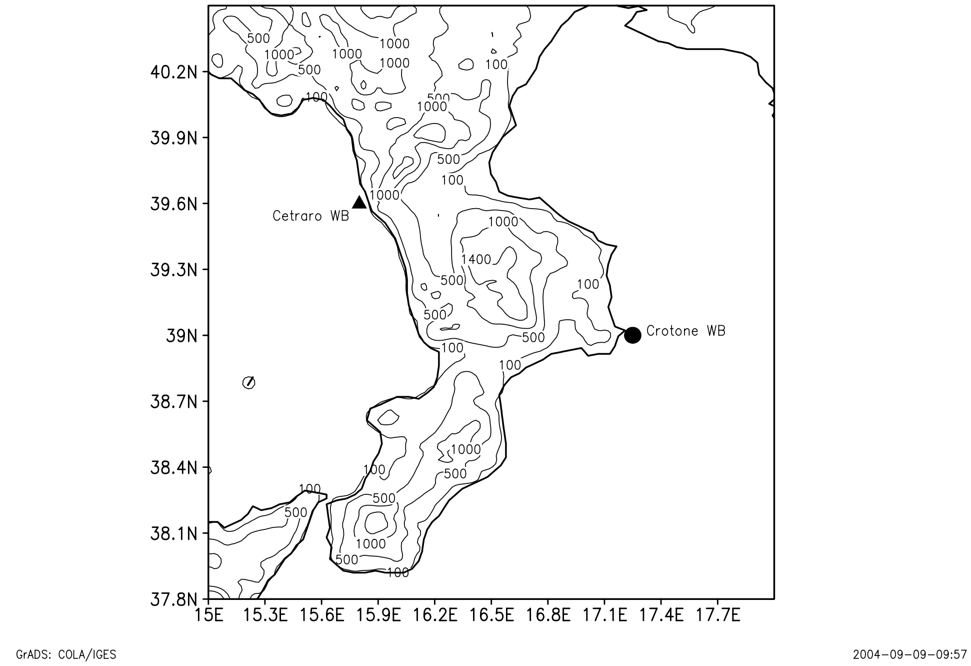

Fig. 1. – Orography of Calabria averaged over 5 km^2. Main orographic features and buoy positions are also reported.

1. – Introduction

The present quality of modelled ocean surface wind fields is generally good and gives good simulations of waves in open seas. However, the situation is different for closed basins [1]. In this case the lack of detailed physiographical features on winds forcing wave models produces a general speed underestimation that has a significant impact on wave modelling. An extensive comparison between modelled wave height using ECMWF wind fields to force WAM and measurements coming from the Italian RON (Rete Ondametrica Nazionale) network, shows that wave heights are underestimated by a 30% factor [1, 2].

In this paper we study the impact of a mesoscale model generated wind field on sea wave hindcast around Calabrian coasts.

The Calabrian peninsula (see fig. 1) ranges between 37° 55′ and 40° latitude North and between 15°30′ and 17° 15′ longitude East. Its western side is bounded by the Tyrrhenian Sea, the southern and eastern parts are bounded by the Ionian Sea. The Apennines run along the peninsula and are characterized by five main ranges from North to South: the Pollino, the Catena Costiera, the Sila, the Serre and the Aspromonte. The Serre and Catena Costiera peaks are about 1500 m high while the other ranges peak at about 2000 m.

Federico and Bellecci ([3], hereafter also referred as FB) gave a preliminary analysis of sea-wave hindcast around Calabrian coasts in seven case studies. In their paper they selected events with recorded significant wave height larger than 3.0 m. In the present work the impact of enhanced horizontal resolution is assessed in a "typical" situation, *i.e.* considering the whole dataset from 1 October 2003 up to 31 March 2004.

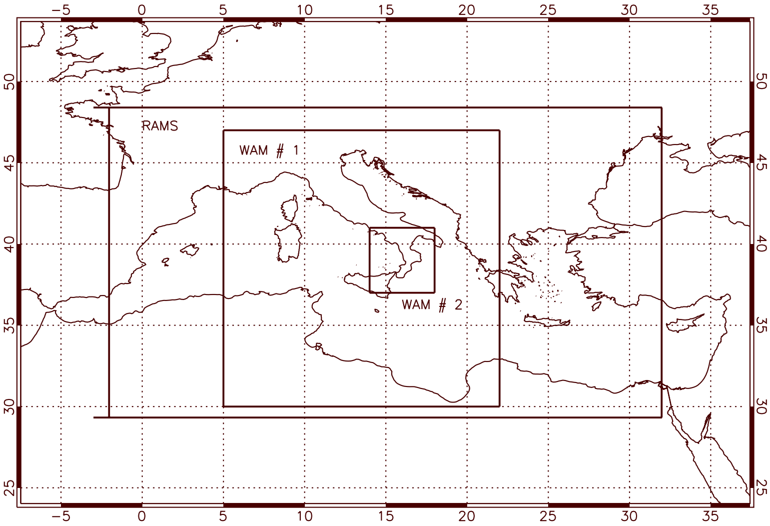

Fig. 2. – Models domains. RAMS uses one grid only; dynamic boundary conditions for the smaller WAM grid (no. 2) are taken from the largest one (no. 1).

The main conclusion in FB was that "*there is a large impact of R20 (i.e. RAMS 20 km horizontal resolution) wind fields on simulated sea storms. Configuration that uses R20 wind fields always performs better than ECMWF (surface wind) analysis. When large scale forcing is well represented in the general circulation model, the maximum significant wave height error (i.e. the error for the maximum significant wave height during the sea storm) and the mean absolute error are more than halved. When large scale forcing is not well represented in ECMWF analysis, improvements are smaller and results unsatisfactory even when using R5 wind fields (i.e. RAMS 5 km horizontal resolution wind field)*". The finest horizontal resolution adopted in FB was 5 km, due to the relatively short integrations performed. However, it was noticed that the CPU (Central Processing Unit) time required to compute R5 winds is large and its operational implementation still poses feasibility problems. Consequently, in this paper we consider the impact of 20 km horizontal resolution that is feasible in our operational environment or in the building-up of wave climatology, when integrations last for several years.

To assess the impact of the RAMS wind fields on the WAM runs we compare two simulation sets. The first one uses ECMWF surface-wind analysis to force WAM, the second simulation set uses RAMS 20 km horizontal resolution winds. The coupling between meteorological models and WAM is one way, *i.e.* winds are pre-computed (RAMS case) or downloaded from MARS (Meteorological Archive and Retrieval System; ECMWF case) and customized to force WAM.

To better represent the coastline geometry, WAM is run in a nested configuration. Domains for both WAM grids and for RAMS grid are shown in fig. 2. WAM resolutions are 0.1° and 0.05° for the coarse (no. 1) and the fine (no. 2) grid, respectively. WAM resolution is the same in both North-South and East-West directions.

