NOTES AND CORRESPONDENCE

In Search of the Correct Wind and Wave Fields in a Minor Basin

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26 May 1996 and 26 October 1996

ABSTRACT

The authors analyze the accuracy of the surface wind of the Adriatic Sea from a global model. They find it to be substantially underestimated and propose a calibration by a suitable enhancement of the strength of the fields. The reasons for the underestimate are discussed.

1. Introduction

During recent years we have carried out an extensive verification of the quality of some of the surface winds available for the Mediterranean Sea from large-scale meteorological models (e.g., Cavaleri et al. 1991; Komen et al. 1994). A convenient, if not the best, way to carry out such a verification is to use the surface winds to drive a reliable numerical wave model. Waves are an integrated effect, in space and time, of the driving wind fields. Because at present (see Komen et al. 1994) the most advanced wave models are more accurate than the meteorological models, the quality of their results is a very good indicator of the quality of the driving wind fields.

Checking the output of the global model of the European Centre for Medium-Range Weather Forecasts (ECMWF, Reading, United Kingdom) and the accuracy of the derived wave fields for the Mediterranean Sea, we have found a general underestimate of the significant wave height H_s of between 20% and 30%. A typical result is shown in Fig. 1. The percent bias varies from place to place, as a function of the local orography, of the dimensions of the local basin, of the correct representation in the wave model grid of the coastal details, and of the possible islands. An obvious example is the practical impossibility of properly representing in the grid the more than 2000 islands scattered throughout the Aegean Sea.

Expectably, the largest errors are found in the smaller basins. There are several reasons for this. First, for a given resolution, the smaller the basin, the poorer its representation in the model. The smaller basins and the associated orography often lead to an increase of the local complexity of the fields. Finally, in the small basins any error in space and time in the global meteorological model leads to an immediate response (error) of the wave field.

We have focused our attention on the Adriatic Sea, the elongated basin to the east of Italy. Apart from our direct interest, from the wave modeling point of view we have here the advantage of a practically isolated basin with no or little influence from the larger Mediterranean Sea. In addition, three wave measuring stations, suitably distributed, have been operational for many years.

As the comparison with the data measured in the Adriatic Sea turns out to be particularly unsatisfactory, we try to resolve the following question: Is it possible to introduce an empirical calibration in the wind fields so as to obtain satisfactory wave results? To give an answer is the main aim of this paper. After describing the Adriatic Basin (section 2), in section 3 we list the available data. The results are in section 4, followed in section 5 by the proposed correction of the fields. The overall results are summarized and discussed in section 6, where we hint also at the possible causes of error in the wind field.

2. The Adriatic Sea

The Adriatic Sea (see Fig. 2) is located to the east of Italy, between the Italian peninsula and the Balkans. It is an elongated basin, spanning 750 km by about 200 km, aligned in the northwest to southeast direction. Shallow in its northern part, it gradually deepens moving south, until when, at the border of the continental shelf, it drops to more than 1000-m depth.

The orography is rather complex. The Apennines border the sea to the west, facing the Dinaric Alps to the east. The Alps close the northern side, leaving only the

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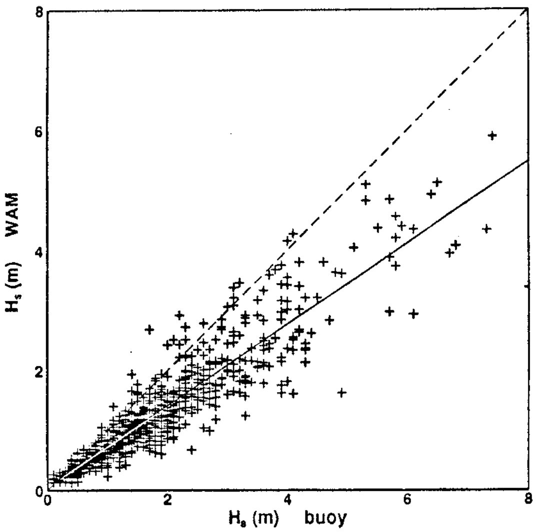

FIG. 1. Scatterplot of the model vs measured wave height at Alghero, on the west coast of Sardinia. The position is shown in Fig. 2.

entrance to the Po Valley. The basin is connected to the Mediterranean Sea through the Strait of Otranto, at its southern end.

The Adriatic Sea is dominated by two well-defined winds, sirocco, blowing from southeast along the axis of the basin, and bora, a northeast cold, dry, and gusty wind. While sirocco often stretches the whole basin, bora is mostly confined to its most northern section. Channeled between the Alps and the Dinaric Alps, and enhanced by a cathabatic effect, it can reach very high speeds (up to 30 m s^{-1}) with strong spatial gradients.

In general, the relatively small dimensions and the dominating orography contribute to the complexity of the local fields. A full description of the climatology of the area is given in Cavaleri et al. (1997).

3. Available data

There is a large number of operational meteorological models that provide information for the Mediterranean Sea. In this paper we restrict our attention to the products of the ECMWF. The ECMWF is the official source of meteorological data for Italy, its results being daily available through the Meteorological Service of the Italian Military Air Force.

Since September 1991, ECMWF has run the T213 version of its meteorological spectral model, with 31 layers and a spectral resolution of about 90 km (Simmons 1991). Starting from July 1992 the analysis and forecast winds are used to drive WAM (wave model), an advanced third-generation wave model (Komen et al. 1994), to also obtain analysis and forecast wave fields. Still with the same wind source, WAM is run in two versions: one for the globe, with a resolution too coarse to be of any significance in the minor basins, and one for the Mediterranean Sea. Here the resolution was 0.5° until 1995; it was later extended to 0.25°. For our present purposes the model output, available at 6-h intervals, includes the significant wave height H_s, the mean period T_m, and the mean direction θ_m. However, particularly with the 0.5° resolution and due also to its slanting orientation, these results are not fully representative in the Adriatic Sea (Fig. 2). Hence we have preferred to use here a 20-km resolution grid (see Fig. 3), aligned with the main axis of the basin, that better fits the shape of the coasts.

