On the sheltering effect of islands in ocean wave models

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[1] The effect of resolving relatively small islands in a third-generation wave model covering the whole North Atlantic is shown to have noticeable effects at long distances from the islands in addition to the local effects that have been reported earlier. To resolve the islands, a very fine grid is adopted locally, which is then nested in the overall model. The examples presented show the shadowing effect of Azores Islands for three specific wave conditions: when they come from the southwest, from the west, and from the northwest. The sheltering effect of the islands was demonstrated by a reduction of the significant wave height in the region on the leeward side of Azores Archipelago when comparing the wave model results with the island resolved and unresolved.

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1. Introduction

[2] Wave models have become established as robust tools to predict wave conditions generated by wind fields. The third-generation models such as WAM [*WAMDI Group*, 1988] and WAVEWATCH [*Tolman*, 1991] have been shown to provide good predictions and are widely used by meteorological offices.

[3] The skill of these models is good, but it depends much on the quality of the input wind fields, as has been demonstrated in several studies [*Teixeira et al.*, 1995; *Holthuijsen et al.*, 1996; *Ponce de León and Ocampo-Torres*, 1998]. The interest of climatology in reanalyzing past data so as to produce consistent data sets of atmospheric data is very useful as the wind fields can be used to force wave models and also to produce consistent sets of wave data.

[4] In the scope of a European project, a 40 year reanalysis has been done in order to produce consistent wave predictions over that time period for the waters around Europe as described by *Guedes Soares et al.* [2002]. It takes advantage of the 40 year atmospheric reanalysis done by the National Centers for Environmental Prediction (NCEP) for the period 1958–1998 [*Kalnay et al.*, 1996], which provides the basic wind fields used in that study. These wind fields were used to force a local area atmospheric model, which produces fine-grid and high-time-resolution wind data for the Atlantic coasts of Europe. This local area model takes due account of the land topography and thus is able to produce better wind fields close to the coast than the global atmospheric model that is used to force it. Waves are being predicted by the WAMc4 model [*Günther et al.*, 1992] in the deep water mode, which produces good hindcasts for the offshore areas around Europe.

[5] As a follow-up activity, an effort has been started to hindcast the wave conditions in coastal shallow waters using an appropriate shallow water model. Several models have been developed to take into account the specific effects that occur in shallow waters. *Ris et al.* [1999] have developed SWAN, a near-shore model that deals with wave generation, dissipation, and nonlinear transfers in addition to several shallow water processes such as depth-induced wave breaking and triad interactions. It allows for different possibilities of parameterizing the different laws.

[6] A different approach was adopted by *Schneggenburger et al.* [2000] in the *K* model, which only captures the main physical processes, i.e., it accounts for wind input energy, nonlinear dissipation, and bottom interaction dissipation.

[7] A still different approach was adopted by *Monbaliu et al.* [2000], who have modified the original code of WAMc4 by adapting it for shallow waters and high spatial applications. This work has been done during the PROMISE project, and this version of the model is being denoted as WAM-PRO, which is thus a third-generation wave model that describes the evolution of the directional wave spectrum through the energy balance equation, or the so-called transport wave equation [*Komen et al.*, 1994].

[8] The new version of WAM-PRO has implemented additional source terms to deal with the shallow water physics, a depth-induced wave breaking, and six new bottom friction formulations, two of them taking into account wave-current interaction, and it also incorporates a new fetch growth limiter according to *Luo and Sclavo* [1997]. Another improvement related to the numerical methods was introduced in WAM-PRO by *Osuna* [2002] for the nested run procedure and for the generation of boundary conditions to avoid a large amount of disk space.

[9] WAM-PRO was adopted for the present study, and comparisons with WAMc4 results and with buoy measurements are reported by *Ponce de León et al.* [2004a, 2004b]. In deep water the differences between the models are negligible, but on the coastal regions, some differences were identified, as expected.

