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Assessment of wind quality for oceanographic modelling in semi-enclosed basins

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Abstract

The quality of surface winds derived from four meteorological models is assessed in the semi-enclosed Adriatic Sea over a 2-month period: a global hydrostatic model ECMWF T511 (40 km resolution), a hydrostatic limited area model LAMBO (20 km), and two non-hydrostatic limited area models: LAMI (7 km) and COAMPS™ (4 km). These wind models are used to drive a 2 km resolution wave model (SWAN) of the Adriatic, and wind and wave results are compared with observations at the ISMAR oceanographic tower off Venice. Waves are also compared at buoy locations near Ancona and Ortona. Consistently with earlier studies, the ECMWF fields underestimate the wind magnitude and do not reproduce the known spatial structure of strong wind events. The results show that the higher-resolution, limited area models LAMI and COAMPS exhibit better amplitude response than the coarser ECMWF: there is a 3- to 4-fold reduction of the wind underestimation at the platform (from 36% to 8–11%). The wave response is also improved with LAMI and COAMPS: there is a 2-fold reduction in the underestimation of wave heights at the platform. These non-hydrostatic models also produce wind fields with more realistic small-scale, spatial structure during strong wind events. The temporal correlation between observed and modelled wind, however, is highest with the global ECMWF model due to the fact that large-scale features can be predicted deterministically, whereas small-scale features can only be predicted stochastically. Models with less small-scale structure have better correlation because they have less "noise." This explanation is supported by increased correlation between modelled and observed waves, the waves representing a smoothing of the wind over fetch and duration. Although there is

Abbreviations: ECMWF; European Centre for Medium-Range Weather Forecasts, LAMBO; Limited Area Model Bologna, LAMI; Limited Area Model Italy, COAMPS™; Coupled Ocean/Atmospheric Mesoscale Prediction System, registered trademark of the Naval Research Laboratory, SWAN; Simulating Waves Nearshore, ISMAR; Istituto di Scienze MARine.

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room for improvement, the high-resolution, non-hydrostatic models (LAMI and COAMPS) offer significant advantages for driving oceanographic simulations in semi-enclosed basins such as the Adriatic Sea.

Keywords: Wind modelling; Wave modelling; Adriatic Sea; Skill assessment; Wind quality

1. Introduction

Wind often plays a dominant role in the dynamics of semi-enclosed seas. In these regions, the limited extent makes errors in the wind fields immediately visible in the derived oceanographic fields. Wind waves are well suited to show the quality of the driving surface winds derived from meteorological models. Particularly in a small basin, they are sensitive and react rapidly to changes in the driving winds. Wave data are typically more readily available because of the difficulties of making long-term wind measurements over the ocean. It is accepted in the literature (e.g., Komen et al., 1994) that, as a general rule, the wave model errors are smaller than those due to the wind. Therefore, when modelled and observed wave results are compared, the wave height errors can be used to identify deficiencies of the driving wind fields.

The Adriatic Sea, a semi-enclosed basin to the east of Italy, connected to the Mediterranean Sea by the Strait of Otranto, was selected as the test area. In the Adriatic Sea, strong southeasterly winds create storm surges that, in conjunction with the astronomical tide, cause damaging floods in the Venice lagoon (Fig. 1). The associated waves not only damage coastal structures, but significantly increase flood levels in the region inshore of where they break (Bertotti and Cavaleri, 1985). The wind is also the controlling factor of the local sea state within the Venice lagoon, a critical component in coupled wave–current models for sediment transport (Umgiesser et al., 2004).

The performance of oceanographic simulations, whether for research or operational forecasting, depends on the quality of the driving wind fields. It is important to note that the best source of surface wind fields to drive the oceanographic models does not necessarily correspond to identifying the "best meteorological model," as surface winds are not the main focus of an operational meteorological model. Even for oceanographic applications, the best model might depend on the specific problem and on the use of the input winds.

The purpose of this study was to identify the wind field, which in conjunction with the wave model under consideration would produce the best wave results in the Adriatic Sea. It is expected that the results apply to other semi-enclosed basins with similar characteristics.

The Adriatic Sea is a particularly challenging region for atmospheric models as the nature of the weather systems, combined with the complex orography of the region, has defied accurate prediction. In the last decade, fortunately, increased computing power and operational meteorology technology has resulted in a proliferation of "limited area" models which are typically driven by global models at their open boundaries. Their grid spacing is typically 5–10 km, allowing a more accurate description of the orography and better representation of small-scale physics.

This paper describes an initial assessment of the quality of surface winds from these new limited area models, comparing the output of four operational or near-operational wind models for the Adriatic Sea and the derived modelled waves to observed data. Both wind and wave data were available at the ISMAR "Aqua Alta" tower and additional wave observations were available at Ancona and Ortona (Fig. 1). Section 2 describes the physical background for the test; Section 3 explains the meteorological and the wave models. The results in Section 4 are followed by discussion in Section 5 and conclusions in Section 6.

2. Background

The Adriatic Sea is a long narrow basin, extending for about 800 km along the major axis from SE to NW, with a width of about 200 km (Fig. 1). Strong wind events in the Adriatic Sea are generally of two

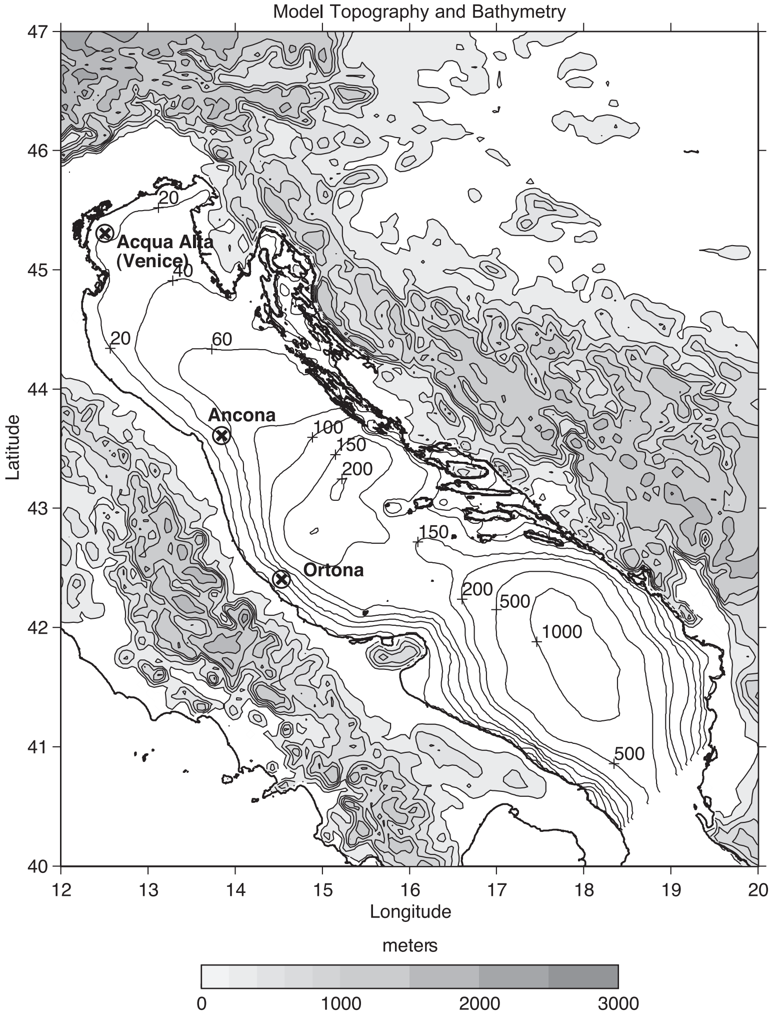

Fig. 1. Model orography and bathymetry. The grey-shaded orography is from the 4-km COAMPS wind model, and the isobaths are from the 2-km SWAN model. The three large crosses show the wave measurement locations; the northernmost location is the oceanographic tower Aqua Alta, where wind and wave measurements were obtained; the central and southern locations are Ancona and Ortona, where only wave measurements were obtained.