RAMS wind fields are interpolated bilinearly to both WAM grids. Moreover the first RAMS level is 20 m above the surface and the winds are extrapolated to 10 m a.g.l. (above ground level) height assuming a logarithmic vertical profile. ECMWF winds are 10 m a.g.l. and are interpolated bilinearly to WAM grids. We will refer to the first simulation set as WAM_RAMS and to the second as WAM_ECM. In summary we will discuss the following numerical experiments sets:

1) WAM_ECM, for WAM runs using ECMWF surface wind fields on both WAM grids;
2) WAM_RAMS, for WAM runs using RAMS 20 km horizontal resolution surface-wind fields on both WAM grids.

The quality of surface-wind fields when passing to a higher resolution is expected to be higher, of course. However, the aim of this paper is to quantify the impact of this "*expected*" improvement on wave hindcast. This is a less obvious issue because it depends on models used on their interfaces and on the target area. So, even if there are several LAMs (Limited Area Models) operational in the Italian sea (albeit at finer resolutions than our LAM), this paper conveys new information about this particular model set-up and target area. For this same reason and because of higher WAM resolution around Calabria, we limit our analysis to the Cetraro and Crotone WBs (Wave measuring Buoys). These are free-floating TRIAXIS buoys that record directional wave data (Axys Technologies Inc.). Their locations and the main topographic features of Calabria are reported in fig. 1. Data and models outputs are available every three hours, providing significant wave height, mean wave direction and mean wave period.

The paper is organized as follows: sect. **2** gives a short description of models set-up. Then the results are discussed in sect. **3** and conclusions are drawn in sect. **4**.

2. – Models

2˙1. *RAMS model.* – In the following we give a brief description of the RAMS set-up. The reader should refer to Pielke *et al.* and Cotton *et al.* [4, 5] for details. Its domain extension is shown in fig. 2 and the grid spacing is 20 km. We use thirty levels, up to 15000 m, in the terrain following coordinate system. Levels are not equally spaced: within the PBL (Planetary Boundary Layer) the layers are about 50–200 m thick, while in the middle and upper troposphere they are 1000 m thick. The first RAMS level is 20 m above the ground and winds are reduced to 10 m, as requested by WAM, assuming a logarithmic profile.

Initial and dynamic boundary conditions are provided by ECMWF analysis and are available every 6 hours. The horizontal resolution of the ECMWF analysis used in this paper is half a degree. The ECMWF model is a spectral model whose resolution is typified by the truncation level of the two-dimensional Fourier series used to represent horizontal fields. At the time of writing the ECMWF horizontal resolution is T511 (it will be soon enhanced to T799). In this paper we use results from the T511 model with a practical resolution of 0.5°. ECMWF surface products for the Mediterranean basin are also available at 0.25°, although for this paper they were available to us with 0.5° horizontal resolution. It should be considered that this study concerns the effects of enhanced horizontal resolution on sea wave hindcast around Calabrian coasts and not the direct comparison between ECMWF and RAMS models and, in respect to the basic issue of this paper, the conclusions are still valuable.

All the RAMS simulations account for a 12 h spin-up time and they last three days. The LAM simulation scheme is as follows: the integration starts at 12:00 UTC of a given day d_0 and lasts 84 h. The first twelve hours are discarded and RAMS output is available, every three hours, from 00:00 UTC of $d_0 + 1$ day to 00:00 UTC of $d_0 + 4$ days. Next

RAMS integration starts at 12:00 UTC of $d_0 + 3$ days and lasts 84 h. This scheme is repeated until the whole period of simulation, from 1 October 2003 to 31 March 2004, is covered. Wind fields are stored every three hours and used to force WAM.

Figure 2 shows that the southern RAMS border is close to the sea. This implies that the southern wind may not be well resolved by RAMS in part of the wave generating area, most likely in the Gulf of Sirte. In addition it should be realized that waves at a given location depend not only on waves generated by local winds but also on swell coming from long distances. At the same time we need to reduce computing times in order to have real-time availability of the products, so extension and resolution of the RAMS domain are a compromise between enhanced horizontal resolution and computing time. Finally, ECMWF and RAMS wind quality is expected to be similar near RAMS domain borders.

2˙2. *WAM model.* – In this subsection we give a brief description of the WAM configuration. For a complete reference the reader should refer to the relevant bibliography [6,2].

At a given time t and location (λ, ϕ) the wave conditions are represented by the two-dimensional spectrum $F(\lambda, \phi, \theta, f, t)$ where f and ϑ are wave frequency and direction and λ, ϕ are the longitude and latitude. The evolution of $F(\lambda, \phi, \theta, f, t)$ is described by the wave energy balance equation, which, on spherical earth, has the following form:

$$\frac{\partial F}{\partial t} + \frac{1}{\cos\phi}\frac{\partial\left(\dot{\phi}\cos\phi F\right)}{\partial\phi} + \frac{\partial\left(\dot{\lambda}F\right)}{\partial\lambda} + \frac{\partial\left(\dot{\vartheta}F\right)}{\partial\vartheta} = S. \tag{1}$$

In eq. (1) dots are time derivatives, S takes into account the physical processes, listed below, while the left-hand side describes the wave energy advection.

Source term S can be divided as follows:

$$S = S_{\rm in} + S_{\rm nl} + S_{\rm dis}\,. \tag{2}$$

In (2) $S_{\rm in}$ is the energy input from the wind field, which is parameterized from Miles theory [7]. $S_{\rm nl}$ takes into account non-linear energy transfer between different waves and it is parameterized following Hasselmann *et al.* [8].

$S_{\rm dis}$ parameterizes dissipation processes. In deep water the only relevant process is represented by wave breaking [8], while in shallow water other relevant processes are possible, depending on bottom conditions. The bottom friction term is taken into account from the JONSWAP study [9]:

$$S_{\rm bf} = -\frac{\Gamma}{g}\frac{\omega^2 F}{\sinh^2(kD)}\,,$$

where $\omega = 2\pi f$, D is the bottom depth, k is the wave number, g is the gravity and $\Gamma = 0.038\,{\rm m}^2\,{\rm s}^{-3}$ is a constant.

$S_{\rm in}$ depends on surface wind-speed through friction velocity u^*; it is the primary term that changes in our simulations. Obviously, changes in $S_{\rm in}$ affect, along the integration, the other terms in (2). The differences among the simulations, however, derive from differences in forcing winds.

The WAM model is used in the nested configuration shown in fig. 2. Grid one has 0.1° grid spacing in both North-South and West-East directions, whilst grid two spacing is 0.05°, in both directions. We use a discretized spectrum of 25 frequency bands in a

TABLE I. – *a) Main statistics for Cetraro significant wave height (see text for explanation); b) the same but for Cetraro wave direction.*

Cetraro	Buoy	WAM_ECM	WAM_RAMS
a)			
μ (m)	0.89	0.44	0.54
σ (m)	0.69	0.42	0.55
BIA (m)	-	-0.44	-0.35
MAE (m)	-	0.45	0.37
ERR_REL (%)	-	55	49
b)			
μ (°)	255	260	257
MAE (°)	-	38	39

logarithmic scale with $\Delta f/f = 0.1$. Frequency spans from 0.042 Hz to 0.41 Hz. Direction resolution is 30° (12 bins).