The T213 winds are interpolated to this grid and the WAM model is run to produce the corresponding wave fields. This has been done from September 1991 until February 1995, and the results are made available at 3-h intervals. Note how, due to the small dimensions of the basin and the consequent absence of swells, the parameters H_s, T_m, and θ_m are well indicative of the local wave conditions. An exception is the northernmost part

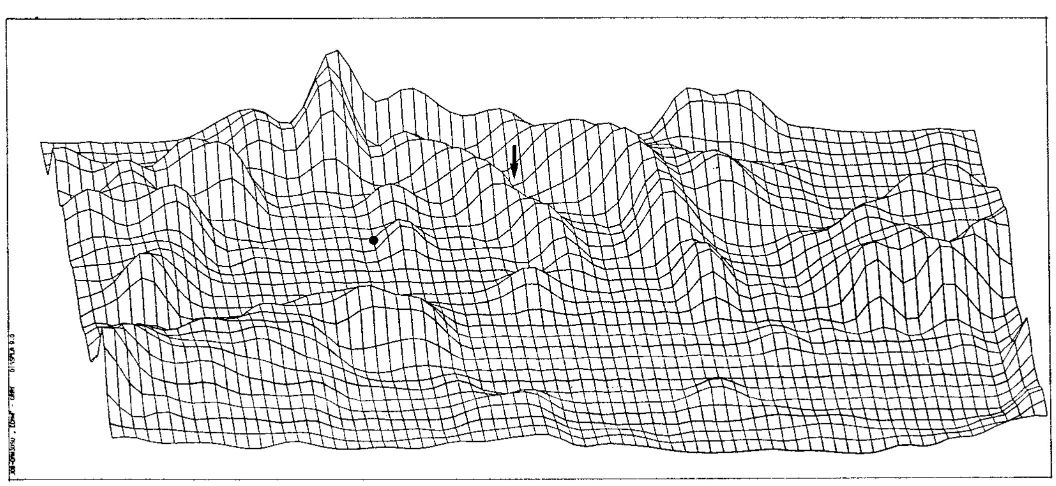

FIG. 2. The orography of the Mediterranean Sea as represented in the T213 spectral model. The dot shows the position of Alghero (see Fig. 1). The arrow indicates the Adriatic Sea.

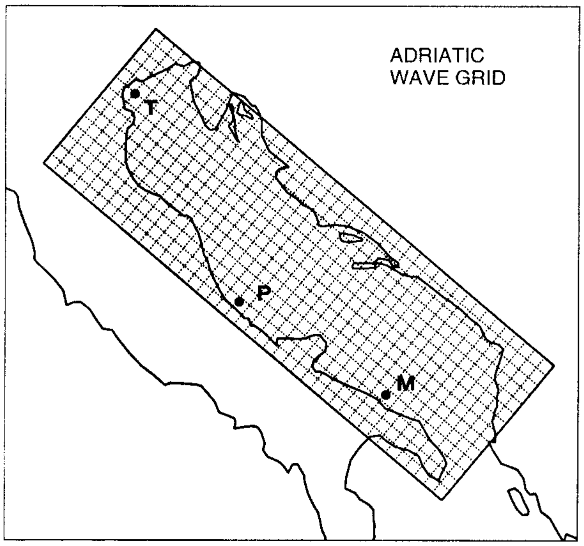

FIG. 3. The grid fitted to the Adriatic Sea. The dots show the positions where wave-measured data are available (T—tower, P—Pescara, M—Monopoli).

of the Adriatic Sea, where the orography often forces the sirocco to turn left, with an abrupt 90° shift, thus leading to local cross-sea conditions.

Wind speed and directions are regularly measured at the meteorological stations sparsely located along the coast of the Adriatic Sea. In principle these data could be used to verify the quality of the model wind. However, the influence from the local orography leads to substantial differences between the coastal and the open sea wind conditions, making the former unsuitable for any verification purpose. The only open sea meteorological station available in the Adriatic Sea is an oceanographic tower located 16 km off the coast of Venice. This is also a wave measurement location, the wave being directionally recorded by three pressure transducers located on three legs of the tower. Directional wave data, obtained by free-floating WAVEC buoys, are available also at Pescara and Monopoli. Their position is shown in Fig. 3. The two systems are described, respectively, by Cavaleri et al. (1981) and De Boni et al. (1993). In both cases the data are available with the same characteristics of the model, that is, H_s, T_m, θ_m given at 3-h intervals, at synoptic times (0000, 0300, 0600 UTC, . . .).

4. Results

Figure 4 shows the scatterplot of WAM H_s versus measured data for the measuring stations in the Adriatic Sea (T—tower, P—Pescara, M—Monopoli; see their locations in Fig. 3). The data are shown for 1992, but the results for the other years are practically the same. There is an obviously strong underestimate by the model. Note that the minimum wave height assumed by the model is 20 cm.

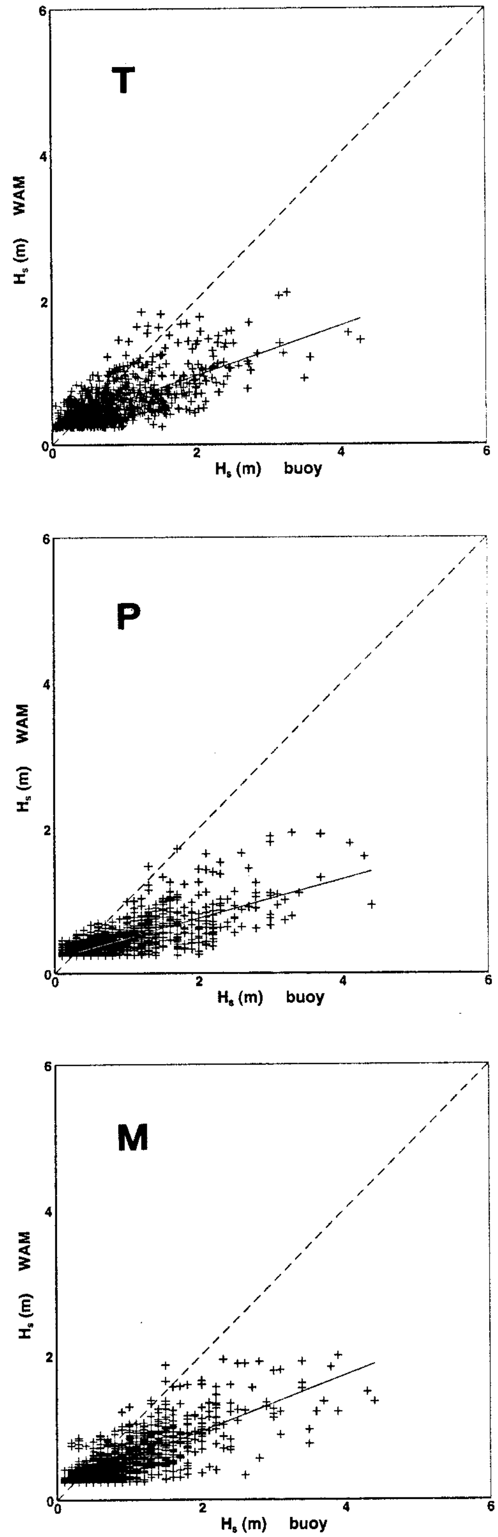

FIG. 4. Scatterplot of the model vs measured wave height for 1992 at the three positions shown in Fig. 3.