types. When a strong southeasterly "sirocco" wind blows over the Adriatic, water level increases in the NW causing flooding in the shallow coastal regions. The sirocco is generally considered a basin response with large spatial scales. By contrast, when there is a strong northeasterly "bora" flow, the complex orography of the Dinaric Alps on the eastern Adriatic coast creates fine structured jets and lee wakes with strong sub-basin scale spatial gradients across the northern Adriatic. Both types of wind events can generate large waves off Venice, although the sirocco-driven waves can be larger and have longer periods (Cavaleri et al., 1997; Poulain and Raicich, 2001).

The effect of wind forcing on simulated oceanographic processes has been addressed in several recent studies. Cavaleri and Bertotti (1997), simulating waves in the Adriatic using the WAM model, found that the ECMWF winds (version T213, about 100 km resolution) need to be enhanced by a factor of 1.50 in order to obtain modelled waves close to the measured ones near Venice (Aqua Alta) and at two other locations along the Italian coastline. Zavatarelli et al. (2002), adopted this factor to force a 3D model of circulation in the Adriatic. In a subsequent study, Cavaleri (2002) found that, if higher resolution ECMWF winds were used (version T511, about 40 km resolution), the factor could be reduced to 1.35. Consistently with this result, Wakelin and Proctor (2002), conducting storm surge simulations for the Adriatic, found that wind from the ECMWF model underestimated the heights of surges and stated that a suitable limited area model "would need to include a realistic orography since the high spatial variability of the winds is due to the effects of the mountain ranges that border the Adriatic on three sides." Manca et al. (2002), studying dense water formation in the southern Adriatic Sea, also found it necessary to increase ECMWF winds by 30%, so that the bulk formulae would yield realistic results for the heat budget, and declared a need for a wind model capable of describing the local orography.

One of the reasons why global meteorological models do not succeed in providing high-quality surface winds in enclosed basins is the relatively coarse resolution with which they describe the local geometry, in particular the orography that surrounds the basin. This lack of resolution implies a spatial smoothing that removes fine resolution effects due, for instance, to valleys and ridges. Therefore, it is reasonable to assume that limited area models, focused on the area of interest and with the consequent capability of using much higher resolution, may provide better results.

Results from a high-resolution model with finely resolved orography were recently presented by Pullen et al. (2003). They compared observed wind fields from a 4-km nested grid for the Adriatic [Coupled Ocean/Atmosphere Mesoscale Prediction System (COAMPS)] with fields from a coarser resolution 36 km nest. For a 125-day period (February–May 2001), the authors showed that the higher-resolution model produced more realistic levels of wind variability as found in the records of two land-based meteorological stations. Interestingly, the 4-km model had virtually the same model/data wind correlations at these sites as the 36-km model. Employing the two different resolution wind fields to drive a 2-km resolution 3D ocean circulation model of the Adriatic Sea, they proceeded to compare model-derived and ADCP-measured currents at two northern Adriatic locations away from the direct influence of the bora. Utilizing simple statistics (mean, standard deviation and rms error) they found that the 36-km forced ocean model generally yielded better agreement with observations. However, over the shelf at subsurface depths, where correlation with wind was greatest, the ocean model forced by the higher resolution meteorological model produced higher correlation with the measured velocity. In addition, the pattern of strong spatial gradients in the 4-km COAMPS during a fall 1999 bora event (Doyle, 2002) was in good agreement with research aircraft measurements (J. Doyle, personal communication).

3. Methods

3.1. Meteorological models

There are at least 15 different operational wind models that provide forecasts of wind at 10 m height for the Adriatic Sea (http://www.westwind.ch). Many of these are coarse-resolution models that cover all of Europe, but some are local models that in the Adriatic region have resolutions of 6–7 km. The four models described below were selected because they represent a wide range of resolution, forcing and numerics, and offer access to archived results.

3.1.1. ECMWF model

The ECMWF global operational atmospheric model adopted is version T511, currently operational at the European Centre for Medium-Range Weather Forecasts (Reading, UK); it is a spectral, 3D, sigma-coordinate hydrostatic model with 60 vertical levels. Current configuration provides two daily forecasts with output every 6 h. To allow the model dynamics some time to adjust after initialization, forecast winds at 06, 12, 18 and 24 h were used (00 + 06, 00 + 12, 00 + 18, 00 + 24). The practical horizontal resolution of this model is about 40 km.

Comprehensive documentation of the analysis and forecasting system is given in the ECMWF Meteorological Bulletins 1.5/1, 1.6/2 and 1.6/3. Further reading can be found at http://www.ecmwf.int and in Komen et al. (1994).

3.1.2. LAMBO model

Limited Area Model BOlogna (LAMBO) is an operational atmospheric, limited area model at Servizio Meteo Regionale-Agenzia Regionale per la Protezione dell'Ambiente, regione Emilia Romagna (SMR-ARPA-EMR) in Bologna, Italy. This version is a finite difference, 3D, sigma-coordinate hydrostatic model. Initial fields are obtained from ECMWF 00 and 12 UTC operational analysis; boundary conditions from ECMWF operational forecast. The configuration provides two daily forecasts with data every 6 h. As with the ECMWF winds, forecasts at 06, 12, 18, 24 h (00 + 06, 00 + 12, 00 + 18, 00 + 24) were used. Horizontal resolution is about 20 km. For detailed and extensive descriptions of the applications and numerics of the model, see Janijc (1990), Mesinger et al. (1988) and Paccagnella et al. (1992).

3.1.3. LAMI model

Limited Area Model Italy (LAMI) is the Italian operational implementation of LOKAL MODELL, the limited area model originally developed by the German Meteorological Service [Deutscher Wetter-Dienst (DWD)] for meso/micro-scale weather prediction and simulation, and developed by several European meteorological services belonging to the COSMO (COnsortium for Small scale MOdelling) consortium. LAMI is managed by SMR-ARPA-EMR, UGM (Ufficio Generale per la Meteorologia, Italian Airforce) and Regione Piemonte. It has been operational since the beginning of 2001 at the CINECA super-computing Centre in Bologna. It has a 7-km grid spacing and 35 vertical terrain-following levels. It is a fully compressible, non-hydrostatic 3D model in which initial and boundary conditions are obtained from the DWD global circulation model GME (Majewsky, 1998; Majewsky et al., 2002). LAMI gives output every 3 h and produces a 48-h forecast once each day. We therefore used forecast winds at 03, 06, 09, . . ., 24 (00 + 03, 00 + 06, 00 + 09, . . ., 00 + 24). For further details, see Doms and Shattler (1999), Cacciamani et al. (2002) or the COSMO web site (http://www.cosmo-model.org).