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[10] As the study was aimed at the conditions very close to the coast, a fine grid of 0.25° was used around continental Portugal and the Azores Islands. When using the fine grid, the Azores Islands could be discriminated, and their effect became apparent in the wave calculations. In performing different studies, it was observed that in some cases the presence of the Azores Islands would induce a sheltering effect that was felt at unexpected large distances from the islands.

[11] Observations of wave shadows induced by islands of arbitrary shape are limited, and one of the few examples are *Pawka* [1983] and *Pawka et al.* [1984], which reported experiments in southern California to evaluate a numerical model of the sheltering of waves by islands.

[12] The sheltering effect of islands has been studied in connection with its effects in the relative vicinity of the islands by *O'Reilly et al.* [1999]. They studied the dissipation of wave energy by the reflection from cliffs on the coast of California using the spectral analysis derived from a data buoy, showing that swell is affected by the sheltering of Point Conception and Channel Islands. Also, *Oliveira-Pires et al.* [1997] have studied the effect of sheltering at close proximity to the Azores Islands using a ray model.

[13] *Tolman* [2003] has discussed the problem of unresolved islands in ocean wave models, which were identified as a source of major local errors. He developed a scheme to deal with the presence of the islands without having to use a fine grid at those locations.

[14] This paper considers the effect of unresolved islands in ocean wave models not only locally but also at long distances from the islands. In the present work a fine grid is adopted around the Azores Islands, and it will be shown that resolving the islands has, in addition to the strong local effect, a noticeable effect at large distances from the islands. In order to assess the influence of the Azores archipelago on the wave field, two independent hindcasts were performed, first by omitting the islands and second by taking them into account.

[15] It was observed that in certain wind conditions the spatial distribution of the significant wave height exhibits a strong spatial distortion when the presence of the islands was considered in the hindcast. In the region of the Azores Islands the significant wave height could be reduced by up to 4 m compared with the case in which the islands were not discriminated in the wave modeling, while for distances of the order of 500 km, reductions of 1 or 2 m can still be observed. This was observed when waves come from the west, the northwest, or the southwest.

2. Modeling the Azores Area

[16] The Azores archipelago is located between Europe, North America, and Africa. It is characterized by a relatively strong seismicity and active volcanism. Landscape features are characteristic of volcanic formation, with sharp peaks and ridges, craters, ravines, and lava fields.

[17] The nine islands that form the Azores archipelago lie between longitudes 25° and 32°W and latitudes 37° and 40°N. The archipelago has three groups of islands: first is the western group composed of the Flores and Corvo Islands, the second group is composed of the Terceira, Faial, Pico, São Jorge, and Graciosa Islands, and the third group is composed of the São Miguel and Santa Maria Islands. The eastern group is 760 nautical miles west of Portugal, and the western group is about 1070 nautical miles east-southeast of Cape Race, Newfoundland. The whole archipelago is oriented west-northwest to east-southeast and is about 330 nautical miles in extent (Figure 1).

[18] When a cyclonic low pressure in the open ocean is formed, some specific wind field is generated associated with it and generates a system of wind waves. When the wave systems propagate across the North Atlantic Ocean, they will encounter the Azores archipelago in the middle of the Atlantic Ocean.

[19] The islands are exposed to the wind and waves generated by the extra tropical storms and by the tropical cyclones usually approaching from the southwest and south. According to *Brand* [2002], the most severe winds on record in the last 50 years occurred during the winter storm in 1980 (120 mph). Several container vessels were lost in the open seas of the Azores area. They pointed out that extra tropical storm winds and seas tend to have a more westerly component than tropical cyclones.

[20] In this work the wind fields adopted are the ones that have been produced in the HIPOCAS project [*Guedes Soares et al.*, 2002]. The NCEP results of *Kalnay et al.* [1996] were used to force the fine-grid REMO regional model of *Jacob and Podzum* [1997]. The REMO output, described by *Feser and Weisse* [2003], for the northeast Atlantic was then complemented with the NCEP fields in the areas away from Europe. In this way the entire North Atlantic Ocean region was covered to deal properly with the spatial scale of the wind wave systems associated with the atmospheric depression that often appear in the area of Azores. The final product is a wind field with 0.5° of resolution in latitude and longitude and a wind input time step of 1 hour.