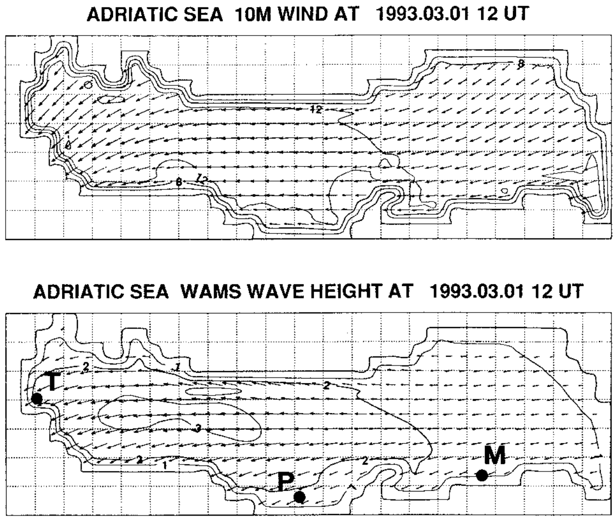

FIG. 5. Wind and wave situations on the Adriatic Sea (as seen by the model) at 1200 UTC 1 March 1993. The dots show the positions where wave-measured data are available (T—tower, P—Pescara, M—Monopoli).

For a more detailed analysis we concentrate on two storms with different characteristics, one of sirocco, the other of bora, thereby representing the two main classes mentioned above.

Figure 5 shows the wind and wave situation at 1200 UTC 1 March 1993. Wind and waves are aligned along the main axis of the basin, with a left turn in its most northern part, a classic sirocco event. The time series at T, P, and M are given in Fig. 6, while Fig. 7a shows the corresponding scatterplots. The underestimate is about 50%, regularly distributed throughout the time series.

The situation is repeated in the bora storm, in this case extended to the whole basin, whose general fields, time series, and scatter diagrams are given, respectively, in Figs. 8a, 9, and 10.

In a similar fashion we have analyzed 11 more storms, practically considering all the possible stormy situations, both as intensity and as details of the shape of the fields. The results are remarkably consistent, fixing the average underestimate of H_s at 50%, with a variability of $\pm15\%$. However, even more remarkable in this apparently poor situation is that the mean direction θ_m at all the stations (not shown here) does not show any substantial bias, a fact true not only on the average,

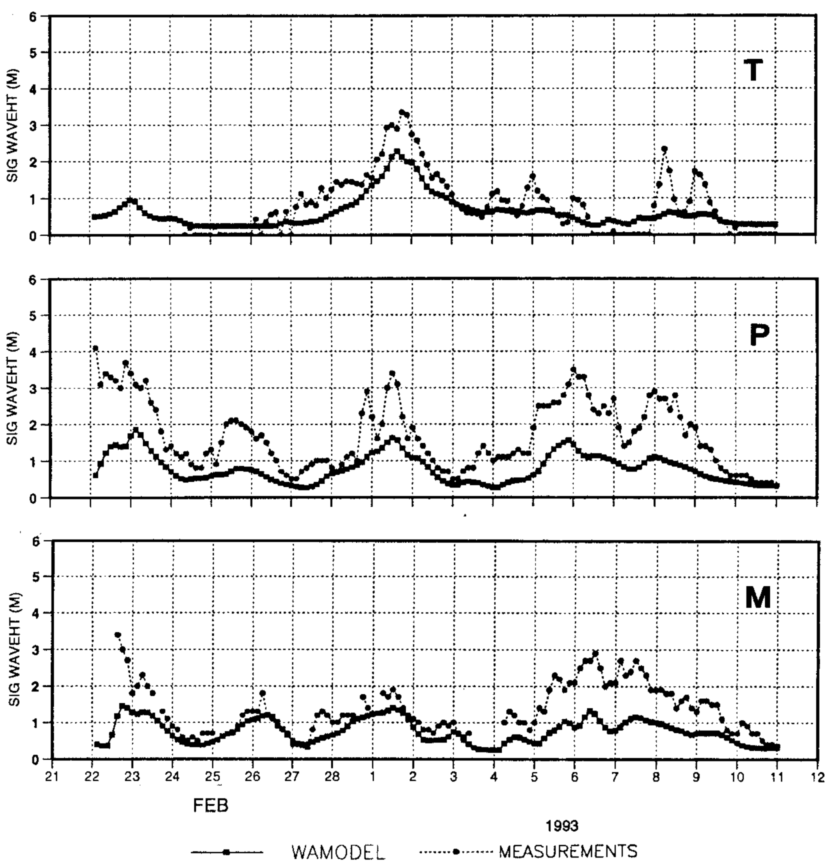

FIG. 6. Time series of the modeled and measured wave height at the three positions shown in Fig. 5 during the storm of February–March 1993.