3.1.4. COAMPS model

The Coupled Ocean/Atmosphere Mesoscale Prediction System (COAMPS) is a 3D finite difference, non-hydrostatic, sigma-coordinate model developed by the Naval Research Laboratory (Hodur, 1997). The version adopted was run in a re-analysis mode using three-nested grids with the finest 4-km grid mesh centred over the Adriatic Sea. The two outer meshes are a 12-km grid covering the majority of the Mediterranean and a 36-km resolution European grid. The global NOGAPS model provides lateral boundary conditions for the 36-km grid at 6-h intervals. In the reanalysis configuration, analyses are performed twice daily with forecasts for the following 15 h. Forecast winds at 03, 06, 09, . . ., 24 h (00 + 03, 00 + 06, 00 + 09, 00 + 12, 12 + 03, 12 + 06, 12 + 09, 12 + 12) were used. Further details and an evaluation of the COAMPS system are documented in Hodur et al. (2001) and (for the Adriatic re-analysis) in Pullen et al. (2003).

3.2. Wave model

3.2.1. SWAN model

In order to simulate the wave characteristics using these four wind models, a third-generation wave model, SWAN (Simulating WAves Nearshore), has been implemented for the Adriatic Sea. The SWAN model was developed for shallow waters at Delft University of Technology (TU Delft), with support from the Office of Naval Research (USA) and the Ministry of Transport, Public Works and Water Management (The Netherlands). The basic model used in this paper was SWAN version 4.11, which contains important improvements in the advection schemes, which significantly reduce diffusion, extending the application of SWAN from shallow water to basin-scale simulation (Rogers et al., 2002). The code was enhanced for parallel processing using OpenMP by the US Naval Research Lab (R. Allard, personal communication).

Waves in SWAN are described with the two-dimensional wave action density spectrum, the balance equation of which, takes into account the local rate of change in time, the propagation in geographical space, the shifting of the relative frequency due to variations in depths and currents and the depth-induced and current-induced refraction. The sink-source terms take into account the generation by wind, dissipation by white-capping, dissipation by depth-induced wave breaking, dissipation by bottom friction and redistribution of wave energy over the spectrum by non-linear wave–wave interactions. A full description of the SWAN model is given by Holthuijsen et al.

(1989), Booij et al. (1999) and Ris et al. (1999), and http://www.swan.ct.tudelft.nl.

A total of 36 uniformly distributed directions were used with 26 frequencies geometrically distributed: $f_{n+1}=1.1f_n$, and $f_1=0.05$ Hz. The model time step was 10 min and the spatial grid had a uniform resolution of 2 km over the Adriatic. The bathymetry for the 2-km grid was interpolated from the finite element tidal model of Cushman-Roisin and Naimie (2002). The wind components from the four wind models were linearly interpolated onto the 2-km wave model grid prior to running the simulations. Incoming waves at the open southeastern boundary of the Adriatic were assumed to be zero. The model was run in non-stationary mode with wave breaking enabled and Madsen bottom friction with default parameters.

3.3. Observations

Wind and waves were recorded at the ISMAR oceanographic platform Aqua Alta located 16 km off Venice (45°18.8′ N, 12°30.55′ E). The local water depth is 16 m. The wind is measured with a Micros SVVA anemometer at a height of 15 m above mean sea level and recorded every 10 min. The wind at the standard height of 10 m was computed from the wind at 15 m assuming a neutral stability log layer (Large and Pond, 1981). Waves are recorded with 2 Hz frequency for 17 min every 3 h, at synoptic times, using the system described by Cavaleri et al. (1997). Data from the Ancona (43°37.00′ N, 13°51.00′ E) and Ortona (42°24.07′ N, 14°32.03′ E) wave buoys were obtained at 3-h intervals. The 10-min wind data were averaged hourly, and then interpolated onto the 3-h wave time base. As two of the meteorological models had wind information every 6 h, wind and wave data were averaged to 6 h data for comparison with model results.

4. Results

For this analysis, the wind and wave comparison was carried out during the 2-month period (March 1–April 30, 2001), during which all the archived fields could be readily obtained. All the wave model results were saved at 3-h intervals. The results at the wind and wave locations were then averaged to 6 h data for comparison with the wind and wave observations.

Although the focus of this paper is on the comparison of wave model results, it is instructive to examine the spatial structure in the output of the various models, illustrated by snapshots of the wind field during the two dominant types of strong wind events: the sirocco and the bora.

4.1. Descriptive analysis

4.1.1. Sirocco

On March 8–10, there was a moderate sirocco event in the Adriatic, with southweasterly winds directed up the axis of the Adriatic generating significant wave heights, H_S, in excess of 2 m in the northern part of the basin (also as recorded at the Aqua Alta tower).

Although the sirocco is usually thought of as a relatively simple event to model with large spatial structures, there are significant differences in the wind and wave fields between the four models (Fig. 2). The ECMWF winds are very smooth and relatively weak, with only an indication of higher wind speeds off Istria, the peninsula between Trieste and Croatia. The LAMBO results show a stronger field, without well defined structure. The improvement is with the LAMI and COAMPS results, particularly with the latter, which shows the effect of the orography on both sides of the basin. On the Italian side, the mountainous Gargano peninsula controls the wind speed and direction. In Croatia, the winds tend to parallel the coast due to the constraint of the Dinaric Alps, leading to a local maximum, after which the flow proceeds uniformly along the axis of the sea with the exception of the opposite coastal area, near Ancona, where one of the buoys is located. Here, there is a well-defined area of low winds, illustrating the difficulties of using sparse coastal wind stations to derive quantitative information on the situation in the open sea.

The wave fields derived from the four different sources reflect these characteristics, although in a smoother way, because of the characteristics of the waves to be an integrated product, in space and time, of the driving wind fields. So the ECMWF wave field is smooth, again with only a limited peak off Istria. LAMBO produces a similar smooth field, but the

