Effect of Reduced Diffusion on Surface Wind and Wave Fields

LUIGI CAVALERI AND LUCIANA BERTOTTI

Istituto Studio Dinamica Grandi Masse, Venice, Italy

MARIANO HORTAL AND MARTIN MILLER

European Centre for Medium-Range Weather Forecasts, Reading, United Kingdom

28 May 1996 and 4 March 1997

ABSTRACT

Horizontal diffusion is used in meteorological models to reduce noise in the shorter spatial scales and to increase numerical stability. In turn, this affects the surface wind distribution. A series of tests on real situations in the Mediterranean Sea has been done to explore the practical consequences on wind and wave fields. The results indicate a substantial reduction of the peak values, particularly in areas with strong spatial gradients, and a general smoothing of the fields, more evident where these are dominated by the local orography.

1. Introduction

Wind fields, as evaluated by meteorological models, are the basic input information to wave modeling, that is, to the evaluation of the wave conditions on the ocean by the numerical integration of the representative differential equations. A complete treatment of the subject is given by Komen et al. (1994). As waves are very sensitive to even small variations of the driving wind field, the accuracy of the latter is obviously a subject of interest.

Meteorological models integrate numerically in time a set of equations that describe the evolution of the state of the atmosphere. This produces a sequence of three-dimensional distributions of the quantities of interest (pressure, temperature, wind speed, etc.). The general formulation can be done using either finite difference methods or the spectral technique, where the horizontal distribution of the physical quantities is described using a two-dimensional spectral representation [see, among others, Holton (1992) and Eliasen et al. (1970) for a thorough discussion of the subject].

In either case a low-pass filter is applied to limit the noise in the high-frequency part of the spectra and to avoid numerical instabilities. In practice this can be obtained by allowing a horizontal diffusion at each integration step, effectively causing a smearing of the shortest characteristics of the fields. For the T213 spectral model presently operational at the European Centre for Medium-Range Weather Forecasts (ECMWF, in Reading, United Kingdom; 213 represents the number of the highest wavenumber of spherical harmonics with which the fields are two-dimensionally described), the cutoff is at a wavelength of 188 km [see Simmons (1991) for a description of the model].

The aim of this study is to explore the consequences of horizontal diffusion (henceforth indicated as HD) on the estimated surface wind fields and consequently on the associated wave fields. Our interest has been triggered by the results obtained in the Mediterranean Sea, using as input the analysis wind fields from T213. By comparing the wave results with measured data, we have found that to the west of Sardinia the wave heights, mostly associated with the mistral, a cold north-westerly wind blowing down from the Carcassone pass between the Pyrenees and the Massif Central in France, were on the average underestimated by 30%. On the contrary, similar data close to the west end of Sicily show an almost perfect fit between model and measured data. Our hypothesis was that, close to its generation area, the very narrow mistral jet is more affected by HD. Moving south, the jet widens and the higher wind speeds are less affected by the smoothing of the field.

Parallel to these results, we had also found a steady underestimate of the ECMWF wind speeds in the Adriatic Sea of about 30%, and we have considered the possibility that lower wind speeds on land could, because of HD, negatively affect the wind on the sea.

To explore the above possibility, a series of tests has been designed to compare the wind and the associated wave fields obtained 1) with the operational T213 model (reference) and 2) with T213 with reduced HD (experiment). Three different periods have been considered

Corresponding author address: Dr. Luigi Cavaleri, Istituto Studio Dinamica Grandi Masse, San Polo 1364, 30125 Venezia, Italy.
E-mail: gigi@ocean.isdgm.ve.cnr.it