3. – Results

3·1. *General overview.* – Tables I and II report a summary of the simulations and the buoy statistics for Cetraro and Crotone. Considering the whole dataset, and because of missing data, Cetraro and Crotone have 1263 and 1353 records, respectively.

The first row of table Ia) shows average significant wave heights for Cetraro. The first column refers to measurements, whereas the second and third columns are for WAM_ECM and WAM_RAMS. Both models underestimate significant wave height but WAM_RAMS performs slightly better. The difference between models averages is 0.1 m; this value although modest, is statistically significant. Statistical tests, discussed below, reveal that modelled distributions are different at 99% level. WAM_RAMS average is closer to WAM_ECM than to the buoy and similar considerations apply to standard deviations that are reported in the second row of table Ia).

The third row shows bias (hereafter referred as BIA) computed for WAM_RAMS and

TABLE II. – *a) Main statistics for Crotone significant wave height (see text for explanation); b) the same but for Crotone wave direction.*

Crotone	Buoy	WAM_ECM	WAM_RAMS
a)			
μ (m)	1.10	0.74	0.96
σ (m)	0.75	0.54	0.77
BIA (m)	-	-0.36	-0.14
MAE (m)	-	0.38	0.28
ERR_REL (%)	-	35	28
b)			
μ (°)	115	136	133
MAE (°)	-	35	35

WAM_ECM. It is defined as

$$\mathrm{BIA}(m)=\frac{\sum_{i=1}^{N}\left(H_{\mathrm{mod}}(i)-H_{\mathrm{meas}}(i)\right)}{N}, \tag{3}$$

where N is the number of data for the buoy in question, H_{meas} is the measured wave height and H_{mod} is its paired simulated significant wave height. A positive BIA means that the model overestimates wave height whereas a negative value represents a model underestimation. BIA is negative for both models and confirms their well-known tendency to underestimate wave heights in closed basins and coastal regions.

Two additional measures of models performance, reported in the fourth and fifth rows of table Ia), are the mean absolute error and mean relative error. The mean absolute error is defined as

$$\mathrm{MAE}(m)=\frac{\sum_{i=1}^{N}\left|H_{\mathrm{mod}}(i)-H_{\mathrm{meas}}(i)\right|}{N}, \tag{4}$$

and mean relative error is defined as

$$\mathrm{ERR\_REL}(\%)=\frac{100}{N}\sum_{i=1}^{N}\frac{\left|H_{\mathrm{mod}}(i)-H_{\mathrm{meas}}(i)\right|}{H_{\mathrm{meas}}(i)}, \tag{5}$$

where symbols are defined as above. Referring to table Ia) fourth and fifth rows, it follows that absolute errors and BIA are very similar, *i.e.* errors in modelled wave heights are largely due to model underestimation. Relative errors are high considering the whole dataset. There is an improvement when RAMS forces WAM, however also for this case the relative error is about 50% and results are not impressive when taking the whole dataset into consideration.

Results for Cetraro WB are summarized in figs. 3a, b. Figure 3a shows the scatter plot between buoy and WAM_ECM. Results underestimate measurements, mainly for significant wave heights greater than 1.0 m. The slope for the least-square fit is 0.55. Figure 3b shows the same graph for WAM_RAMS and highlights better performance in this case. The slope for the least-square fit is 0.72.

We performed two statistical tests to assess the difference between measured and modelled significant wave-heights distributions. The tests are the Wilcoxon signed-rank and χ^2 [10]. The Wilcoxon signed-rank test is a classical non-parametric test for the difference in location between data samples. It is based on ranks rather than on numerical values of the data, therefore it does not depend on the distribution of the underlying data and it is resistant to outliers [10]. For χ^2, data are binned in 0.5 m amplitude classes. Both tests reveal that differences between modelled and measured wave height are significant at 99% level. The same result is obtained for WAM_ECM and WAM_RAMS, *i.e.* also in this case the distributions are different at 99% level.

Table Ib) shows results for Cetraro wave directions. Average values simulated by WAMS_RAMS and WAM_ECM are similar and no significant improvement is introduced by RAMS. The second row of table Ib) shows mean absolute errors for direction. It is defined by the following expression:

$$\mathrm{MAE}(^\circ)=\frac{\sum_{i=1}^{N}\left|\mathrm{WAVE\_DIR}_{\mathrm{mod}}(i)-\mathrm{WAVE\_DIR}_{\mathrm{meas}}(i)\right|}{N}, \tag{6}$$

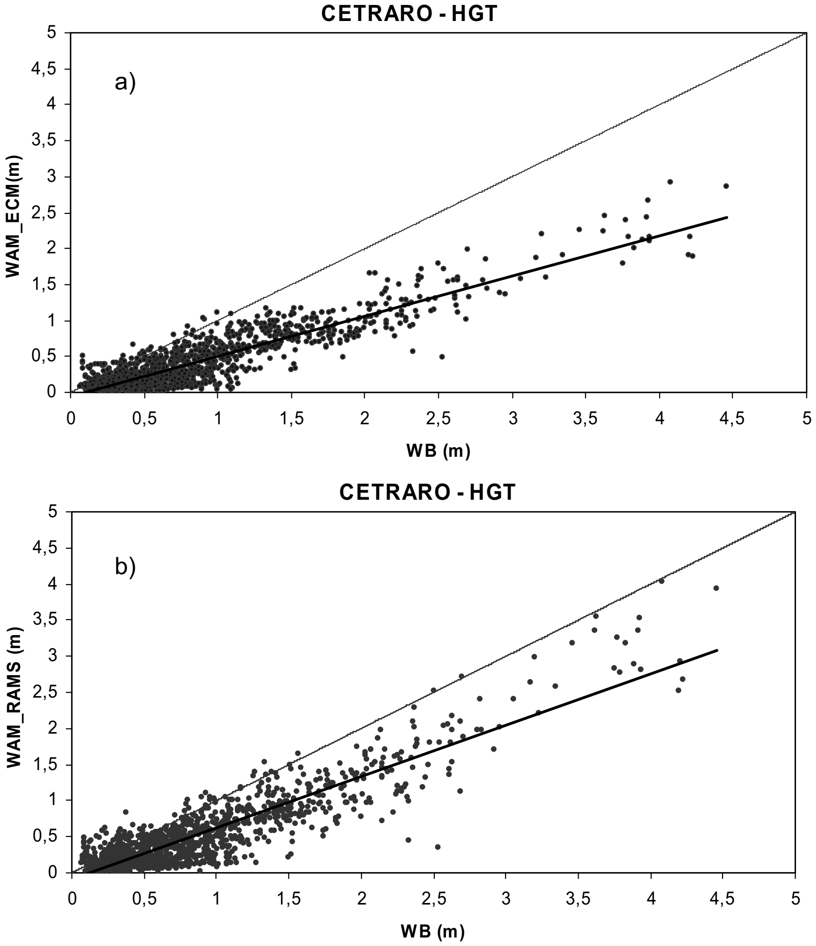

Fig. 3. – a) Scatter plot of WAM_ECM and data for the Cetraro buoy; b) as in a) for WAM_RAMS.

where N is 1263 for Cetraro and 1353 for Crotone and $\mathrm{WAVE\_DIR}_{\mathrm{meas}}$ is the measured wave direction and $\mathrm{WAVE\_DIR}_{\mathrm{mod}}$ is its paired simulated value. Errors are similar considering WAM_RAMS and WAM_ECM models.