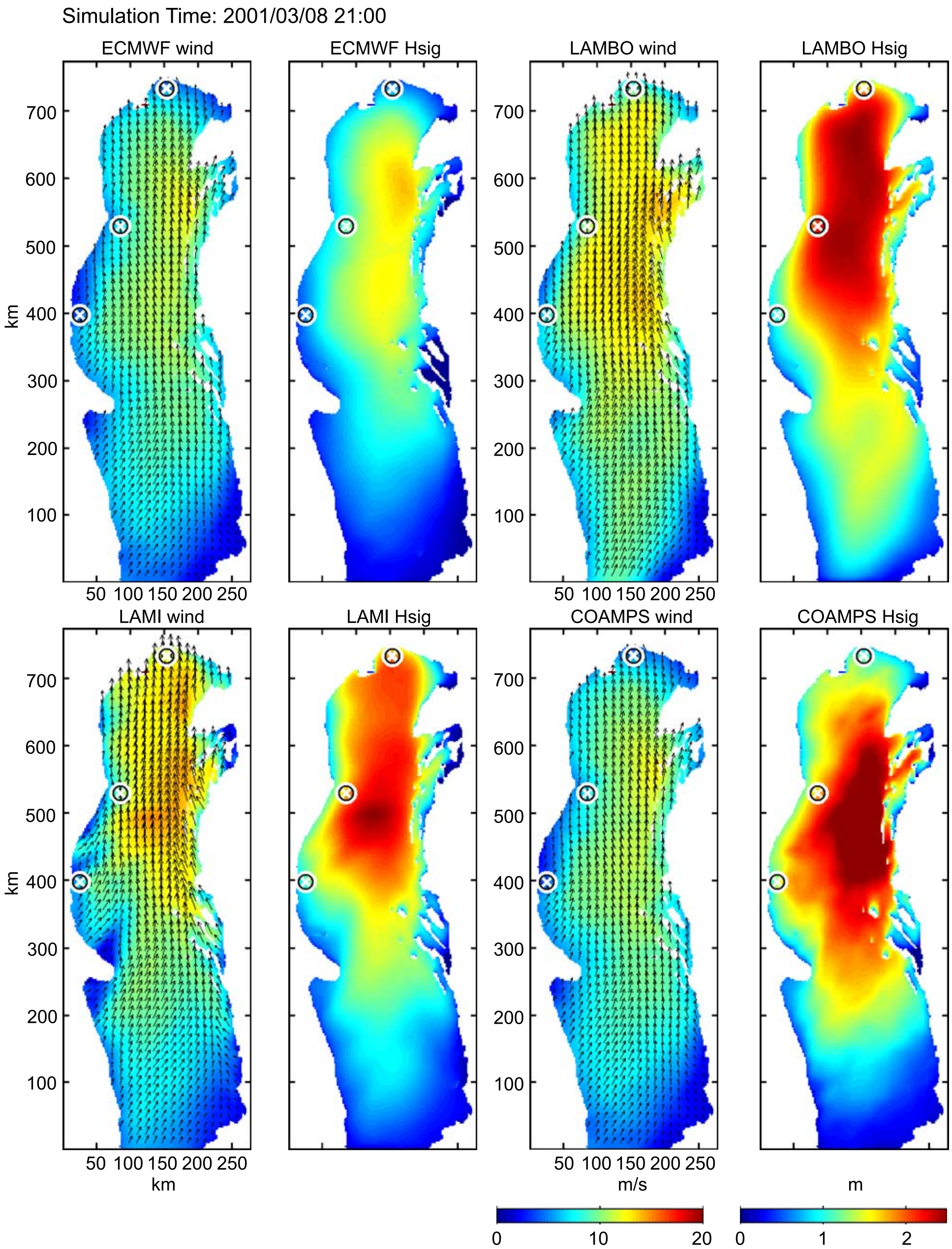

Fig. 2. Wind and wave snapshots from the different wind models during a sirocco event on March 8, 2001. Even though the sirocco is considered as a "simple" event to model (along the Adriatic with little structure), the models show significant differences in spatial and temporal structure.

whole field is shifted with respect to ECMWF towards higher values. In particular, a seemingly small difference in the input winds at the most southern part of the basin leads to substantially higher wave heights already in this zone. This initial difference, where the waves are relatively small, is crucial as it is the background against which higher values develop further north.

These results are instructive in that they demonstrate the important role of the whole field in generating waves at relatively distant locations.

4.1.2. Bora

On March 29–April 2, a moderate bora event occurred in the Northern Adriatic, with northeasterly winds generating significant wave heights in excess of 2 m at Aqua Alta. In this case, the structure of the wind field is controlled by the orography of the Dinaric Alps, and major differences are clearly visible between the fields of the four models.

The ECMWF winds are smooth, with only a mild maximum in the upper part of the basin and limited effects from the Istria peninsula, probably due to the smooth orography associated with the relatively coarse resolution of T511. To the south, after an area of low winds, the wind speed increases. However, this is associated with a different meteorological structure, involving a larger part of the Mediterranean Sea, and is therefore not relevant in the present discussion.

The LAMBO winds show a similar structure, but with higher values, characteristics found also in the sirocco case. The maximum is slightly shifted to the south, apparently because of the orographic effect of Istria.

The full structure of the surface wind field is revealed when analyzing the LAMI and COAMPS results. The jets protruding from the coast are clearly visible, leading to a highly variable structure with strong horizontal gradients. The 4-km COAMPS winds have stronger gradients than the 7-km LAMI winds. Analysis of RADARSAT images during bora events (Askari et al., 2003) suggests that the width of the shear zones on the edges of the jets are 1 km or less, thus further refined meteorological models should continue to show improvements.

Again, the wave fields clearly reflect the wind characteristics, although with the expected smoothing. The LAMBO wave heights are larger than the ECMWF ones, but still smooth. The highly structured LAMI and COAMPS fields show remarkable differences. The H_S in LAMI are larger in the northern part, a clear consequence of the stronger wind jet south of Istria, and there is a clear separation from the most southern structure mentioned above. In this case, the COAMPS waves show a stronger concentration in the central-southern part of the basin, due to the lack of interruption in the wind overall structure.

4.2. Quantitative analysis

The qualitative differences between the models are illustrated by the time series comparison of modelled and observed wind speed at Aqua Alta (Fig. 3). The ECMWF model captures the timing of the wind events well, but often with dramatically reduced magnitude, consistently with prior studies. Some events are reduced more than others: the wind speeds during the event of March 3 are reduced by a factor of three, while the event of April 14 is well represented. During strong short wind events, such as on April 5, 7 and 13, the modelled values are reduced by about a factor of two. The LAMBO model behaves qualitatively similarly to ECMWF, the reason, discussed in the next section, being that the ECMWF model provides the initialization and boundary conditions. With higher resolution, however, LAMBO has a somewhat better amplitude response during most periods (March 3–13, April 13–22). Some events, for example March 29–April 1, show no improvement over ECMWF.

With the LAMI and COAMPS models, we see a dramatic improvement. For both of the models, most of the major peaks identified at speeds greater than 10 m/s are well predicted, although the quality of performance varies from case to case. Occasionally events are simulated that did not occur (March 23 for both models, April 9 for LAMI). Analysis of the spatial structure for the March 23 event (not shown) shows a northwesterly wind in both LAMI and COAMPS with strong winds over the Po Delta weakening rapidly toward the northeast, with strong spatial gradients at the location of Aqua Alta. Thus, a slight shift in the spatial field would result in a large change in the model results at the tower.