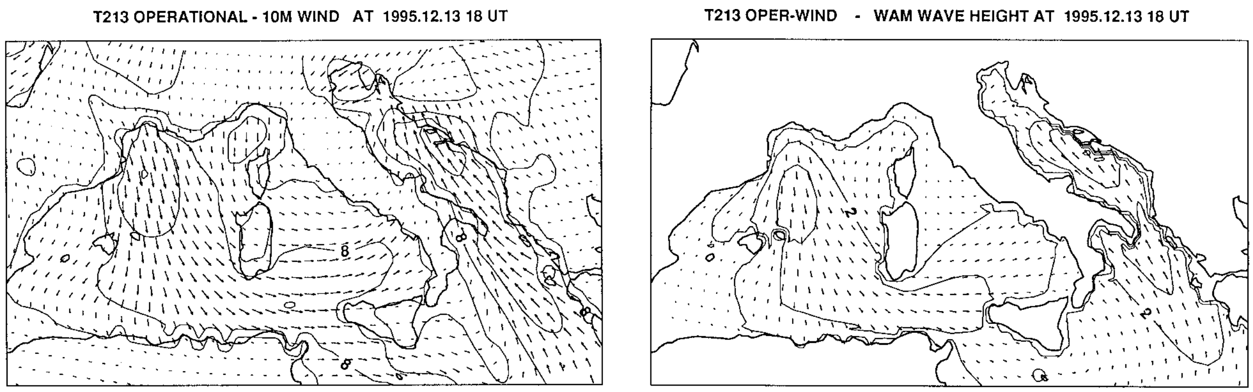

FIG. 1. Wind and wave fields at 1800 UTC 13 December 1995: (a) Wind, isolines at 4 m s^{-1} intervals, (b) waves at 1-m interval.

and analyzed. As explained in the following sections, care has been taken to extract from the ECMWF archive both the reference and the experimental fields in exactly corresponding conditions, so that any difference of the results is due only to the different original conditions, that is, to a different HD. All the wind fields have been retrieved from the ECMWF archive using a resolution of 0.5° both in latitute and longitude. At ECMWF the fields are archived on a Gaussian grid with 0.5625° resolution at the equator, corresponding to approximately 60 km.

For the evaluation of the wave fields we have used WAM, an advanced and well-tested wave model based on physical principles. The model describes the wavy surface of the sea as the superposition of a two-dimensionally distributed (in frequency and direction) number of sinusoidal components, each controlled in its evolution by the energy balance equation on a grid characterizing the basin of interest. WAM is widely used both in the scientific and operational communities. It is amply documented in the literature; see the two classic references WAMDI Group (1988) and Komen et al. (1994).

In the three considered periods we analyze three storms in the Mediterranean Sea, two of them discussed in the two following sections (2 and 3). The results of the third storm are reported in the final section, where we also summarize and discuss the overall findings. WAM has been run with 0.25° resolution. However, for better clarity, a 0.5° resolution has been used in plotting the fields.

In this paper, *ope* identifies the results obtained with the operational T213 model; *exp* refers to the experiments done with different conditions.

While, to judge the results, one would like to refer to the analysis fields, we were forced to intercompare *exp* and *ope* forecasts because, contrary to the analysis, no data assimilation was performed in the experiments. This does not affect the *exp–ope* intercomparison, but it puts the validation versus measured data on a more qualitative perspective.

2. Case 1: 12–17 December 1995

This period has been chosen as a combined case of mistral in the western Mediterranean Sea and sirocco (southeasterly) wind in the Adriatic Sea, the narrow

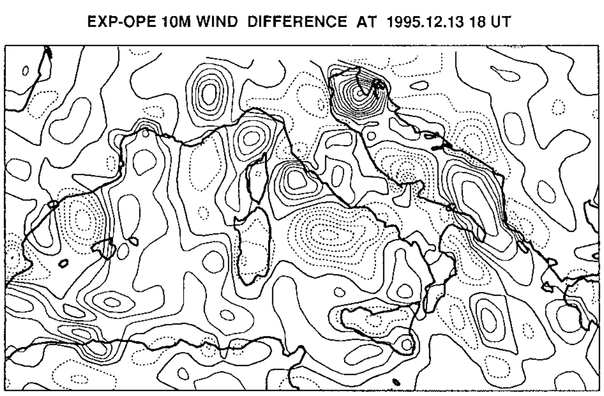

FIG. 2. Wind speed difference between fields obtained with reduced and normal horizontal diffusion, 1800 UTC 13 December 1995. Isolines at 20 cm s^{-1} intervals. Continuous lines represent positive values, dotted lines are for negative ones.