[21] Two representative wind conditions from this period are illustrated in Figures 2 and 3, showing predominant winds in the Azores region coming from the southwest (20 February 1994 at 0000 LT) and the northwest (26 February 1994 at 0000 LT), respectively. In these two cases the wind fields were associated with storms crossing the region of the Azores.

3. Setup of the Wave Model

[22] The nine Azores Islands have been represented in this work by one point each in the fine grid. As the real forms and dimensions of the Azores differ, it is not possible to represent all of them at a spatial resolution 0.25°. A higher resolution than 0.25° would increase the computational cost because the amount of grid points would increase. For this reason, each Azores Island was represented by one point placed in the grid carefully to imitate the "real" island's location, as shown in Figure 1.

[23] With the 0.25° resolution grid only (from the DbDbV bathymetry data), four islands were captured (represented in Figure 1 by the stars). The other five islands were introduced by creating one dry point of land in the grid point closest to it, which produced a displacement of the real location of the islands. In this way the Corvo Island was displaced 0.1° to the west in longitude and 0.25° to the south in latitude. Flores was represented by a dry point

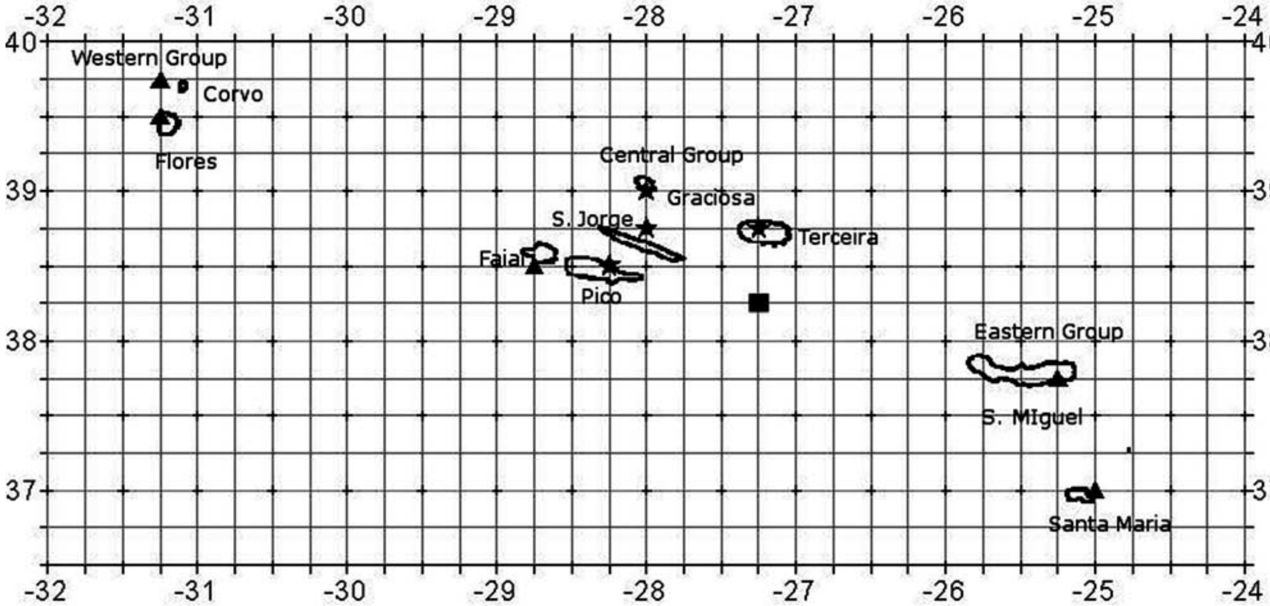

Figure 1. Locations of the Azores Islands, where the coastline is given from the Military Chart of the Portuguese Geographic Institute. The plus symbols represent the grid points where the HIPOCAS wind input information is at every 0.5°. Triangles show the dry points inserted for representing the missed islands in the bathymetry data 0.25° spatial resolution (equal to the nested model mesh), while the stars represent the islands captured with the grid. The location of modeled spectra at latitude 38.25° and longitude −27.25° (Figures 13 and 18) is marked by a square.