The χ^2 test is performed in order to assess statistical differences between modelled and measured data distributions and between modelled data distributions. Data are grouped in twelve 30° amplitude classes and datasets are: WB-WAM_ECM, WB-WAM_RAMS and WAM_ECM-WAM_RAMS.

The results show that the differences between modelled and WB values are significant at a test level of 99%. Differences between models are significant at 95% for the whole data set, but χ^2 does not show significant differences between the modelled direction distributions for higher wave heights (see next subsection).

Table IIa) shows the same statistics of table Ia) for Crotone. The differences between WAM_RAMS and WAM_ECM are larger compared to those from Cetraro and RAMS has a better performance. The average WAM_RAMS significant wave height (0.96 m)

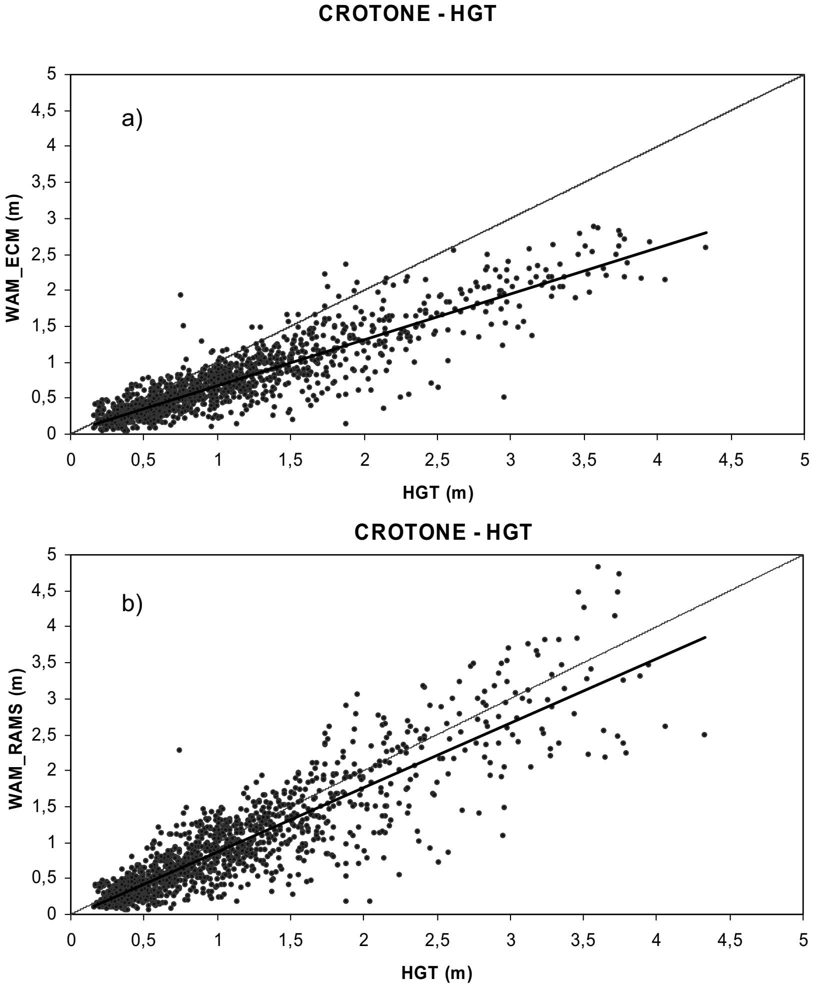

Fig. 4. – a) As in fig. 3a, but for Crotone; b) as in fig. 3b, but for Crotone.

is closer to buoy measurements (1.10 m) than to WAM_ECM (0.74 m). BIA is halved when using RAMS wind fields. Absolute error and BIA are very similar for WAM_ECM, whereas there are differences for WAM_RAMS.

From tables Ia) and IIa) we conclude that the performance is better for Crotone than for Cetraro. This is an appealing feature because Crotone was characterized by higher sea waves during the period analyzed, as can be inferred comparing mean significant wave height at the two WBs.

The results for Crotone WB are summarized in figs. 4a, b. Figure 4a shows the scatter plot between buoy data and WAM_ECM. Compared to Cetraro there is a greater scatter, as can also be inferred by standard deviation values (tables Ia), IIa)), and a systematic underestimation of wave heights is evident. The slope of the least-square fit is 0.64. Figure 4b shows the scatter plot for WAM_RAMS and WB data. The least-square slope is 0.90. The results of statistical tests show that, despite the improvements introduced by RAMS, the differences between modelled and measured values are significant at 99%. This confirms that resolution is only one issue of the problem and additional improvements need to be introduced in our models chain so as to have a more reliable wave hindcast.

For wave direction, see table IIb), the model performance is very similar and no improvement is gained by RAMS. Errors are similar for Cetraro and Crotone WBs. The model averages show a tendency to underestimate eastern components when compared to measurements.

From figs. 3a, b and 4a, b it is evident that WAM_RAMS has a larger scatter compared to WAM_ECM and that there are also evident problems with this model set-up. The larger scatter is related to several features of WAM_RAMS. First of all there are RAMS deficiencies and varying capabilities for handling different physical processes and meteorological situations.

An important problem with current meteorological models is the convective, *i.e.* not explicitly resolved, precipitation. Convective parameterization is used to redistribute heat and moisture in a grid column when the model generates a region which is convectively unstable or superadiabatic and when the grid resolution is too coarse for the model to develop its own convective circulation. Ideally, resolving a convective circulation would require at least a few grid cells to span an updraft horizontally, which means a horizontal resolution of 1 or 2 kilometers. Unfortunately, the convective parameterization schemes currently available assume the grid cell size in the horizontal to be around 20 kilometers or greater. This means that convective parameterization may be activated on any grid of this resolution, but that at resolutions between about 2 and 20 kilometers, no adequate convective adjustment scheme exists.

Another important problem is related to the simulation of the atmospheric variability. Abdalla and Cavaleri [11] studied the impact of wind gustiness on the evolution of wave fields on ECMWF models, extensively. The introduction of gustiness leads to an evident average increase of the resulting wave heights both in the Atlantic and, although to a lesser extent, in the Mediterranean. This result applies also to RAMS and should be studied extensively.