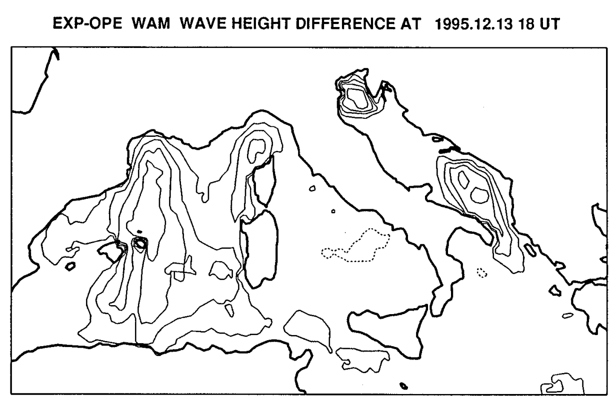

FIG. 3. Wave height differences when using input wind fields with reduced or normal horizontal diffusion, 1800 UTC 13 December 1995. Isolines at 5-cm interval.

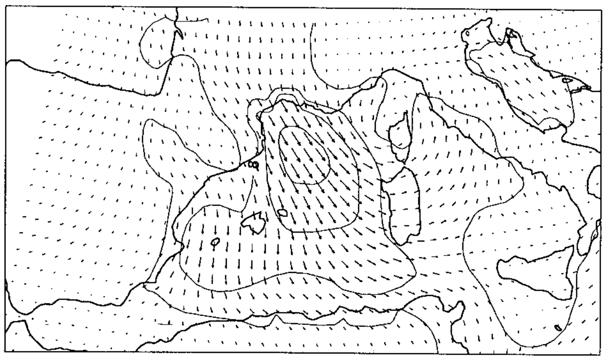

FIG. 4. Wind field at 1200 UTC 21 March 1986. Isolines at 4 m s^{-1} intervals.

basin between Italy and the Balkans. The case was not particularly intense, but it offered the possibility to study both the basins at the same time.

With respect to the operational results of T213 (*ope*), the case has been analyzed with a series of experiments, running the T213 model with reduced horizontal diffusion in the lowest model layers. The reduction in diffusion coefficient was such as to progressively multiply the coefficient by $1/\sqrt{2}$ from layer 27 down to the lowest layer, 31, thus reducing the near-surface value by a factor of $4\sqrt{2}$. One experiment per each day of the period has been performed, each lasting 72 h and starting from the 1200 UTC analysis. The initial analysis fields had been obtained with the operational T213 model. Direct inspection shows that regime conditions are reached after at most 6 h (time interval between sequentially archived fields). Together with other reasons, this led us to consider for the actual comparison the +12-h to +30-h fields from the start. On the whole, this provided a several-day sequence of wind fields (*exp*), at 6-h intervals.

The reference fields (*ope*) from the operational T213 runs have been extracted from the daily archived forecasts with the same timing rule. We have therefore two parallel sequences of similar wind fields, the only difference between them being the different HD.

Figure 1 shows the wind and wave situation at 1800 UTC 13 December 1995, the 30-h forecast. Maps at different times show similar characteristics. Note that for the general view we always use the maps of the reference fields. The fields are described by isolines at 4 m s^{-1} interval for the wind and at 1-m interval for the wave height (the significant wave height is used throughout the paper). The arrows point in the flow direction and their length is proportional to the modulus. In the text we always refer to the 10-m wind, because it is the one used to drive the wave model. This wind is obtained from the lowest (31st) layer of the meteorological output, by suitable modeling of the surface boundary layer. Hence it is fully representative of the model results.