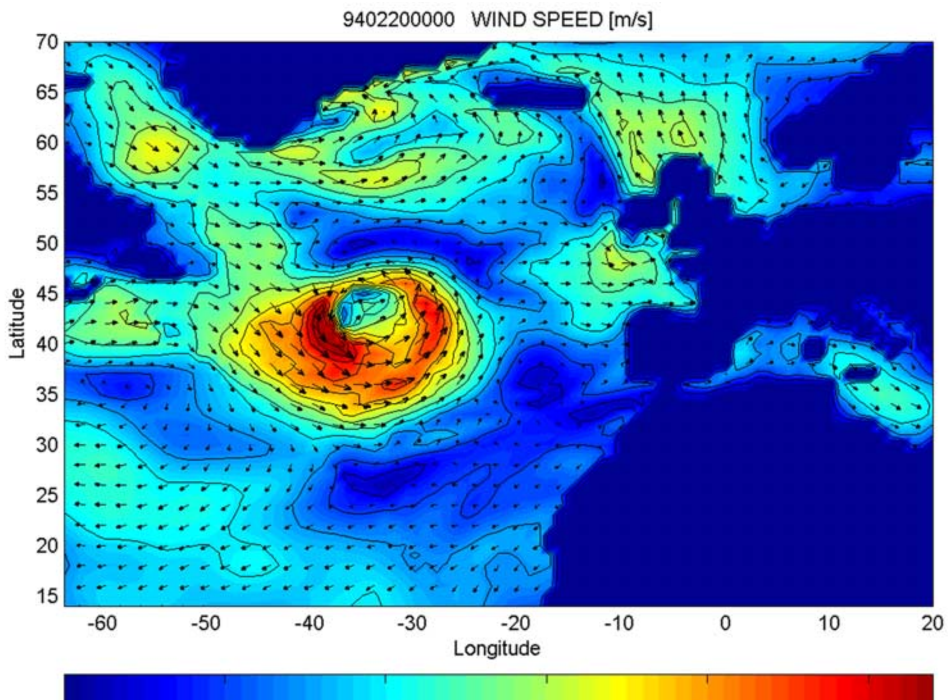

Figure 2. Wind field with 1° spatial resolution grid. Date is 20 February 1994 at 0000 UTC. The wind direction in the region of the Azores Islands is from the southwest, and the wind speed is about 20 m/s.