So, meteorological models and RAMS in particular are not able to handle all the meteorological situations properly. An example of this issue is reported in fig. 5 which shows, on the 22 February 2004, 12:00 UTC: i) the difference between RAMS hindcast and ECMWF surface pressure analysis (solid lines); ii) the difference between RAMS and ECMWF analyzed wind speeds (dashed lines). From fig. 5 it follows that a West-East pressure gradient and wind speeds over the Ionian sea are overestimated by RAMS and a careful subjective analysis of RAMS outputs reveals that the model overestimated the deepening of a cyclone on the lee of the Alps which, compared to the analysis, changed the whole circulation pattern in the Central Mediterranean basin. Simulated convective precipitation was high (> 100 m over the Alps) and contributed to the cyclone deepening because of the release of latent heat. Simulated waves for Crotone were higher than 4.5 m for this day while measurements were between 3.0 m and 4.0 m. This event is evident in fig. 4b and gives a contribution to WAM_RAMS larger scatter, that increases the errors although not the bias. In fact, the overall result is an underestimate of the model significant wave height but, for this "particular event", the model overestimates this parameter, so reducing the overall bias.

Another point to highlight is that the quality of LAM wind fields is strictly related to that of the GCM. A LAM starts from a given situation and, driven by GCM initial and dynamic boundary conditions, integrates on its own. Its results, due to enhanced

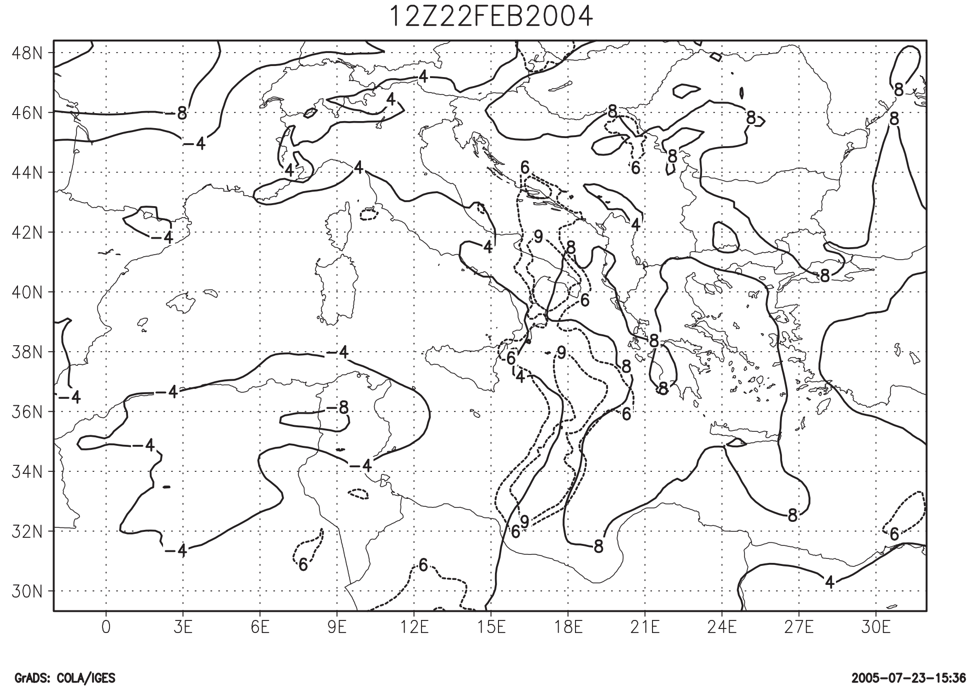

Fig. 5. – Surface pressure difference (solid lines) and wind speed difference (dashed lines) between RAMS and ECMWF analysis for the 22 February 2004, 12:00 UTC. Solid contours are shown for $-8, -4, 4, 8\,\text{hPa}$. Dashed contours are reported for $6\,\text{m/s}$ and $9\,\text{m/s}$.

horizontal resolution and, depending on cases in question, to physical parameterizations will be more detailed but correct as far as initial and boundary conditions are representative of the actual atmosphere. If large-scale fields are wrong, LAM cannot correct GCM forcing if there are no additional measurements that enter the LAM data assimilation process. This point was already noticed in FB. In particular for two sea storms which occurred on the Tyrrhenian side of Calabria, the quality of GCM wind fields was poor and no improvement was given by RAMS, even with 5 km horizontal resolution. Another case study where this issue was significant, occurred on 12 February 2004. The meteorological situation (not shown) was characterized by a low-pressure pattern over the Balkans that generated high wind speeds over the Ionian Sea. Crotone WB reported waves higher than 3.5 m. Figure 6 reports wind fields for ECMWF (little arrow heads) and RAMS on 12 February 2004, 09:00 UTC. RAMS winds are larger and have a greater component from North. Zonal wind is positive and the fetch is limited for Crotone WB. Even if RAMS shows a tendency to correct the wind fields, simulated waves for Crotone WB are between 2.5 m and 3.0 m and no significant improvement is introduced by the LAM.

A final very important remark concerns data assimilation. RAMS simulations assimilate measurements only by ECMWF analysis through latent heat nudging technique and the better wind field quality is expected to be only due to enhanced horizontal resolution and different physical parameterizations. While the aim of this paper is to assess this topic, additional improvements should be introduced by a LAM that performs its own forecast/analysis cycle and ingests new measurements coming from the mesoscale

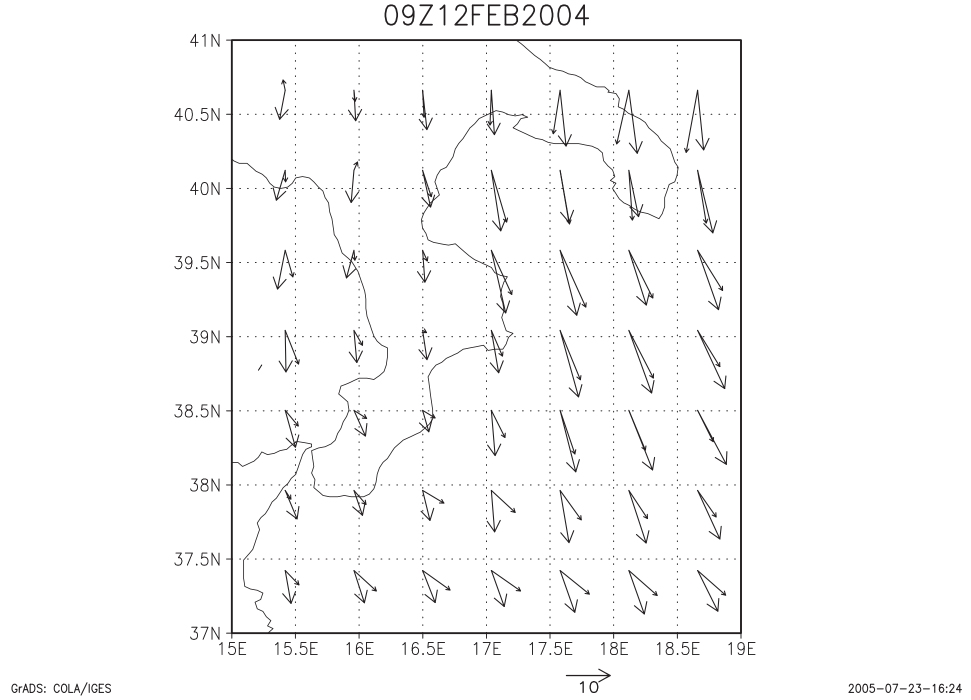

Fig. 6. – Wind fields for ECMWF (little arrow heads) and RAMS on 12 February 2004, 09:00 UTC.

that are not included in the ECMWF analysis/forecast cycle. This is an open question and research is currently in progress in the meteorological community to exploit this potential.