The general situation in Fig. 1 can be described as a mild mistral, while the eastern side of the depression leads to sirocco in the lower part of the Adriatic Sea and bora, from the northeast, in its most northern part. Note the dense isotachs along the Croatian coast, typical of this situation. The waves follow accordingly.

Figure 2 shows the wind speed differences (of the moduli; all the differences refer to the moduli and are evaluated as *exp* minus *ope*). The isolines are at 20 cm s^{-1} interval. The lines are continuous for positive values, dotted if negative. Clearly any plot of the differences is better interpreted with reference to the general situation.

With respect to *exp* (which we take as reference for all our comparisons), in Fig. 2 *ope* leads to lower mistral values by 0.4–0.6 m s^{-1} in the area of higher wind speed. The difference is more marked on the right edge of the jet (see Fig. 1a), where the transversal gradient is larger. This area is flanked by two areas of negative values, which is consistent with the possible consequences of smoothing. A highly concentrated jet, when smoothed, will show lower values on its axis and increased values on its sides.

Similarly lower *ope* values are found for sirocco in the Adriatic Sea by about 0.8 m s^{-1} out of 16 m s^{-1} (5%). This is likely to be associated to the different wind speeds on land (lower) and on the sea (higher) because of the different surface drag coefficient. The local redistribution of wind speed due to HD locally increases the wind speed on land and decreases it on the sea in the area close to the coast. This is evident also for the bora, a very local wind in the northernmost part of the basin, controlled by the local orography, and in general all along the coasts of the Mediterranean Sea. Some evident examples are along the coast of Algeria, Spain, the Ligurian Sea, and, not included in the figure, Egypt, Turkey, the Sea of Marmara, the Aegean Sea, and the area of Gibraltar. The effect is enhanced whenever a large island is close to the continent, as in the case of Corsica.

The wave differences follow accordingly (see Fig. 3, isolines at 5-cm interval). Note that the redistribution of wind speed (i.e., of energy flux to waves) due to HD has clear consequences on the local wave heights, as in the case of the southern and northern Adriatic. It is not so effective on the wave characteristics in the far distance. This point will be further discussed in the final section.

3. Case 2: 20–23 March 1986

This is a case of mistral with contemporary easterly flow on the eastern Mediterranean. In 1986, T213 was not operational, hence two 72-h experiments have been run, starting from the 1200 UTC 20 March 1986 analysis. The first (reference, *ope*) experiment has been performed with the operational T213 meteorological model. The second one (*exp*) has been performed using the

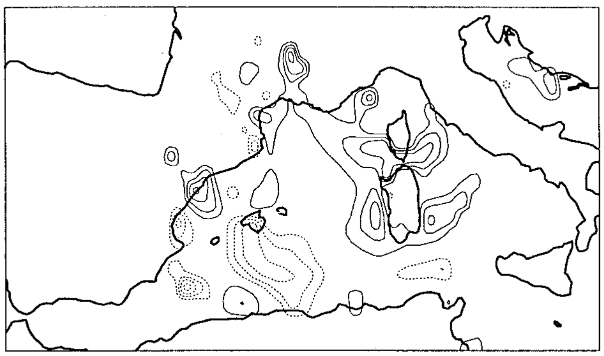

FIG. 5. Percentual wind speed differences between fields obtained with T319 and T213 spectral models, 1200 UTC 21 March 1986. Isolines at 5% interval. The differences are evaluated only where both the fields are larger than 5 m s^{-1}.