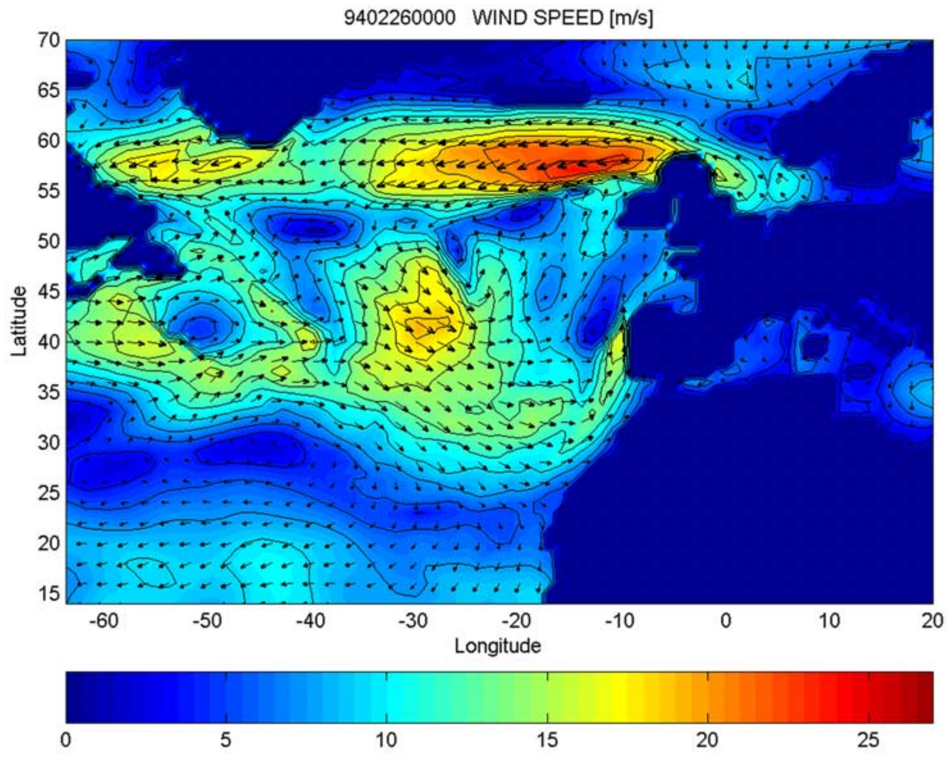

Figure 3. Wind field with 1° spatial resolution grid. Date is 26 February 1994 at 0000 UTC. The wind direction in the region of the Azores Islands is from the northwest, and the wind speed is about 20 m/s.

0.05° to the left in relation to the real location, Faial was inserted in the left corner of the real location island dislocated in 0.1° in latitude to the south and 0.05° to the west, San Miguel 0.05° to the east and Santa Maria in 0.1° to the east. These five dry points are represented by triangles in Figure 1.

[24] The bathymetry data set comes from Naval Oceanographic Office DbDbV v4.2 web interface, with resolution of about 5 min of degree (approximately 9 km) in latitude and longitude, and it was interpolated spatially to the 0.25° finest grid. A 1° coarse grid was used as the external domain (covers 14°N, 70°N, 20°W, −64°E), followed by a nested 0.25° fine grid, in a strip extending between longitudes −8° and −33°E and latitudes 35° and 41°N (Figure 4). Performing 1 month of simulation with the coarse grid takes about 5 hours for 4845 grid points. Increasing the resolution to 0.25° in the nested grid increases the total number of points by 2525 and increases the computation time by approximately 3 hours.

[25] Before deciding the final setup, studies were made to compare the results of the wave model with wind input time steps of 1 hour and 6 hours. It was concluded that for this region of the North Atlantic Ocean the differences in *Hs* winds were not significant, and thus for this work the wind input time step adopted in the final setup was 6 hours. The wave model interpolated internally this wind field to specify the components at every grid point in the 0.25° model mesh. The time step of output of the results was 12 hours. The time step of output boundary conditions was 2400 s.

[26] The wave simulation period is from 1 December 1993 at 0000 UTC (9312010000) to 1 March 1994 at 0000 UTC (9401030000). The sheltering effect of the islands presented a noticeable effect in the distribution of the *Hs* isolines only under certain conditions, mainly with winds from the southwest or northwest (Figures 2 and 3).

[27] In order to make clear the effect of the presence of the islands, additional calculations have been made by eliminating the presence of the islands. This situation would be similar to the one in existing studies with a coarse grid of 1° or 2° typical in ocean models, in which the presence of the islands would not be reproduced because of their small size.

[28] The energy balance equation was integrated for 24 directions and 25 frequency bands, and the energy was integrated with an integration time step and source function time step of 600 s. The lowest resolved frequency is 0.0418 Hz. The initial condition for the WAM-PRO model was the usual JONSWAP spectrum, with the following parameters: Phillip's parameter, 0.018; peak frequency, 0.2 Hz; overshoot factor, 3; left peak width, 0.07; right peak width, 0.09; averaged wave direction, 0.0°; and fetch, 30 km.

[29] The WAM-PRO model has the option to shift (IDIR = 1) or not to shift (IDIR = 0) the grid by $0.5\Delta\theta$. It has been observed earlier that not shifting the grid could introduce an artificial sheltering effect which is related to the preferential energy traveling in the north-south or east-west direction (J. Monbaliu, personal communication, 2004). Therefore in the preparation of the final setup a study was made of the resulting wave fields when the model was run with the options IDIR = 0 and 1, and results are shown in Figures 5–7.