3˙2. *Additional considerations.* – Results of the previous subsection suggest that it is interesting to study absolute and relative errors as a function of significant wave height measured value. To assess this subject we divided the whole dataset into bunches selected by a minimum measured threshold. Several thresholds were taken into consideration and data number exceeding each threshold is reported in fig. 7.

Cetraro and Crotone records with significant wave height of more than a 2 m threshold are 96 and 183, respectively. In order to assess differences between modelled and measured significant wave height distributions we use the Wilcoxon signed-rank test because, due to the low number of 0.5 m amplitude classes for the higher thresholds, we cannot apply χ^2.

Figure 8a reports absolute and relative errors for the Cetraro buoy as a function of significant wave height for WAM_ECM and WAM_RAMS. For both models the absolute error increases with significant wave height. For the 2.0 m threshold, the WAM_ECM error is 1.2 m whereas it is 0.8 m for WAM_RAMS. Differences between models errors increase with significant wave height and WAM_RAMS exhibits a tendency to error saturation. This confirms results obtained in FB, *i.e.* the improvements produced by RAMS are larger for higher significant wave heights.

The relative errors decrease with significant wave height for both models. The WAM_ECM relative error saturates for thresholds greater than 1.0 m (about 45%), whilst

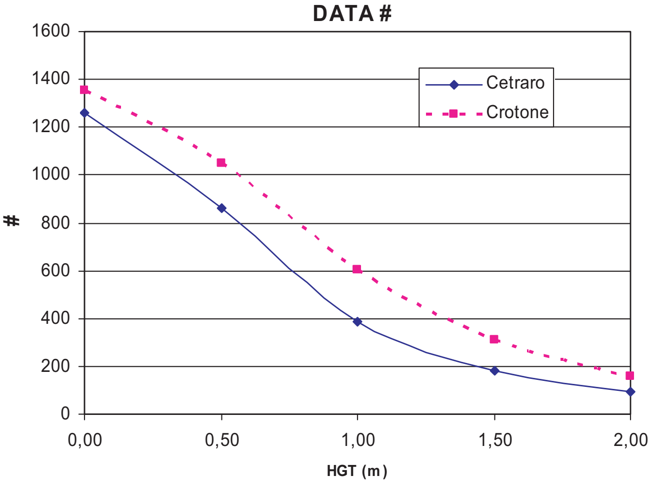

Fig. 7. – Data number for the Cetraro and Crotone buoys as a function of significant wave height threshold.

the WAM_RAMS relative error is still decreasing for 2.0 m wave height. For this threshold relative errors are 31% for WAM_RAMS and 46% for WAM_ECM.

Figure 8b shows the same result for Crotone. Comparing figs. 8a and b, it follows that the models for Crotone have a better performance for all significant wave heights. The differences between WAM_RAMS and WAM_ECM are greater for Crotone. The relative error decreases for WAM_RAMS whereas it saturates (about 35%) for WAM_ECM; the minimum value for the latter model is for the 1.0 m significant wave height (34%) whereas WAM_RAMS has a minimum for the 2.0 m threshold (22%).

In summary, for both sites, the absolute and relative errors are reduced by the use of RAMS with increasing significant wave heights.

Figure 9a shows absolute errors and mean wave directions for WAM_RAMS and WAM_ECM for the Cetraro buoy *vs.* a significant wave height minimum threshold. Results are satisfactory considering model set-ups for wave direction. The absolute error, for both models configurations, decreases with wave height and reaches a minimum (18°) for 1.5 m threshold, and then increases. However the general behaviour is towards a decrease of the absolute error. For Cetraro, the most intense wave storms are due to Mistral winds.

Crotone WB wave directions show a similar behaviour (see fig. 9b). In this case, however, absolute error still decreases for 2.0 m threshold (22°). For Crotone WB, the main storms are induced by Bora winds, low-pressure systems over the Balkans and cyclones travelling in the southern part of the Mediterranean basin.

In summary, wave direction absolute error decreases with significant wave height threshold for both WBs. This should be expected considering that higher sea waves are associated with well-defined weather systems. For lower heights, local phenomena such as sea breeze circulations are important [12, 13] but the horizontal resolutions adopted in this paper, even for RAMS, are not enough to simulate those phenomena properly. This behaviour confirms results reported in FB for sea storms: the use of RAMS model, at least for the model set-ups used in this work, and improves significant wave height simulations but does not affect wave directions.

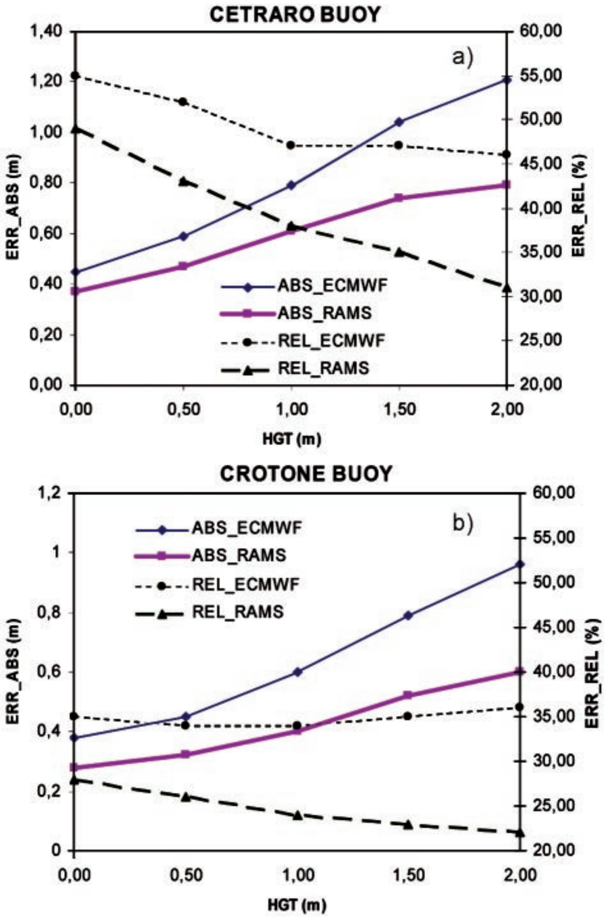

Fig. 8. – a) Absolute error and relative error for the Cetraro buoy *vs.* significant wave height. Absolute error scale is reported on the left y-axis. Relative error is on the right y-axis. Thin solid line is for WAM_ECM absolute error, thick solid line is for WAM_RAMS absolute error. Thin dashed line is for WAM_ECM relative error and thick dashed line is for WAM_RAMS relative errors. b) As in a) for Crotone.