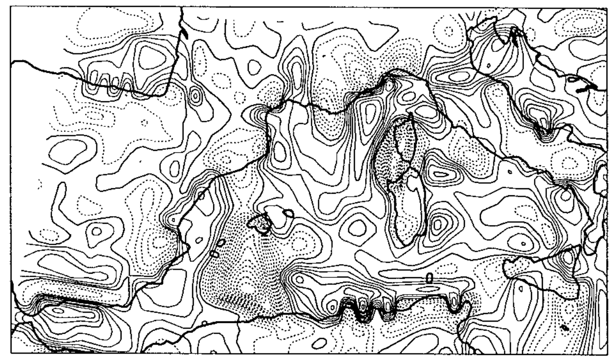

FIG. 7. Wind speed difference between fields obtained with T319 and T213 spectral models, 0000 UTC 22 March 1986. Isolines at 20 cm s^{-1} intervals. Continuous lines represent positive values, dotted lines are for negative ones.

T319 version of the ECMWF spectral model but using the same Gaussian grid of about 60-km resolution. As most of the grid calculations are executed in the grid space, this solution allows an improved resolution with only a 4% increase in computer time. In practice, this corresponds to a better description of the orography and, because of the shift of the cutoff frequency, to a reduced HD, if the HD is specified with the same *e*-folding time at the shortest scales in both cases. Compared with the previous case, we should expect an even stronger impact because of the better resolution. The wind fields are available at 12-h intervals.

Figures 4 and 5 show the wind situation at 1200 UTC 21 March 1986 and the corresponding percentual differences at 5% interval. Two features deserve attention. The first one is the channeling between Corsica and Sardinia. Clearly the improved orography in T319 leads to a more detailed description of the wind fields around, and in particular between, the two islands, with an enhancement of the funneling between the two mountain ridges. The reduced HD allows the permanence of this feature in the final field. Note that the differences are shown only where the wind speed is larger than 5 m s^{-1}, which cancels in the plot the corresponding negative differences in the side areas, that is, above the two islands.

The second feature is the shadowing by the Balearic Islands in the *exp* fields, again due to the combined action of the better orography and of the reduced HD. In both the cases the differences are up to 15%.

This shadowing is even more spectacular 12 h later. Figures 6 and 7 show, respectively, the wind and wave situations and the wind field differences, the latter at 20 cm s^{-1} interval. Advection from the northeast has directed the mistral flow more to the south, toward the Balearic Islands. There is a 3 m s^{-1} difference out of 10 m s^{-1} (30%) on the lee of the islands. Other remarkable shadowings are evident south of Sicily and (not included in the figure) west of the Peloponnesus. There are also higher values (by *ope* with respect to *exp*) of the wind over Corsica, likely to be associated with the different orography in T319 and T213. For the same reason the overall differences field is more articulated than in case 1. All this is quite clear in Fig. 8, showing the percentual differences at 5% interval. The usual areas of Gibraltar and the northern Adriatic are