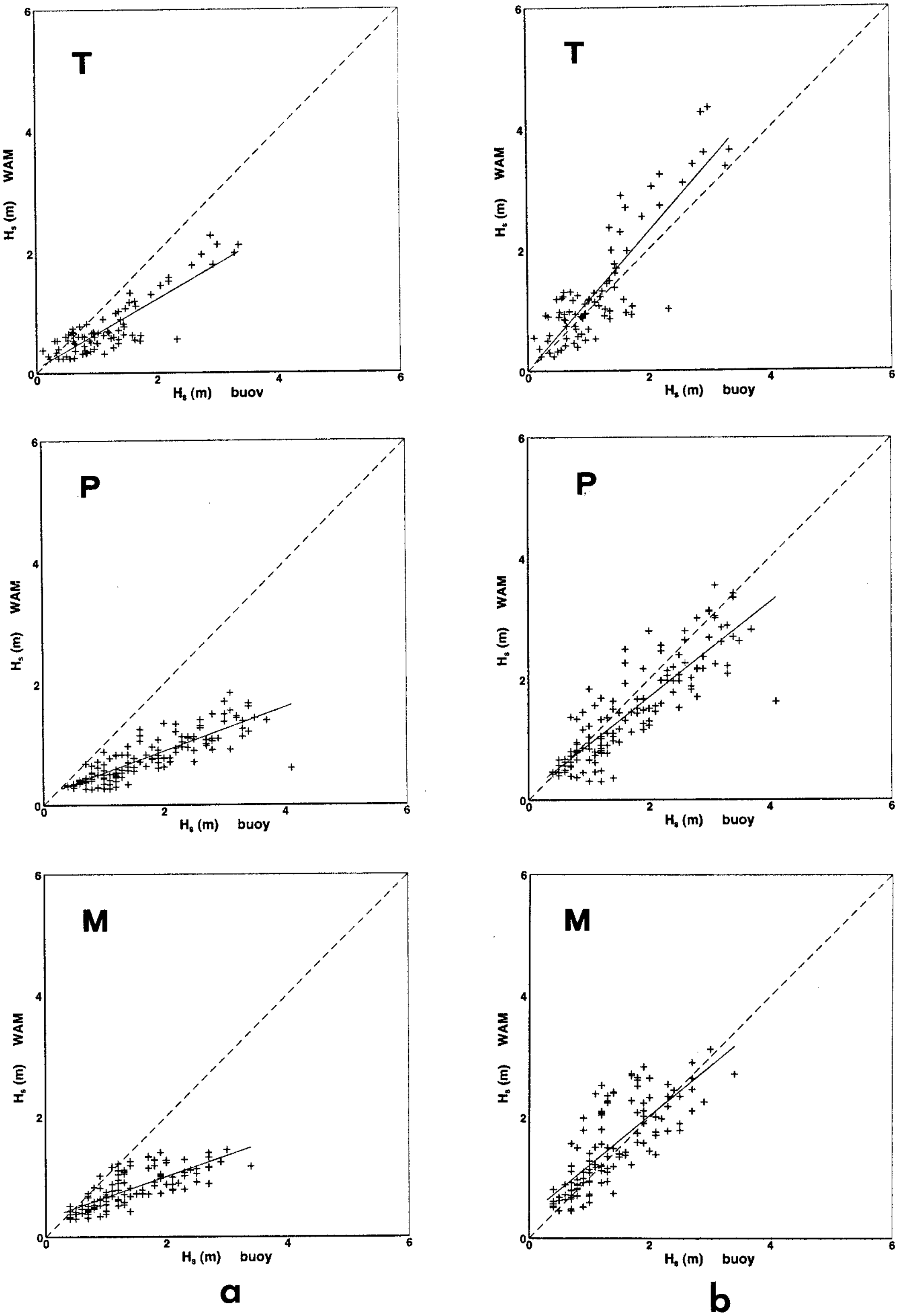

FIG. 7. (a) Scatterplots of the results obtained using the model wind (see Fig. 6) and (b) the same after the wind enhancement.

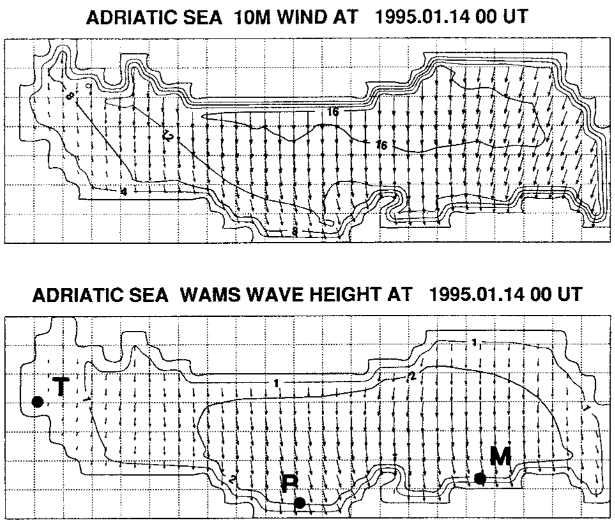

FIG. 8. As in Fig. 5 but at 0000 UTC 14 January 1995.

but also for the single storms. Finally, plainly following the rules of wave generation by wind (SWAMP Group 1985), the mean period T_m is largely underestimated at all the stations.

There is no apparent preferential behavior of the model for any of the three stations, the only exception being θ_m at the tower in the northern Adriatic Sea, expectably, as pointed out above, because of the often complicated wind distribution in the area.

We have mentioned in the previous section the availability of meteorological data at the tower T (see Fig. 3 for its location). Obviously we have carried out a comparison between the model and measured wind at this location. Expectably, the results (not given here) show a large underestimate of the wind speed by the model. However, they are not very informative, because of their very large scatter in modulus and even more in direction, associated with the complexity of the local fields (see section 2). The basic fact, for our concerns, is that the results for H_s are consistent throughout the test and the direction is remarkably correct. This has some strong implications that will be discussed in detail in the next section.

5. Calibration of the input wind fields

We now address the question posed in the introduction; that is, we search for a possible calibration of the wind fields.

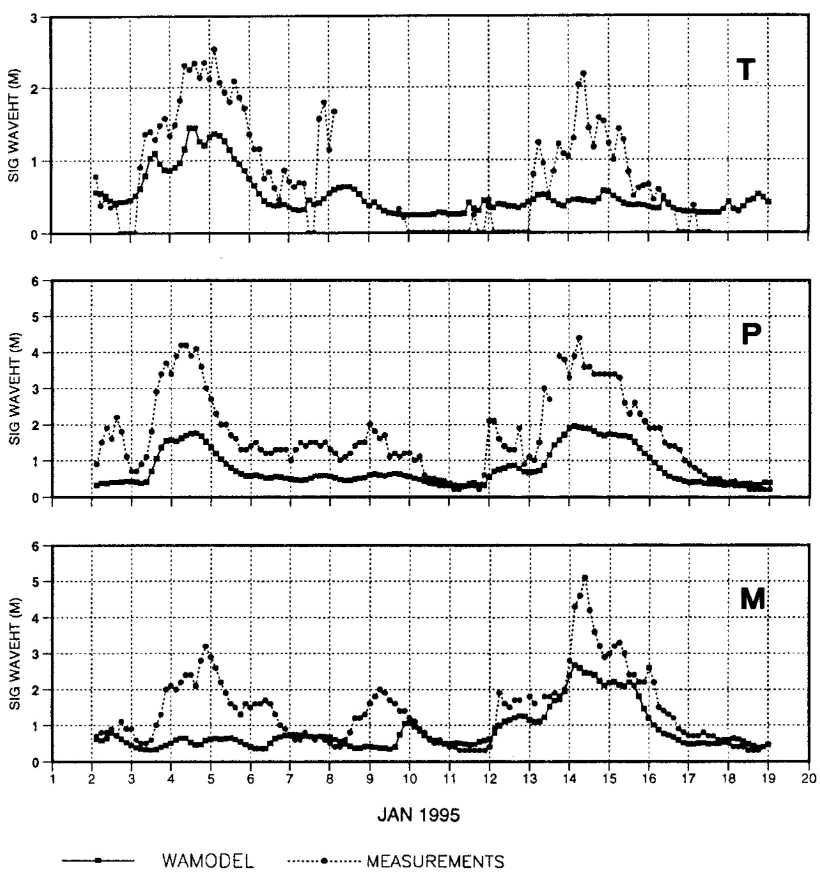

FIG. 9. As in Fig. 6 but for January 1995.