3·3. *Final remarks*. – The basic reason for using a LAM is the presence of strong gradient in meteorological fields that are the result of several physical factors such as for instance, the interaction between air masses and local orography, sea-land contrast, land use and soil heterogeneity, etc. Figures 10a and b show ECMWF and RAMS surface wind fields for 11 January 2004, 12:00 UTC, respectively. These fields refer to a sea-storm which occurred on the Calabrian Ionian coast and was studied in FB. The general structure of the fields is very similar, but the overall wind strength is higher for RAMS, mainly over the Ionian sea. In general, increasing the resolution leads not only to more defined mesoscale structures, but also to higher surface wind speeds. Referring to fig. 10, the average ratio of RAMS and ECMWF wind speed is 1.36 for the whole RAMS domain and 1.25 for the area (9E-21E)-(34N-42N). This area is somewhat more representative of the wind regimes that affect Cetraro and Crotone WBs. Considering the whole dataset,

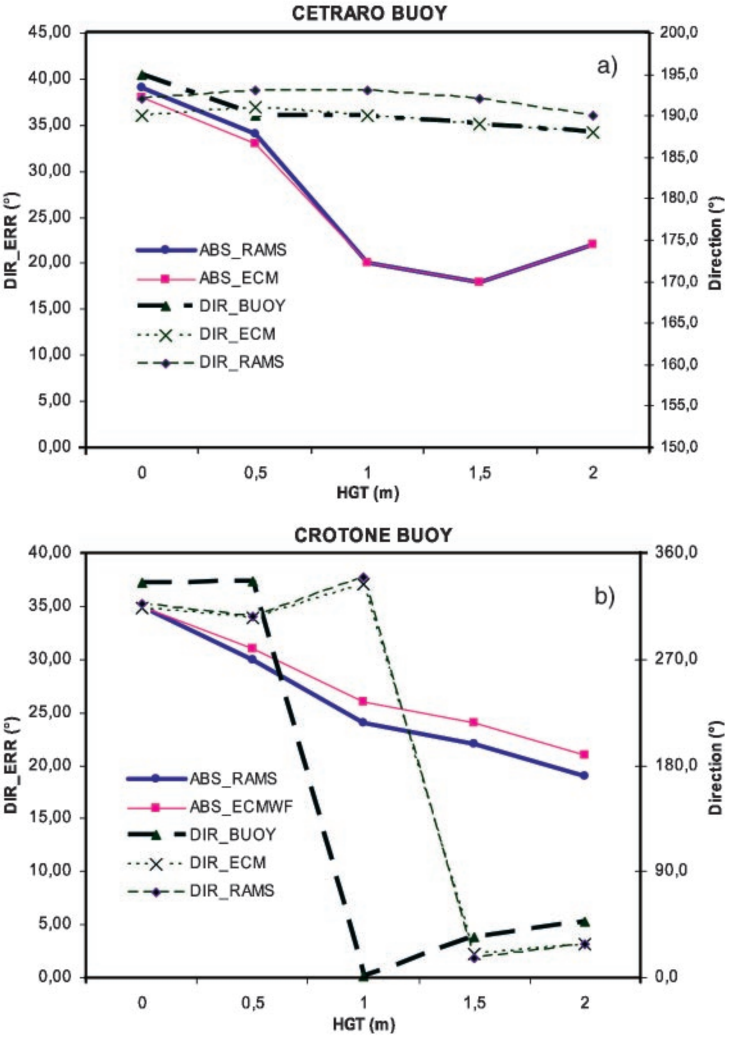

Fig. 9. – a) Cetraro wave direction absolute error and mean value *vs.* significant wave height. Absolute error is reported on the left y-axis. Mean value is on the right y-axis. Thin solid line is for WAM_ECM absolute error, thick solid line is for WAM_RAMS absolute error. Thin short-dashed line is for WAM_ECM mean direction, thin dashed line is for WAM_RAMS, thick dashed line is for WB. b) As in a) for the Crotone buoy.

the average ratio between RAMS and ECMWF wind speed is 1.26 for the RAMS domain and 1.17 for the area (9E-21E)-(34N-42N).

Higher wind speeds and more defined gradients are a consequence of the finer horizontal resolution and, as stated above, there are several contributing factors playing a role. The assessment of the role of each factor is an overwhelming (and probably unnecessary) task because of the number of physical processes involved, although their combined impact on wave modelling was noticeably high for this case study, as reported in FB (see their figure 13 and tables III and IV for statistics).

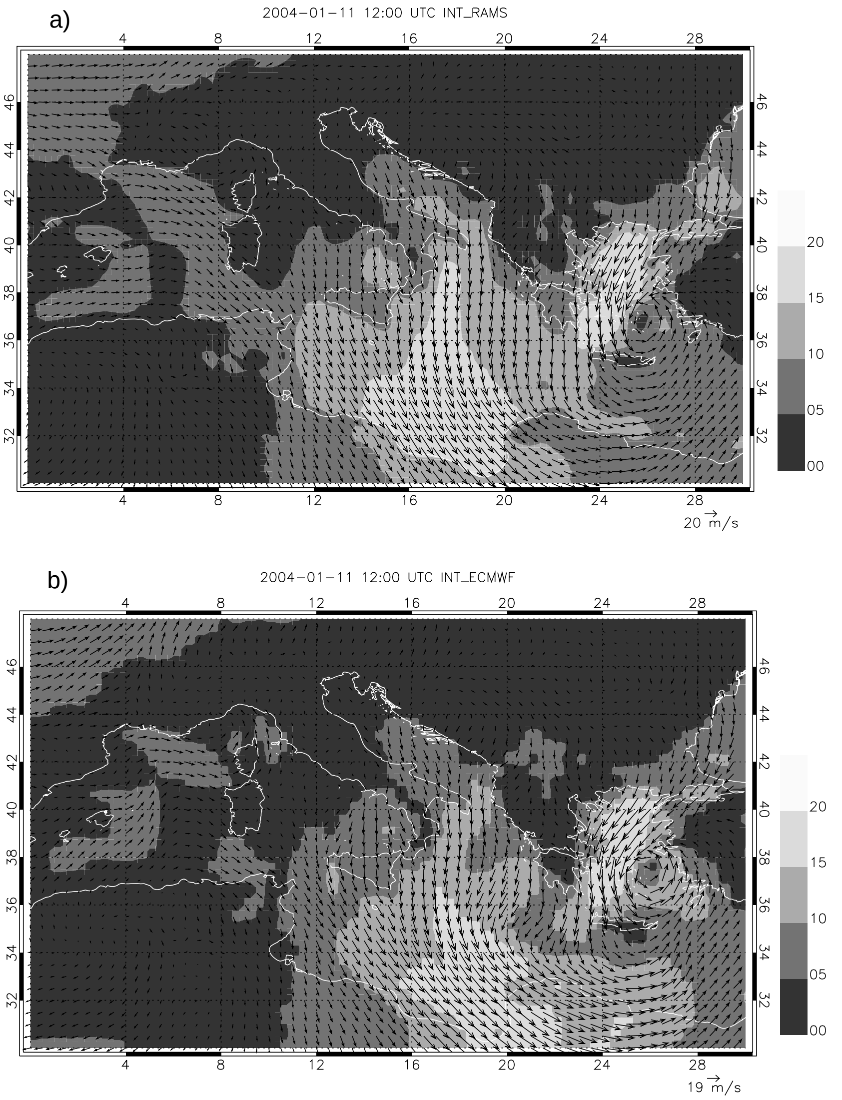

Fig. 10. – a) RAMS wind field (arrows) and wind speeds (filled contours) on 11 January 2004, 12:00 UTC. b) As in a) for ECMWF wind field.