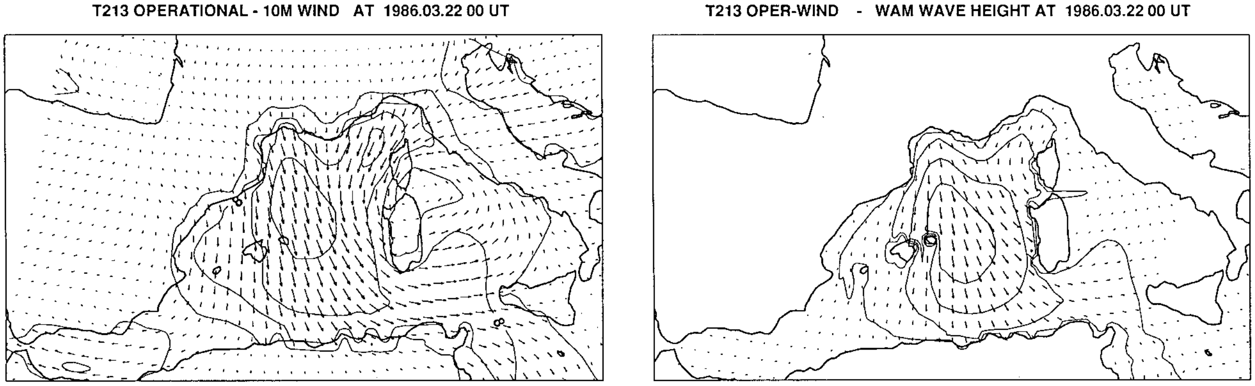

FIG. 6. Wind and wave fields at 0000 UTC 22 March 1986: (a) wind, isolines at 4 m s^{-1} intervals, (b) waves at 1-m intervals.

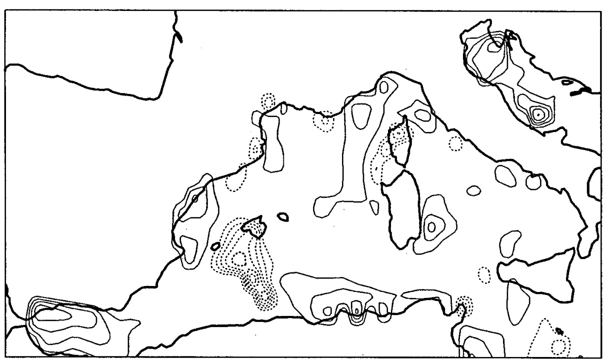

FIG. 8. As in Fig. 7 but for percentual differences. Isolines at 5% intervals. The differences are evaluated only where both the fields are larger than 5 m s^{-1}.

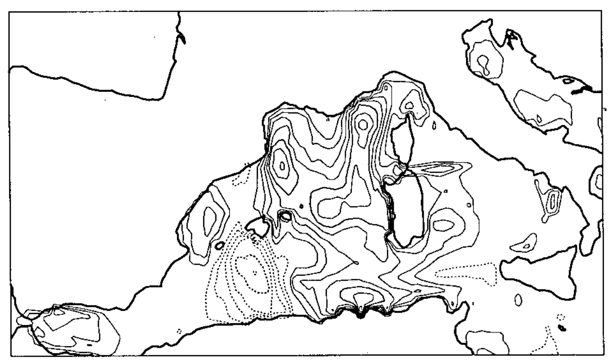

FIG. 9. Wave height differences when using input wind fields from T319 and T213 spectral models, 0000 UTC 22 March 1986. Isolines at 5-cm intervals.

well evident. The shadowing by the Balearic Islands provides much information, its asymmetry reflecting the detailed distribution of the surface wind available with T319.

The wave differences in Fig. 9 reflect the above features. We find lower values by *ope* in the area of mistral. Again, the shadowing of the Balearic Islands is evident, as similarly it is the passage of wave energy into the Tyrrhenian Sea through the Strait of Bonifacio.

4. Discussion

The third case we have considered is a strong mistral storm with a contemporary southwesterly wind on the Adriatic Sea. The peak of the storm was around 1800 UTC 13 May 1995. The results are fully consistent with the two previous cases, hence they are not shown here. Differences (*exp* − *ope*) up to +2 m s^{-1} have been found both in the mistral area (+10%) and in the Adriatic Sea (+20%). In front of Sardinia, the wave height differences are up to +14%. This corresponds to a 30% increase in wave energy.

We summarize our findings in the following points. On the sea, the consequences of horizontal diffusion are more evident where there are large spatial gradients. Mistral, with an initially narrow jet out of the Carcassone pass, is a typical example. Horizontal diffusion leads to a widening of the jet with a consequent decrease of the higher wind speeds. The effect decreases with distance while the jet, flowing south, opens to cover a wider area, and smoothing is consequently less relevant. The smoothing of the jet implies also an increase of the wind speed in the side areas.