The time series comparison of modelled and observed significant wave height at Aqua Alta (Fig. 4) reflects the differences seen in the wind time series comparison (Fig. 3). The wave heights derived from ECMWF winds are underestimated by a large degree, but with an amount varying strongly from event to event. LAMI and COAMPS perform generally better, but also with large changes in performance from event to event. For example, LAMI wave

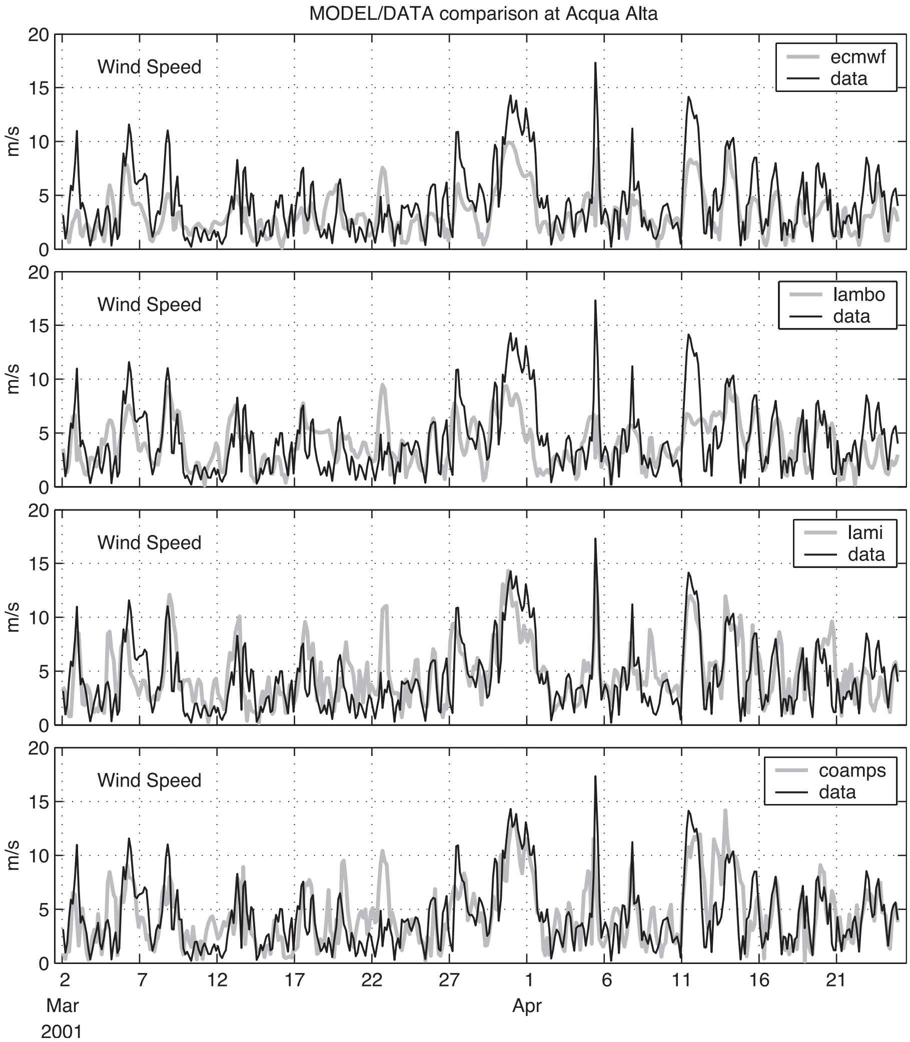

Fig. 3. Time series comparison of modeled and observed wind speed (6 h) at the oceanographic tower Aqua Alta near Venice (see Fig. 1 for location).

heights are nearly perfect during the large event on March 8, but too low by a factor of two during the large event on April 7. For the same events, COAMPS performs worse on March 8 and slightly better on April 7. Note that the strong winds modelled (but unobserved) on March 23 did not result in large modelled waves. This stresses the wave model ability to integrate over time scales relevant to wave formation—in this case the fetch and duration were too small to generate significant waves at Aqua Alta. Thus, although there was a large error in the modelled wind, there was only a small error in the modelled waves. Similar diagrams (not shown) are available at the buoy locations of Ancona and Ortona (Fig. 1). They lead to similar considerations to those at the tower, although the timing of successes and failures can be different.

In addition to qualitative comparisons, it is useful to summarize the model runs with some quantitative measures. Two simple but effective metrics of how well the models match the magnitude and the timing of observed events are the transfer function *m* and the

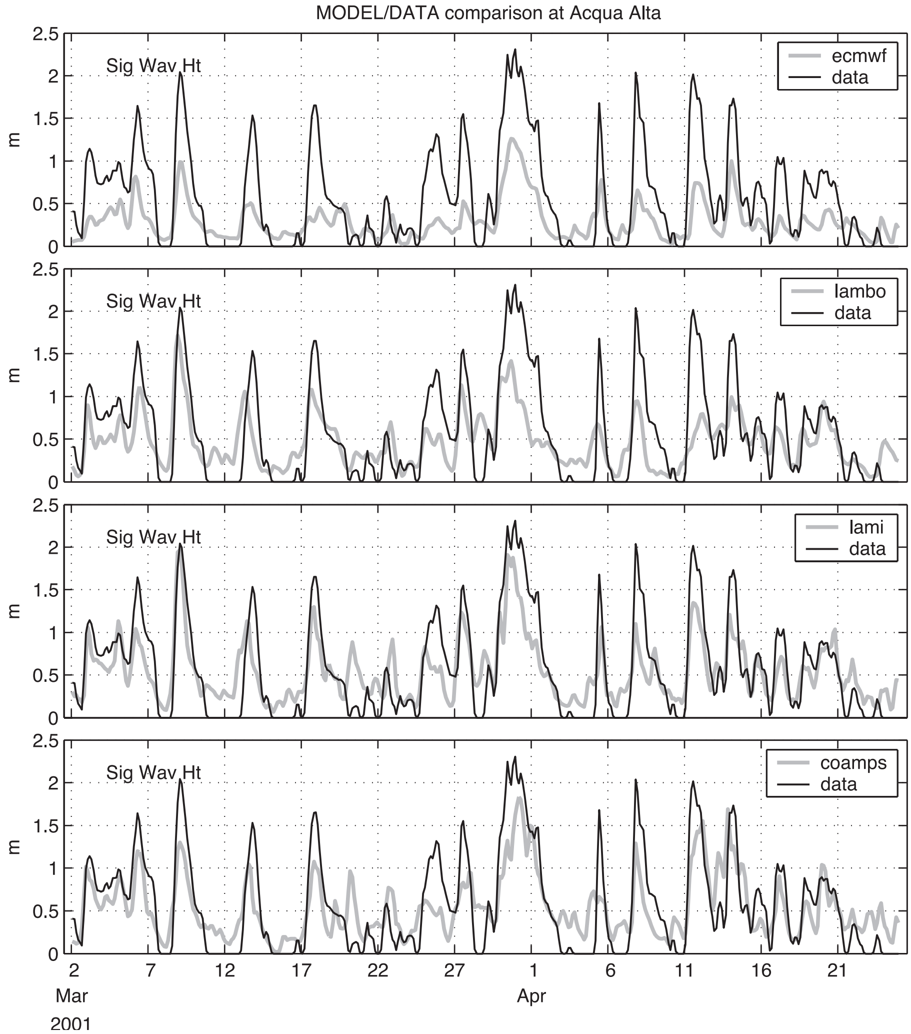

Fig. 4. Time series comparison of modeled and observed significant wave height (6 h) at Aqua Alta.

correlation c obtained by a least-squares fit line between the two time series.

The scatter diagrams for wind speed and wave height at the Aqua Alta tower are shown in Figs. 5 and 6. In each figure, each diagram refers to the results of a specific model. The thick line shows the best fit between model and measured data. Similar diagrams (not shown) are available for wave heights at Ancona and Ortona.