[30] The strong sheltering effect shown in Figure 6 was exaggerated by the way the direction grid was handled in the calculation, which did not account for any change in the

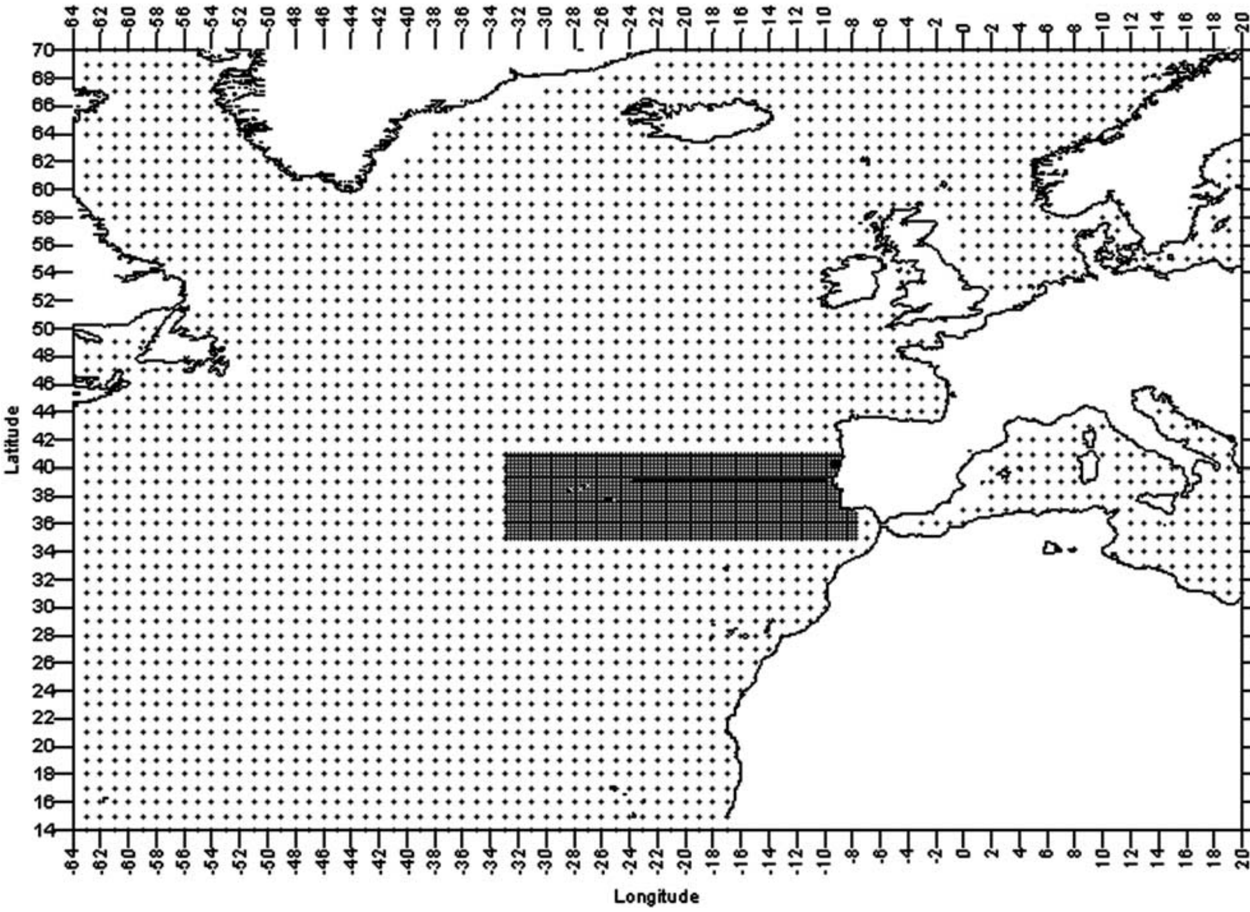

Figure 4. Coarse ($\Delta x = \Delta y = 1°$) and fine ($\Delta x = \Delta y = 0.25°$) grid active points and the Figueira da Foz buoy location marked by a circle. Black lines represent the track along which the *Hs* curves were taken in Figures 15–17.

grid direction. The model was run with a grid shift, and the large sheltering effect disappeared (Figures 5 and 6), although there was still some effect clearly shown in the numerical results.