Close to coasts, the effect is more general. Different surface drags imply higher wind speeds on the sea and lower ones on land. These differences are often accentuated where a complicate orography is present. While this effect is present throughout the Mediterranean Sea, and in general along all the coasts, it becomes dominant in enclosed basins with dimensions comparable to the wavelength of the smoothing cutoff. Typical examples, visible in the figures, are the Adriatic Sea, the Ligurian Sea, and the area of Gibraltar. This partly explains the steadily lower values of wind speed we have found in the Adriatic Sea in a previous series of tests.

The use of the T319 spectral model, with its more detailed orography and a higher cutoff frequency, even with the Gaussian grid used in T213, implies an actual reduction of HD. Hence the differences with respect to the operational T213 model are even more evident. Many features emerge, the most spectacular one in the considered area being the shadowing by the Balearic Islands, with differences in wind speed close to 30%.

Differences of wind speeds up to 14% have been found in the mistral area. The differences in wave height follow accordingly. However, the effect is more evident where the differences in the wind fields occur in the main generation area of the wave field. Acting during their active growing stage, higher wind speeds lead to appreciably higher wave heights.

Contrary to wind, the areas of increased wave heights, in *exp,* are not flanked by corresponding areas of lower values. The reason is that waves are an integrated effect, in space and time, of the generating wind field. Therefore, in the first approximation, the wave height distribution; starting from the locally enhanced *exp* fields, tends to asymptotically approach the *ope* field in the far distance.

More generally, a reduced HD is expected to shape better the wind fields around and on the lee of the islands. With the present configuration of the operational T213 meteorological model, many features around also relatively large islands, like Corsica and Sardinia, are cancelled by the actual scale of HD.

Closer to our original interest on wind waves, the reduction of HD leads to an increase of the wave height in the fields. This is a step in the right direction, even if correcting only part of the negative bias of the model results (Pontes et al. 1995). Several experiments run with high-resolution models (e.g., Dell'Osso et al. 1992) consistently indicate that an increased resolution leads to more articulated fields with substantially higher peak wind speeds. While any move in this direction is basically dictated by the available computer power, the reduction of HD can partly alleviate the limitations associated to the present resolution.

About the consequences of a reduced horizontal diffusion on the general products of a meteorological model: despite the clear benefits shown here, more experimentation is necessary to define an optimal configuration for operational applications.

Acknowledgments. All the computations required for the present research have been performed at the European Centre for Medium-Range Weather Forecasts, Reading, United Kingdom. We are pleased to acknowledge their help and availability in preparing the ground for our work, and we thank Tony Hollingsworth for ensuring the results were available in a timely fashion.

Adrian Simmons has discussed the results with us and made valuable suggestions. The help of Pedro Viterbo was appreciated.

REFERENCES

Dell'Osso, L., L. Bertotti, and L. Cavaleri, 1992: The Gorbush storm in the Mediterranean Sea: Atmospheric and wave simulation. *Mon. Wea. Rev.,* **120,** 77–90.

Eliasen, E., B. Machenhauer, and E. Rasmussen, 1970: On a numerical method for integration of the hydrodynamical equation with a spectral representation of the horizontal fields. Institut for Teoretisk Meteorologi Rep. 2, University of Copenhagen, Copenhagen, Denmark, 85 pp.

Holton, J. E., 1992: *An Introduction to Dynamic Meteorology.* 3d ed. Academic Press, 511 pp.

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.

Pontes, M. T., G. A. Athanassoulis, S. Barstow, L. Bertotti, L. Cavaleri, D. Mollison, and H. Oliveira-Pires, 1995: European atlas of wave energy resource in Europe. Preprints, *Second European Wave Power Conf.,* Lisbon, Portugal, Commission of European Communities, 88–102.

Simmons, A., 1991: Development of the operational 31-level T213 version of the ECMWF forecast model. *ECMWF Newsletter* **56,** 3–13.

WAMDI Group, 1988: The WAM model—A third generation ocean wave prediction model. *J. Phys. Oceanogr.,* **18,** 1775–1810.