Considering first the wind speed, it is evident that all the models to some degree underestimate the wind speed at the Aqua Alta tower. LAMI and COAMPS underestimate the wind speed only slightly, however, while LAMBO and particularly ECMWF underestimate the wind speed substantially. This is summarized in Table 1, where we define an amplitude response error $E = 100(1 - m)$, m being the slope of the best-fit lines in Figs. 5 and 6. The improvement factor shown in the last column is defined as the ratio between the E of ECMWF and the one of COAMPS and LAMI. It can be seen that the two latter models reduce the wind error at the tower in the order of 3–4 times. The three lower lines in Table 1 report the analogous results for wave height for the three wave recording stations. ECMWF performs poorly, with an underestimate always larger than 50%, while the other three models

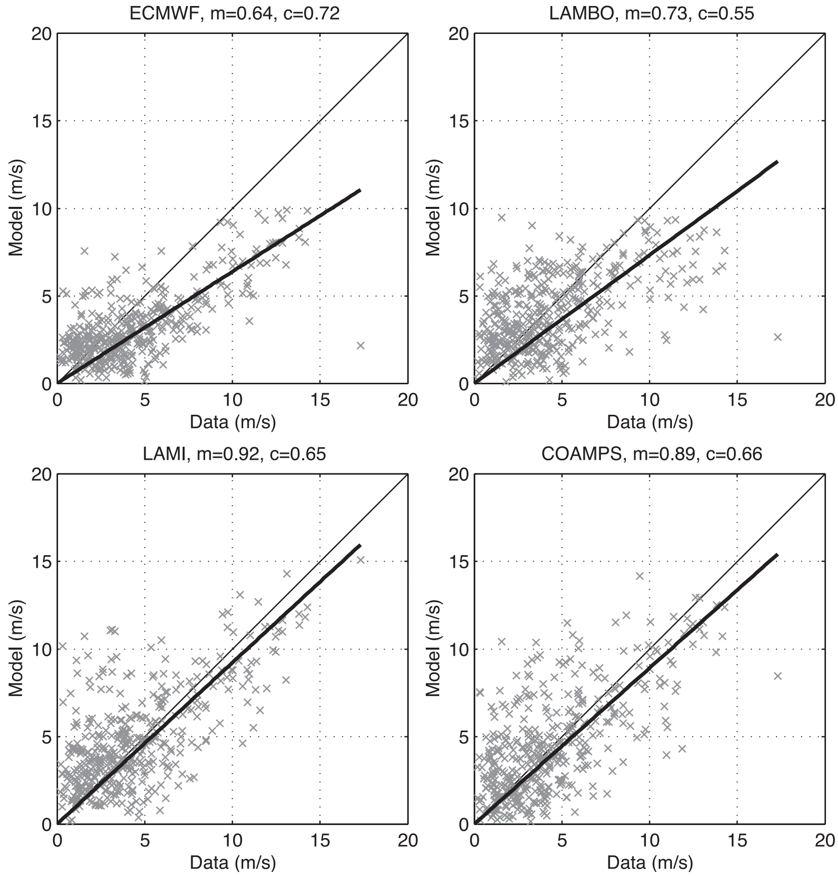

Fig. 5. Model/data scatter diagrams of 6 h wind speed at Aqua Alta. *m* is the slope of the best-fit line (heavy black) forced through the origin. *c* is the correlation factor (measure of the scatter from the best fit line).

perform better, with some indication that LAMI provides on average the best results.

The slope of the best-fit line is a valid indicator of the average amplitude performance of a model. However, for some practical applications the scatter around the line is a relevant quantity. It is evident that the high-resolution models, LAMBO, LAMI and COAMPS show the largest scatter for winds (Fig. 5). The same basic character is reflected in the wave diagrams (Fig. 6), but with less scatter in the higher resolution models, as the wave fields are smoother than the wind fields. The least scatter for wind is provided by ECMWF, which can be quantified by the correlation coefficient *c* between model and data (Table 2), which shows that wind correlation is highest with ECMWF. Comparing wave results, all models have wave correlations higher than wind correlations, and the LAMI and COAMPS correlations have improved to the extent that they are not significantly different to the ECMWF wave correlation.

5. Discussion

The higher-resolution LAMI and COAMPS models show more realistic wind and wave magnitudes than the coarse ECMWF model. ECMWF, on average, underestimates winds by 36%; LAMI and COAMPS by 8% and 11%, a factor of 3–4 improvement. The most likely reason for this is the more accurate representation of the orography. The orography in the global ECMWF model is a spectral representation of the detailed orography at a resolution of approximately 40 km, without fine-scale

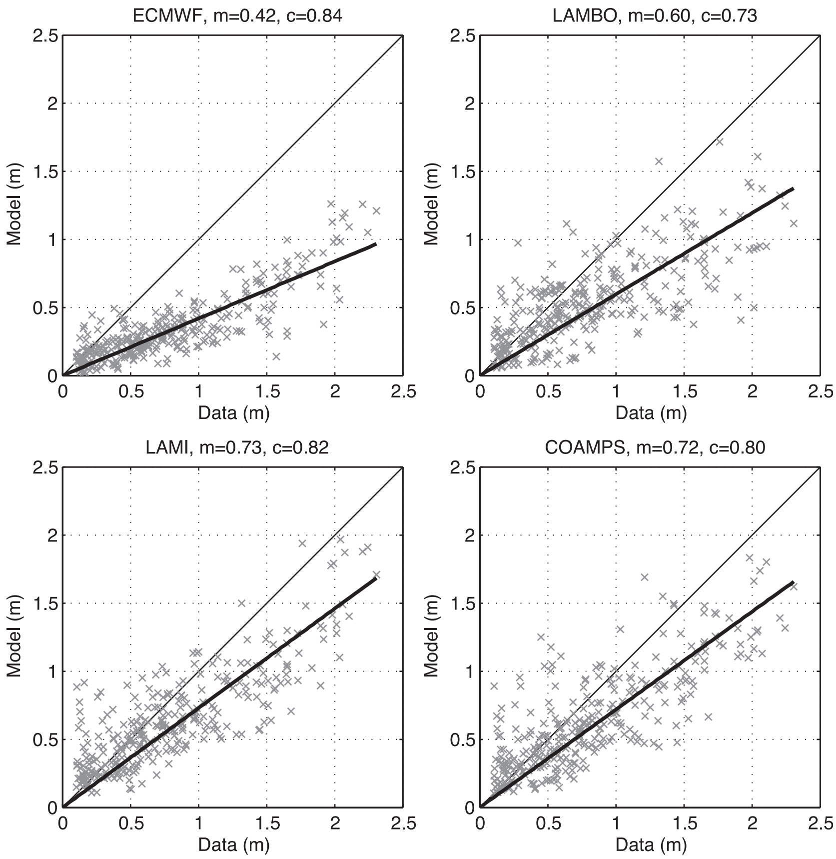

Fig. 6. Model/data scatter diagrams of 6 h significant wave height at Aqua Alta. *m* is the slope of the best-fit line (heavy black) forced through the origin. *c* is the correlation factor (measure of the scatter from the best-fit line).

features of the local terrain. In addition, most global models such as ECMWF parameterize the orographic drag due to the sub grid-scale orography and gravity wave processes (e.g., Lott and Miller, 1997). However, these parameterization methods are not capable of representing the complex air flow response to steep terrain such as the strong down-slope winds and wake regions associated with bora events in this region illustrated in Fig. 7. It follows that as the mountains are relatively smooth in the ECMWF model, the airflow response is smoothed and higher values are considerably reduced. Cavaleri and Bertotti (2003a) have shown how the use of mean orography (see Lott and Miller, 1997), while positive from the point of view of performance of the meteorological model, leads to a decrease of the offshore winds. Higher wind speeds were obtained with envelope orography, but that was not used after the study by Lott and Miller (1997).