[31] It is easy to see (0.5° of resolution) how the wave field enters into the grid coming from the west with maximum values of about 9 m because of nesting. The shadow effect of the Azores Islands is observed to the east of the islands along the latitude 38°N by a strip (located between −22° and −13°) with *Hs* values reduced (IDIR = 0 (Figure 5 (left)) and IDIR = 1 (Figure 5 (right))).

[32] The case study shown in Figure 3, when the wind comes from the northwest associated with the storms crossing the Azores (26 February 1994 at 0000 LT), exhibits the shadowing effect affecting the wave field energy. The simultaneous wave field (Figure 6 (left)) exhibits a strip of lower *Hs* than the surroundings when the WAM-PRO was run with IDIR = 0. The strip is distributed along latitude 38°N between −18° and −13° associated with the only one Azores Island "captured" by the bathymetry data with 0.5° spatial resolution. Also, the wave field propagating from the northwest associated with the wind speed and direction of the storm can be seen. When the calculation is done using IDIR = 1, the strip disappears, as shown in Figure 6 (right).

[33] A visible impact on the spatial distribution of the *Hs* up to the Portuguese continental shelf is shown in Figure 7 when using the IDIR = 0 and 24 directional bins in the numerical simulation with a grid resolution of 0.25° in latitude and longitude. This effect can be mitigated, increasing the angular resolution by using up to 36 directions and making the IDIR parameter equal to unity (see the second and third lower panels in Figure 7).

[34] Having concluded that running the model with option IDIR = 0 leads to erroneous effects, all calculations made with the final setup and reported hereinafter have been made using IDIR = 1, i.e., shifting the directional grid by $0.5\Delta\theta$.

4. Validation of the Wave Results

[35] Calculations have been made with the Azores islands and in the artificial situation of not including the islands and their sheltering effect so as to quantify the effect of the presence of the islands. Lack of routine wave monitoring in the region of Azores Islands made it impossible to perform comparisons with measured data at that location.

[36] WaveRider buoy measurements at Figueira da Foz in the Portuguese coast (Figure 4), reported by *Paillard et al.* [2000], were used to validate the wave hindcasts. A relatively wide continental shelf and a simple topography with a gently sloping bottom and depth contours characterize the west coast of Portugal, around Figueira da Foz, nearly