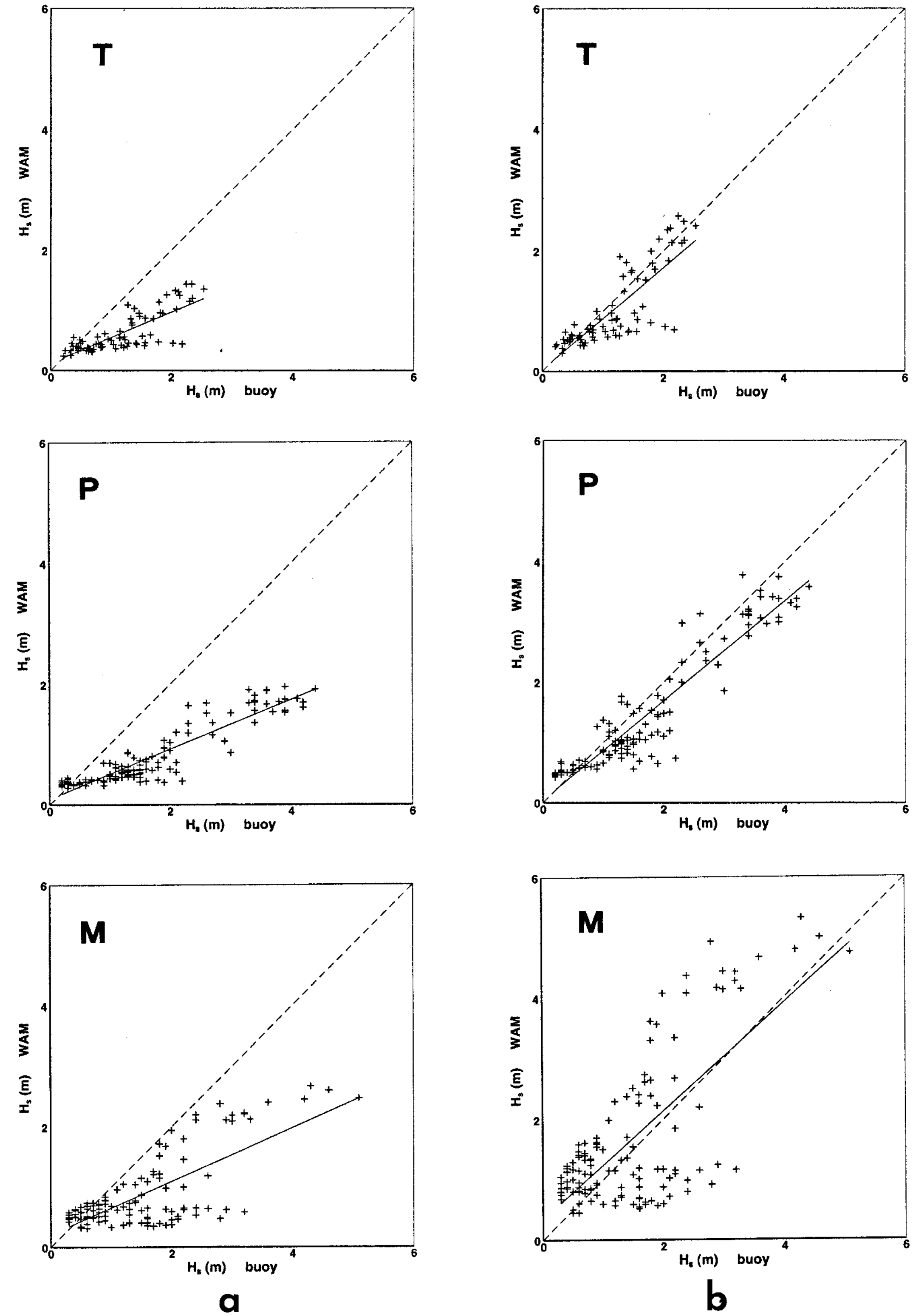

FIG. 10. As in Fig. 7 but for the data in Fig. 9.

The results of the previous section have highlighted a basic point: expressed in very blunt terms, the model wave heights are regularly underestimated, the directions are correct. The logical implication is that the general wind field has the correct structure, but it lacks strength. The distribution of the isobars is correct, the wind has the correct geometry, but we need to increase the spatial gradients and, hence, the wind speed. Therefore we look for a suitable enhancement of the field.

For our purpose the logical sequence is given as model wind (A) $\rightarrow$ real wind (B) $\rightarrow$ wave field (C). We have considered using the classic methods ''perfect prog'' or MOS (model output statistics) [see, e.g., Glahn (1982) for a thorough discussion of the subject]. With the first we would look for a relationship between the wind field and the waves, respectively B and C in the scheme above. However, we are not interested in this, as this step is already well covered by the WAM model, and there is no interest in substituting physics with statistics. A MOS method would be much better in deriving the true wind field B from the model one A. The problem is that, except for the satellite data and the ship reports, we lack completely extensive wind data in the open sea, and we cannot therefore derive a statistical relationship between these two quantities. In this situation, and given the above information, the logical first step is to enhance uniformly the model wind fields, deriving the corresponding factor via the comparison of the associated wave results versus the measured data.

Rather than going through a long and tedious sequence of tests, we can speed up the procedure by assuming the empirical relationship $H \sim U^{\beta}$ between the wave height H at a given point and a representative quantity U of the wind field, with the dimensions of a velocity. While the chosen expression resembles the relationship between wave height and wind speed (SWAMP Group 1985), the β exponent varying between 1 and 2, in so doing we do not want to express here any physical relationship between the two quantities, the only requirement being that an enhancement of the wind fields, that is, a general increase of the wind speeds, is reflected into a corresponding increase of H. Besides, we do not make any assumption about β, which can vary from place to place.