Another issue to consider is the domain extension and its relation to horizontal resolution [14]. Mediterranean weather is characterized by secondary weather systems, *i.e.* meteorological disturbances formed elsewhere reach the basin and are modified locally. Cyclogenesis on the lee of the Alps or over the Aegean Sea are two examples of secondary weather. The Mediterranean basin is characterized by several mesoscale phenomena: local winds such as the Mistral and the Bora, low level jets often associated with the Libeccio Wind, sea breezes and prefrontal rain bands are typical in this region and have a large impact on sea waves. Finally, many of the high-impact weather manifestations are perceived in association with spatial scales of the order of 1–100 km and time scales of the order of hours. To resolve these phenomena, which have a sizeable impact on wave modelling, very high horizontal resolutions ($< 10\,\mathrm{km}$) are needed.

More recently, the hypothesis that planetary-scale agents can determine some preconditions of severe weather in the Mediterranean area has been discussed [15]. In particular the influence of tropical storms and hurricanes has been put forward [15, 16]. Appropriate modelling of Mediterranean weather should take into consideration the interactions between local and global scales and both domain extension and resolution should be chosen accordingly.

On the other hand, computing time requirements and product availability limit these needs and so domain extension and resolution are the result of a compromise between the two opposite needs of high resolution and coverage.

Cavaleri and Bertotti [1] gave an analysis of the ECMWF horizontal resolution impact on wave forecasting for oceans and for the Mediterranean basin. By relative comparison among modelled winds at different resolutions (from T106 to T799) and by ERS1-2 data they found that in oceans, both wind field and wave values gave results which were very close to the measurements. However they found a rather different situation in the Mediterranean Sea. Every increase in resolution leads to an increase of surface wind speed and significant wave height. This suggests that even with a T799 model (about 25 km horizontal resolution) they were below the correct value.

Cavaleri and Bertotti [1] gave a general assessment of the impact of horizontal wind field resolution over the Mediterranean basin and their results are not directly comparable with those reported in this work, which refer to two specific buoys only. Nevertheless, it is interesting to give a qualitative comparison between results obtained in both works. In particular, fig. 6 of Cavaleri and Bertotti [1] shows the distribution of best-fitting slopes between ECMWF T211 modelled wind field, and ERS-1 data over the whole Mediterranean basin. The main characteristic is the underestimation, up to 50%, in the northern part of the basin, gradually attenuating southwards. For the Calabrian-Tyrrhenian coast their fitting value is between 0.6 and 0.7 whilst it is between 0.7 and 0.8 for the Ionian coast. The corresponding distribution for significant wave height (not shown in [1]) has similar but enhanced features due to the relationship between $\mathrm{H_s}$ and the 10 a.g.l. wind speed. Our WAM_ECM fitting slope for significant wave height is 0.55 for Cetraro and 0.64 for Crotone. Considering also the different resolutions used and the different time frames covered by both studies we conclude that our results match in a qualitative sense those reported in [1]. This qualitative comparison gives a "more general" validity to the fitting slopes obtained for WAM_RAMS that are 0.72 and 0.90 for Cetraro and Crotone, respectively.

There are several other meteorological LAMs in Italy, coupled with WAM for wave forecast over the Mediterranean basin, also running with a greater horizontal resolution than our models and results obtained in this work are in between the ECMWF and the LAM ones.

As an example the Prevision Operational System for the mEditerranean basIn and the Defence of the lagOon of veNice (POSEIDON [14]) is an integrated system for the analysis and forecast, specifically designed and set up to bridge the gap between global and local scales for the Venice Lagoon. In Speranza *et al.* [14] the horizontal resolution for the atmospheric LAM, which is the BOLAM (BOlogna Limited Area Model) is 10 km and WAM horizontal resolution is 0.1°. For this model set up a thorough verification for the WAM 2000-2002 sea state forecast is shown for Alghero, Crotone, La Spezia and Mazara. Scatter plot of WAM results and measurements for Crotone (their fig. 5) shows a linear regression coefficient equal to 1.0, a bias equal to $-0.11\,\mathrm{m}$ and a RMSE equal to 0.36 m. Even if a quantitative comparison is not feasible because of the different time period simulated in our study, these values can be qualitatively compared with ours that are 0.9, -0.14 m and 0.38 m for the linear regression coefficient, the bias and the RMSE, respectively.

Simulations around Calabrian coasts by the same authors (unpublished), results reported in FB and our operational environment suggest that 20 km horizontal resolution for RAMS is a good compromise between high resolution and coverage. FB results show that the largest error reduction, compared to ECMWF wind fields, is for 20 km RAMS horizontal resolution whereas a comparatively lower improvement is obtained for 5 km RAMS wind fields.

Further studies are required to better assess this point and to exploit scatterometer and altimeter data. Indeed, whereas this study aims to evaluate results for Crotone and Cetraro WBs, our comparison is obtained using only two buoys and additional data must be used to verify our model set-up and to definitively assess the impact of wind field horizontal resolution on wave modelling around Calabrian coasts. Work is in progress at CRATI Scrl in this direction but results are preliminary and are not discussed in this work.

Considering differences in models set-ups of [1,14] and results of this paper, this qualitative comparison between different models with different horizontal resolutions confirms that higher horizontal resolutions give a better wave forecast, but errors tend to saturation. This confirms that resolution is only one aspect of the problem of wave forecast in an enclosed basin and additional improvements, such as those discussed in this paper, must be considered.

4. – Conclusions

In this paper we have studied the effects of wind field enhanced horizontal resolution, compared to ECMWF surface wind analysis, on wave hindcast for the Crotone and Cetraro buoys. A total of 6 months, from 1 October 2003 to 31 March 2004, were simulated and statistics reported for this period. A few hints are to be derived from this period of comparison.

- WAM_RAMS has better performance than WAM_ECM for significant wave height, as was to be expected. Improvements due to enhanced horizontal resolution are larger for higher significant wave heights. During the period covered in this work Crotone was characterized by larger significant wave heights, and the overall performance is better for this site.
- Despite improvements introduced by RAMS wind fields, statistics show differences between modelled and measured significant wave height distributions at a 99% significant level.
- When we consider model set-up and resolutions, the performance for wave direction is satisfactory. Differences between WB and modelled distributions are significant at the 99% level but this difference decreases for higher waves. Differences between modelled wave direction distributions are significant at a 95% level when considering the whole dataset and the 0.5 m threshold but χ^2 shows no significant differences for higher thresholds.

From the overall results presented in this paper we conclude that, even if resolution is an important aspect of wave modelling, other issues must be developed and studied carefully so as to improve the overall performance. Among others, the proper modelling of convective precipitation, atmospheric variability and (mainly) data assimilation are key factors for the exploitation of a higher horizontal resolution.

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