The finding that higher-resolution models lead to higher wind speeds, especially in coastal areas, is not a characteristic of only the limited area models, as shown by Cavaleri and Bertotti (2003b). They found that, using the same version of the ECMWF meteorological model, but with different resolutions, the average and peak wind speeds showed a steady increase with increasing resolution, exhibiting only a very small negative bias in the ocean, and still an evident underestimate in the enclosed seas. These tests, with a global model, yielded lower resolution than the 7-km LAMI and 4-km COAMPS.

Further support for the present results is given by Cavaleri and Bertotti (1997), who found that with the passage of the operational ECMWF model from T213

Table 1
The amplitude response error (% departure from perfect response) defined by $100(1-m)$, where m is the transfer function

Amplitude response error (E)					Improvement factor over ECMWF: (LAMI and COAMPS)
	ECMWF (%)	LAMBO (%)	LAMI (%)	COAMPS (%)	
Venice wind	36	27	8	11	3.2–4.5
Venice waves	58	40	23	28	2.1–2.5
Ancona waves	50	18	18	23	2.2–2.8
Ortona waves	56	23	10	18	3.1–5.6

Also shown is the "improvement factor" gained by the two higher-resolution, non-hydrostatic limited area models, defined by dividing the error of ECMWF by the error of LAMI and COAMPS.

and T319 (until November 2000) to T511, the wind enhancement factor required to obtain good wave results in the Adriatic Sea could be decreased from 1.50 to 1.35.

Further substantiation of the effect of orography resolution is given by Pullen et al. (2003). In this study, they showed that a 36-km coarse-resolution mesh of COAMPS did not underestimate the magnitude of wind variability. However, the coarse mesh orography was represented using an envelope-type approach, thereby attempting to realistically represent the height of the terrain with the *caveat* that the horizontal scale of the mountains may be too large. Thus, the differences between these two studies reflect the different methods of representing the orography in the two models, although there are other substantial differences in the modelling systems that may also be contributing factors (e.g., data assimilation, parameterization of physical processes such as the boundary layer, etc.).

The magnitude response of the wave heights reflects the improvement in the limited area wind models: at Aqua Alta, the use of LAMI and COAMPS reduced the underestimate of ECMWF by a factor of 2. At the other wave buoy locations, the improvement is even larger, the error decreasing from 50% to 18% at Ancona and from 56% to 10% at Ortona. These

Table 2
The correlation coefficients between modelled and observed data at Venice (Aqua Alta), Ancona and Ortona

	Correlation coefficient (c)			
	ECMWF	LAMBO	LAMI	COAMPS
Venice wind	0.72	0.55	0.65	0.66
Venice waves	0.84	0.73	0.82	0.80
Ancona waves	0.87	0.78	0.83	0.78
Ortona waves	0.88	0.82	0.88	0.86

wave results indicate that the benefit obtained by the limited area wind models is regionally dependent, due to the changing influence of orography with region. This means that any enhancement factor applied to winds in an attempt to produce more realistic oceanographic processes would need to vary regionally as well. This has been recently shown by Cavaleri et al. (2002) who, using a 10-year comparison between model and satellite data, have derived calibration coefficients for the wind and wave ECMWF results that vary from point to point.

In addition to the improved magnitude response, the limited area models also have a more detailed spatial structure, which is strongly connected to a better representation of the coastal orography and the inclusion of smaller scale dynamics that lead to smaller scale instabilities. This is particular evident in the COAMPS wind, analyzing the detailed structure of the fields from the 4 km resolution. Using a higher frequency (hourly) output for the COAMPS winds, and observing the resulting fields in a rapid sequence, produces temporal variability around the average state at given times and positions. Accordingly, the spectral analysis of the wind fields shows that the energy extends to the upper range compatible with the resolution. Therefore, while the low frequency energy, albeit at different levels, is present in all the models, only the high-resolution models show the high frequency variability, which characterizes fields with a detailed variable structure.

A fundamental question arises if this high frequency variability is deterministic or stochastic. In other words, can this information be used to derive deterministic results at a given location, or must this variability be partially interpreted in exclusively statistical terms? This can be important, depending on the intended