Defining the model results with the subscript ''mod,'' we summarize our present results at the three stations with

$$H_{\text{mod}} \sim U_{\text{mod}}^{\beta}. \tag{1}$$

Given the measured wave height H_{meas}, we search for a $U = \alpha U_{\text{mod}}$ value such that

$$H_{\text{meas}} \sim U^{\beta}, \tag{2}$$

α being a suitable enhancement factor. From (1) and (2) we have

$$\frac{H_{\text{meas}}}{H_{\text{mod}}} = \left(\frac{U}{U_{\text{mod}}}\right)^{\beta}. \tag{3}$$

In (3) the unknown quantities are U and β. Here, β is rapidly determined by a second run with an enhanced wind, U', say multiplied by 2. Given the resulting wave height H', β is obtained as

$$\beta = \frac{\ln(H'/H_{\text{mod}})}{\ln(U'/U_{\text{mod}})} \tag{4}$$

and U, or better the enhancement factor α, follows from (3). In practice, rather than with the single H values, we have worked with the slopes of the least square fit lines in Figs. 7 and 10.

The enhancement factor turns out to be almost the same, $\alpha = 1.5$, for the three stations. The new scatterplots are shown in Figs. 7b and 10b for the two storms of sirocco and bora, respectively. The new time series are shown in Figs. 11 and 12.

The above procedure has also been repeated for the remaining 11 storms, each one producing its own α value. The scatter of α is rather small, with a variability less than $\pm$ 0.05. Hence 1.5 has been chosen as general enhancement factor. Table 1 shows the average H_s bias for three different values of α, $\alpha = 1$ obviously representing the model wind fields.

6. Discussion

The question posed in the introduction has been positively answered. In practice, it is possible to enhance uniformly the wind fields in the Adriatic Sea, which leads to a satisfactory fit between modeled and measured wave height at the three stations where data are available. For the T213 model of ECMWF the enhancement factor is $\alpha = 1.5$, with an approximation of 0.05.

In a way this sounds like a crude solution because, whatever the reasons (soon to be discussed), one would expect the correction to vary from spot to spot and with the meteorological situation. However, we lack the wind data for a detailed correction of the wind fields. With the exception of a single location in the northern part of the basin, the only significant data at our disposal are the wave records at three locations. Waves are an integrated effect, in space and time, of the driving wind fields, and we can therefore sensibly derive only integral solutions.

In our search for a solution we have focused our interest only on stormy events, when the meteorological conditions are well defined. We expect a decrease of the overall quality of the results when the situation is calm, with low and sparse wind speeds. On the other hand, these situations are less interesting, particularly for the wave modeler.

It is of interest to try to understand the reasons for the underestimate of the wind speed in the meteorological model. Our experience as wave modelers, hence of users of surface wind products, strongly suggests the lack of sufficient resolution as a likely culprit. As pointed out in the introduction, advanced wave models are at present more accurate than the meteorological mod-

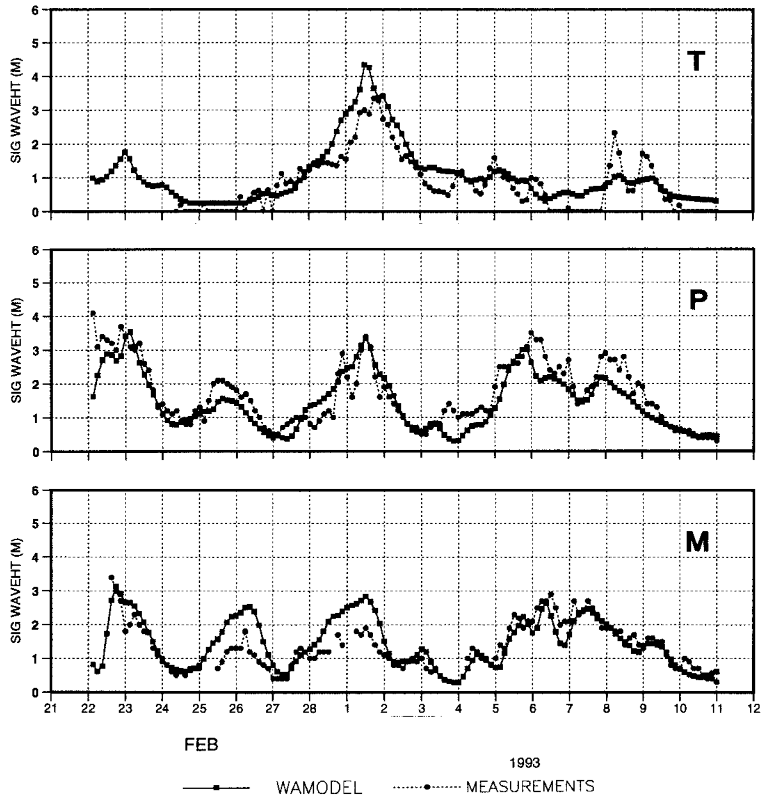

FIG. 11. As in Fig. 6 but with model wind enhanced (×1.5).

els, and they are therefore good indicators of the quality of the driving wind fields. Still using the same wave model (WAM), we have found a drastic improvement in performance passing from T106 to T213 (Cavaleri et al. 1991) and also to T333 (Dell'Osso 1990), where the numbers indicate the number of spectral components in the ECMWF meteorological model. The use of similar results from limited-area models with even higher resolution is consistent with this indication (e.g., Paccagnella et al. 1992). Without arguing about the physics of the models, two obvious factors seem to be the inability of the low-resolution models to properly describe the strong gradients present in the central area of a storm and the orography surrounding the smaller basins. Consistent with this hypothesis, for a given model the quality deteriorates while moving gradually from the open ocean to enclosed and then to small basins (Komen et al. 1994). Besides, higher-resolution models develop higher wind peak values, which is essential for a proper evaluation of the wave conditions.

We have suggested that surface drag and, more in general, the modeling of the surface layer could be responsible for at least part of the underestimatation. While this is certainly a relevant factor in some conditions, we do not consider it a prime culprit. First, the related modeling in the ECMWF model is quite sophisticated (see Simmons 1991). Second, improper modeling would show sparse consequences, certainly not confined to smaller basins. Finally, we have repeated our experiments following the theory of Janssen (1991) that also considers the influence on the surface drag of the underlying wave field. We have not found any substantial variations in the quality of the results.

We have also considered the consequences of horizontal diffusion. This is used in meteorological models to maintain numerical stability by smoothing over the improperly resolved small-scale features. In the T213 model the filter is at a wavelength of the order of 400 km, and it is therefore not surprising that features with the spatial scale of a small basin are affected. To check the consequences, together with two colleagues from ECMWF (M. Hortal and M. Miller), we have carried out a series of numerical experiments by running T213 with a reduced diffusion and comparing the results with the standard ones from the operational model.

A sample of the findings is given in the following figures. Figure 13 shows a classic situation of mild mistral in the western Mediterranean Sea associated with sirocco on the Adriatic Sea. The differences, for wind and waves, between the reduced diffusion and the standard cases are given in Fig. 14. The main results are a general enhancement of the wind speed, particularly in areas of strong gradients and/or close to the coasts. The latter effect is associated with the different surface drag coefficients on land and on the sea, and to the consequently different wind values. Horizontal diffusion

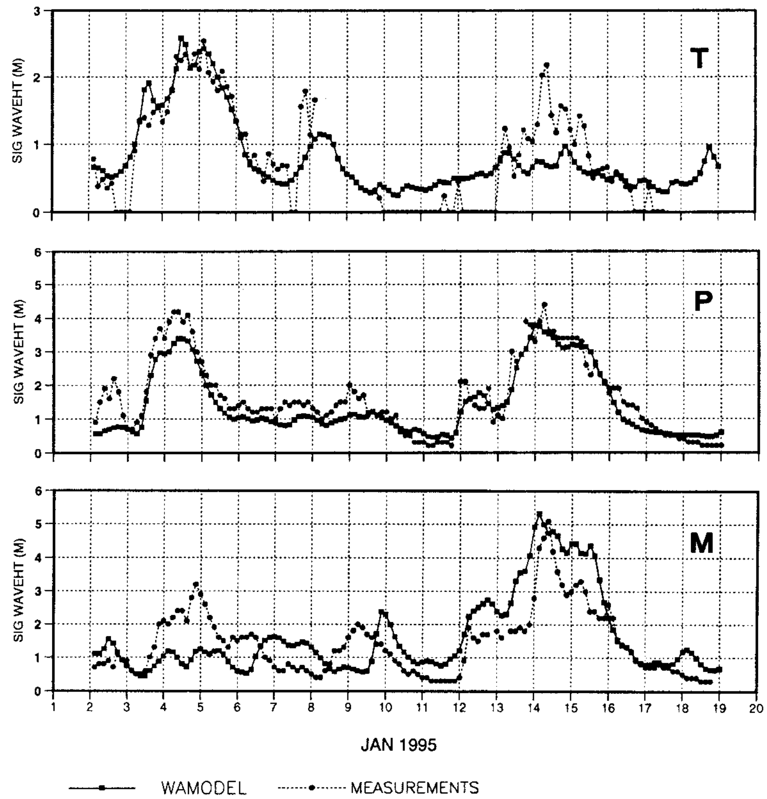

FIG. 12. As in Fig. 9 but with model wind enhanced (×1.5).

smears these differences, increasing the wind speed on land, decreasing it on the sea. Given the cutoff wavelength (188 km) and the dimensions of the Adriatic Sea, it is clear that the whole basin is affected, as is evident in Fig. 14a. The consequences for waves follow accordingly.

We must stress that this finding must not be interpreted as an indication that horizontal diffusion needs to be decreased in the meteorological models. It is clear that extensive testing is required before an overall conclusion is reached. However, the fact remains that horizontal diffusion does affect the surface wind fields, and this is what we have tried to quantify.

The partial lack of data is another possibility. The analysis field of a meteorological model is a combination of the first guess, that is, of the previous day forecast, and of the assimilation of the measured data. Measured data force the model to reproduce their distribution, and it is conceivable that wrong data (but not sufficiently wrong to be disregarded) can locally mislead the analysis and consequently the evolution of the model field. Conversely, the lack of data in an area impedes any local correction and possibly, forced by the data from other areas, leads to a local smoothing of the field.

The gradient on the Adriatic Sea is basically controlled by the values on the Italian coast on one side and by those from Slovenia, Croatia, and Montenegro on the other one. However, due to the recent war events in the area, the flow of measured data from this area has stopped for a long time and has only partially been resumed.

We hypothesized that, due to the lack of data, the fields could be locally smoothed, with a consequent average decrease of the wind speed. However, if this effect does exist, it should be present in the analysis but not in the forecast, because in its progress in time, and without any constraint from the measured data, the model naturally adapts to the area, developing the features associated to the general situation and to the local characteristics of the area.

This can be easily checked by repeating the runs described in the previous sections, using forecast instead of analysis winds. More specifically, we define with 1-day forecast the one covering 24 h following the analysis, with 2-day forecast the next 24 h, and so on. Then we build a sequence of 1-day forecast fields, one per

TABLE 1. Average bias of the model wave height (m), for different values of the wind enhancement factor α.

α	Bias (m)
1	−0.68
1.5	−0.03
2	0.74

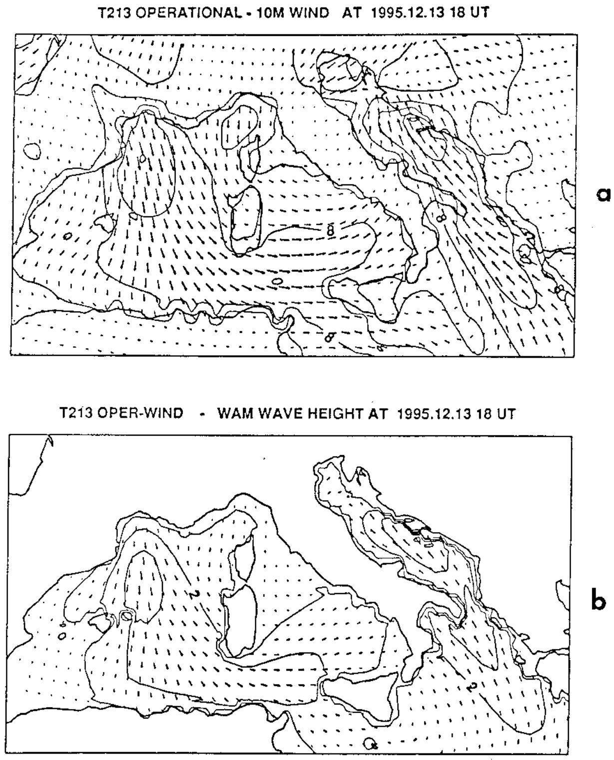

FIG. 13. Wind and wave fields in the western Mediterranean Sea at 1800 UTC 13 December 1995.