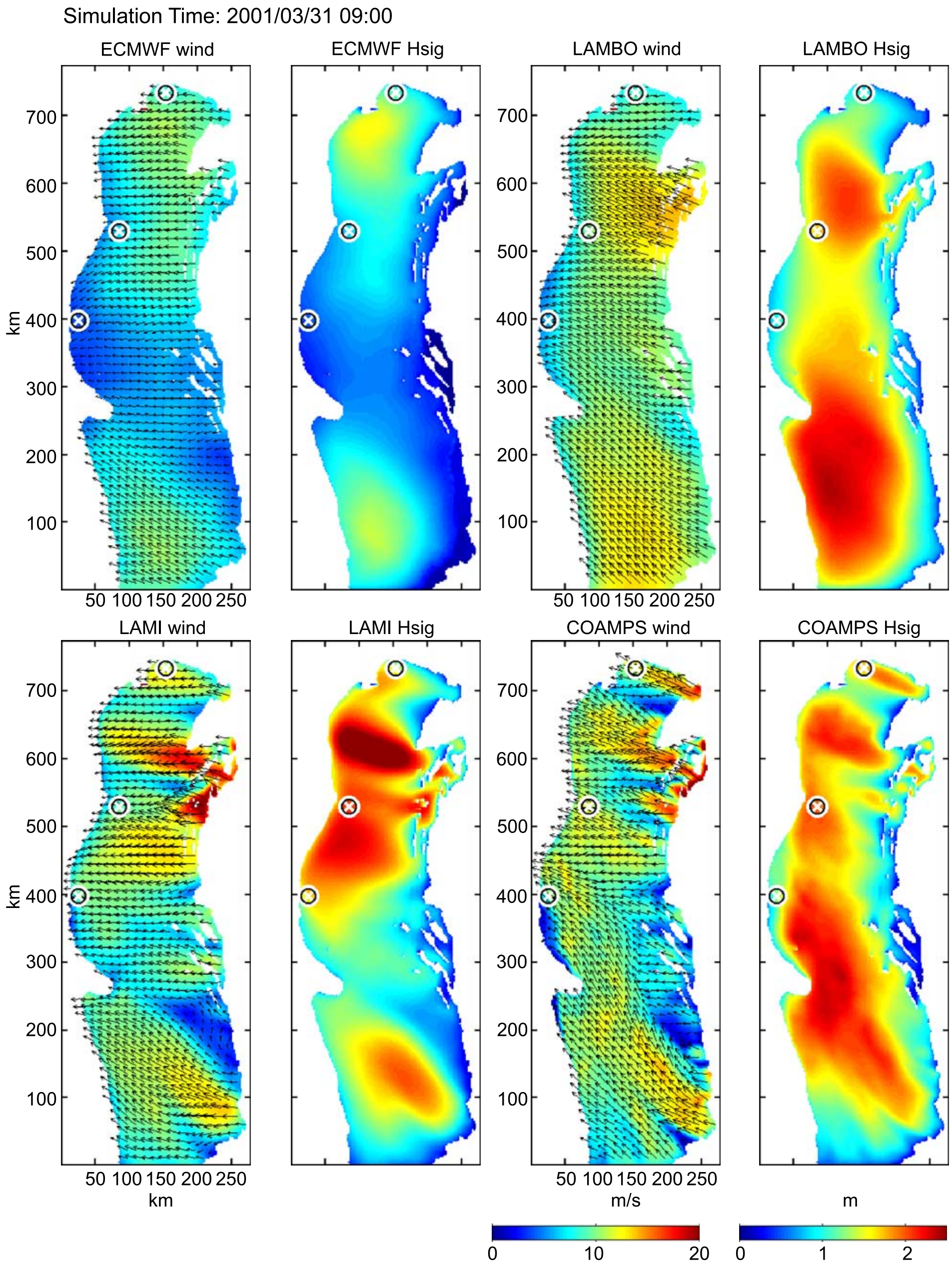

Fig. 7. Wind and wave snapshots from the different wind models during a bora event on March 31, 2001. The limited area models COAMPS and LAMI show the jets as the wind is channeled by the orographic structure around Istria, while LAMBO and ECMWF have progressively less spatial structure.

use of the modelled winds. In the case of long-term wind and wave statistics at a given location, full variability of the real world in the model is desirable. However, should the results be used for real-time decisions, for instance, how to handle the equipment of an open-sea structure, then a statistically significant, but deterministically uncertain result might not be the best choice.

This dilemma is represented in the scatter of the data around the best-fit lines in Figs. 5 and 6 and in the corresponding correlation factors reported in Table 2. The best wind results are provided by the coarse ECMWF model, demonstrating that much of the variability in the higher-resolution models is of a stochastic nature. When compared with the corresponding measured data, this implies an increase of the scatter, hence a decrease of the correlation.

The argument becomes more problematic in relation to the wave results. Because waves are an integrated effect in space and time over the driving wind fields, it is expected that the wave comparisons at the three stations would evidence less scatter, with wave correlations therefore higher than wind correlations. Table 2 and Fig. 6 show that wind correlations are 0.72 and 0.65 for ECMWF and LAMI, respectively, their correlation are 0.84 and 0.82. At Ortona, ECMWF and LAMI wave correlations are identical, with a value of 0.88.

Although the wave correlations for the LAMs are not significantly different than those of ECMWF, it is perhaps surprising that they are not higher. One likely explanation is that high-resolution models also have errors at low frequency space and time scales. A high resolution limited area model obtains the initial state and/or boundary conditions from a parent model with a larger domain, larger spatial scales and perhaps different physics. In most of the cases the LAMs are used in forecast mode (see their description in Section 3). Therefore, a trade-off is required to allow enough time to the LAM to develop the small details of the field, but keeping the forecast horizon short enough so that the model does not diverge too much from the actual evolution of the field. The limit in this approach is that the low-frequency information passed from the parent to the child cannot be improved by the latter. In practice, if the parent model incorrectly represents a particular large-scale feature, the high resolution model will develop further detailed structure on an incorrect field. We suggest this is partly the case in the simulations we evaluated. For instance, the substantial differences between the LAMI and COAMPS fields in the bora snapshot (Fig. 7) suggests that the two underlying large-scale models are representing the large-scale features somewhat differently.

Our objective was to analyze some of the available winds to find out which one, applied to a wave model, provides on the whole the best results in an enclosed basin and, more specifically, in the Adriatic Sea. It is worthwhile to stress that this is different than determining the superiority of a particular high resolution model. If this were the case, we would need to implement the different LAMs on the same grid, using the same initial and boundary conditions. This was far beyond the scope of this work.

Our results suggest that the best wind for forcing oceanographic models depends on the objective one has in mind for the results. For some practical applications, our findings suggest that a properly tuned ECMWF model output could provide quite reasonable data. This finding is similar to the study of Bogden et al. (1996), who found that, on the basis of model/data misfit of currents in Massachusetts Bay, a simple linear barotropic model with wind forcing performed "better" than a 3D primitive equation model with realistic river discharge and surface fluxes. On the other hand, such an approach would hide the high-scale variability that we find in nature (see e.g., Komen et al., 1994, pp. 322–331). Given that the potential capability of the LAMs can be hampered by the partially wrong information passed by the parent model, it would be worthwhile to nest the child models into the best parent, in this case ECMWF T511, because of its higher resolution and the evidence provided by the long-term statistics (Lalaurette et al., 2003). A possible optimal approach would be a combined deterministic–stochastic approach, using the low-pass filtered LAM fields as deterministic information, and superimposing stochastic information derived from the high-pass components of LAM fields. For practical applications, this stochastic information from the LAMs could be used statistically to provide error estimates or the probability of different events. Such an approach has been used by Abdalla and Cavaleri (2002) in describing the gustiness of the atmosphere and its effects on wave growth.

6. Conclusions

Four sources of surface wind fields for use in wave modelling and for potential in other oceanographic modelling have been assessed. The test area has been the Adriatic Sea, but the results have a general validity for other semi-enclosed basins where the orography plays a substantial role. The sources used have a wide range of resolutions, spanning from a global model (ECMWF T511) to high-resolution limited-area nested models (LAMs).

The high-resolution models provide not only more highly detailed structure, but significantly stronger and more accurate overall wind speeds. ECMWF wind fields are the smoothest fields, and show an underestimate of wind speed (and wave height) that depends on the size of the basin and its orographic characteristics. LAM wind fields show a dramatic improvement, with more realistic structure and a strong reduction of the underestimate of wind and waves.

The information introduced into the fields by a LAM is partly deterministic and partly stochastic. The "best wind" to be used for oceanographic purposes depends on the task. In the case of long-term statistics, the direct output of LAMs, with superior average amplitude response, would be the best source of information. For some real time applications and decision making, a smoother field would be preferable. In this case a tuned ECMWF T511 could provide acceptable information. Because of the spatial variability of the tuning parameters needed, however, it would be preferable to use only the lower-frequency, deterministic part of the LAM output, and the higher frequency part of the high resolution fields for an estimate of the likely error in the prediction.

Despite the improvements offered by the LAMs, the quality of a LAM simulation is still influenced by the larger scale parent model from which it derives boundary and/or initial conditions. A LAM cannot improve the low frequency (in space and time) characteristics of the parent. It merely adds high frequency information, developing all the details associated with a better geometric description of the area and the inclusion of smaller scale dynamics; therefore, an error of the parent cannot be corrected in the child model. In our case, the fields provided by the two higher resolution models, LAMI and COAMPS, lead in general to good results, but with often significant differences to be related to the input information from their respective parent models. These parent models have a lower resolution than ECMWF T511. Following the principle that the highest resolution global model has potentially the best analysis, we suggest that a possible improvement could be obtained nesting these LAMs into the T511 model.

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