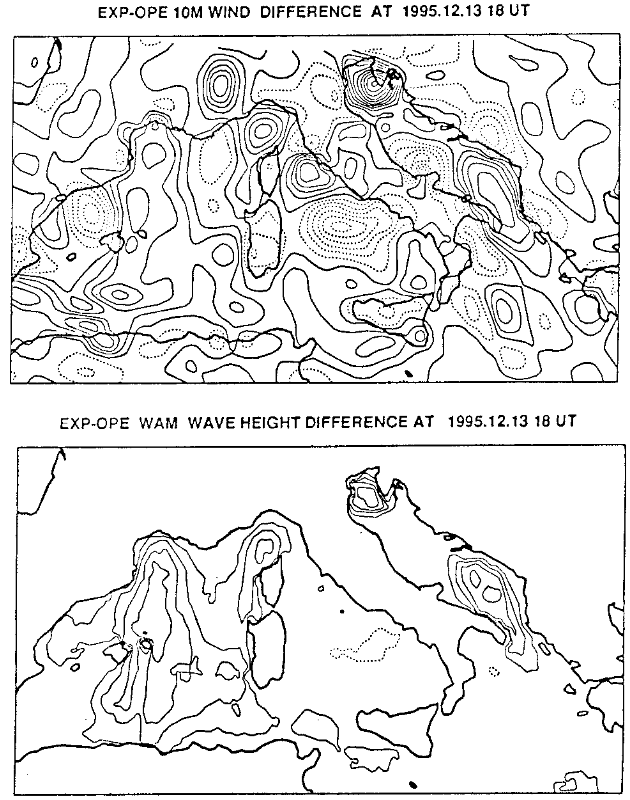

FIG. 14. With reference to Fig. 13a wind speed differences obtained with reduced and normal horizontal diffusion. Isolines at 20 cm s^{-1} interval. Continuous lines represent positive values; dotted lines are for negative ones. (b) As in (a) but for wave height. Isolines at 5-cm interval. (After Cavaleri et al. 1997.)

day, obtaining a sequence similar to the analysis fields but fully representative of the quality of the 1-day forecasts. Different sequences have been built for the 2-, 3-, and 4-day forecasts. The tests done for the calibration of the analysis have been repeated for all these sequences. The results (not shown here) up to 2-day forecasts have practically the same quality of the analysis, requiring a 1.5 enhancement factor to reach a satisfactory agreement with the measured wave heights. There is an initial deterioration at 3 days, and a substantial one at 4 days, which is obviously a consequence of the deterioration of the global forecast at this time span. Following the arguments outlined above, we conclude that the lack of data from the Balkans is not responsible for the poor performance of the ECMWF model in the Adriatic Sea.

Notwithstanding our satisfaction with the possibility to correct, and hence to use, the T213 surface wind in the Adriatic Sea, we must objectively acknowledge that this is not a universal solution. We have looked for an average correction for the average underestimate of the wind fields. However, this does not exclude a variability of the quality of the results, which is what leads to the expected scatter around the best fit lines in Figs. 7 and 10. So the miss of two peaks in Fig. 12, on 5 January 1995 at the M station and at T on 14 January 1995, plainly represents particularly poor analyses in those areas in those days.

As a final comment, we must stress that the correction we have introduced has clearly a very local value. While we expect similar corrections in basins of similar size, their actual value will depend on the characteristics of the basin, that is, on its shape, bordering orography, and typical meteorological conditions. Last but not least, the correction depends on the model itself, and it must therefore be updated, through a new series of tests, after each new release of the model. As this happens with relative frequency (more than once a year), one wonders if the calibration is worth the effort. However, we have carried out independent statistics for the single years since the T213 model was introduced in 1991. There is virtually no difference between the different results, an indication that the various changes introduced since 1991 have not appreciably affected the quality of the surface wind fields. Everything suggests that the real change takes place when the resolution of the model is changed, which is why we strongly point to this as the key factor for the quality of the results in the Adriatic Sea.

Acknowledgments. All the computer activities required for this research were done at the European Centre for Medium-Range Weather Forecasts. We would like to acknowledge their hospitality and to thank them for the help of the many people we interacted with, in particular user support staff Dominique Lucas and Norbert Kreitz.

Also we have appreciated the appropriate and stimulating comments from the two anonymous reviewers.

REFERENCES

Cavaleri, L., S. Curiotto, G. Dallaporta, and A. Mazzoldi, 1981: Directional wave recording in the Adriatic Sea. *Nuovo Cimento,* **4C** (5), 519–534.

——, L. Bertotti, and P. Lionello, 1991: Wind wave cast in the Mediterranean Sea. *J. Geophys. Res.,* **96C,** 10 739–10 764.

——, ——, L. Pedulli, S. Tibaldi, and E. Tosi, 1996: Wind evaluation in the Adriatic Sea. *Nuovo Cimento,* **19C,** 51–66.

——, ——, M. Hortal, and M. Miller, 1997: Effect of reduced diffusion on surface wind and wave fields. *Mon. Wea. Rev.*, in press.

De Boni, M., L. Cavaleri, and A. Rusconi, 1993: The Italian wave measurement network. *Proc. 23rd Int. Conf. on Coastal Engineering,* Venice, Italy, Amer. Soc. Civil Eng., 1840–1850.

Dell'Osso, L., 1990: Some results from the ECMWF spectral limited area model. LAM Newsletter, Deutsche Wetterdienst, Offenbach, German, 220 pp. [Available from Deutsche Wetterdienst, Seewetteramt, Postfach 301190, Hamburg, Germany D-20304.]

Glahn, H. R., 1982: Statistical weather forecasting. *Seminar on Interpretation of Numerical Weather Prediction Products,* Reading, United Kingdom, ECMWF, 263–310.

Janssen, P. A. E. M., 1991: Quasi-linear theory of wind wave generation applied to wave forecasting. *J. Phys. Oceanogr.,* **21,** 1631–1642.

Komen, G. J., L. Cavaleri, M. Donelan, K. Hasselmann, S. Hasselmann, and P. A. E. M. Janssen, 1994: *Dynamics and Modelling of Ocean Waves.* Cambridge University Press, 532 pp.

Paccagnella, T., S. Tibaldi, R. Buizza, and S. Scoccianti, 1992: High-resolution numerical modelling of convective precipitation over northern Italy. *Meteor. Atmos. Phys.,* **50,** 143–162.

Simmons, A., 1991: Development of the operational 31-level T213 version of the ECMWF forecast model. ECMWF Newsletter 56, 3–13. [Available from ECMWF, Reading, Berkshire RG2 9AX, United Kingdom.]

SWAMP Group, 1985: *Principal Results and Conclusions.* Plenum, 256 pp.