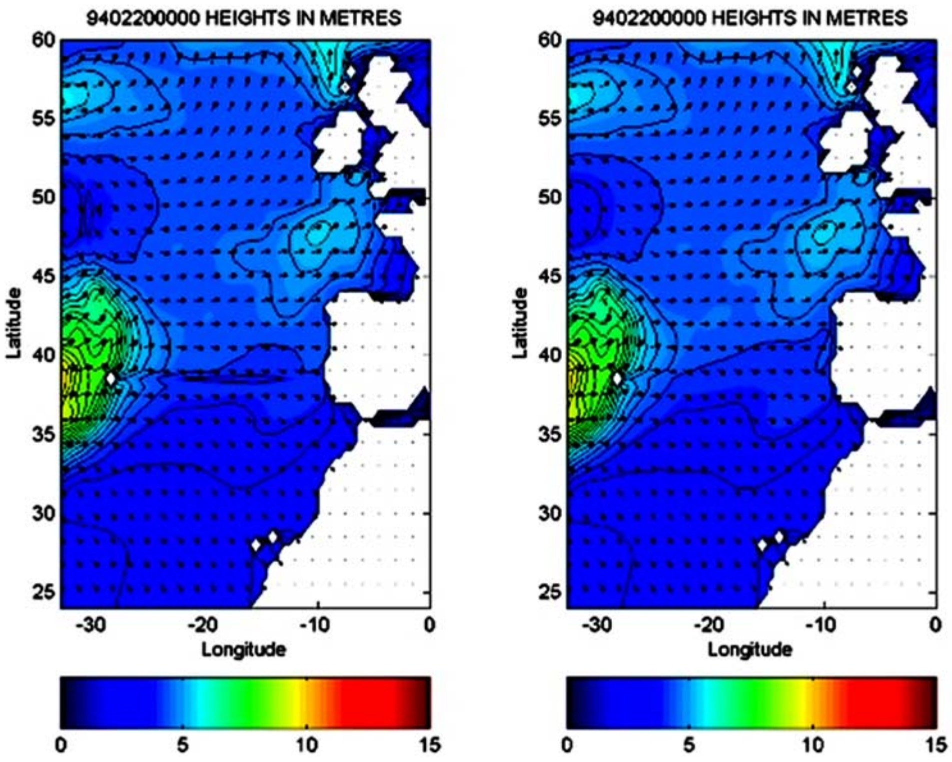

Figure 5. Significant wave height maps corresponding with the same date of the wind field of Figure 2 (9402200000, for 20 February at 0000 UTC). Grid resolution is 0.5°. (left) IDIR = 0. (right) IDIR = 1.

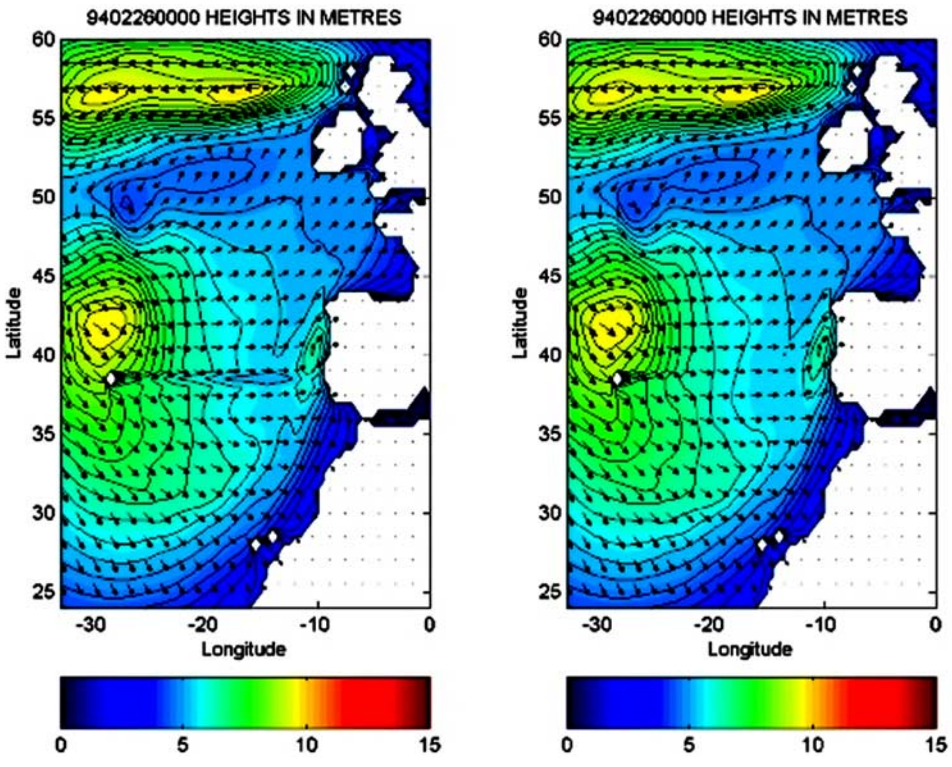

Figure 6. Significant wave height map corresponding with the same date of the wind field of Figure 3 (9402260000, for 26 February at 0000 UTC). Grid resolution is 0.5°. (left) IDIR = 0. (right) IDIR = 1.

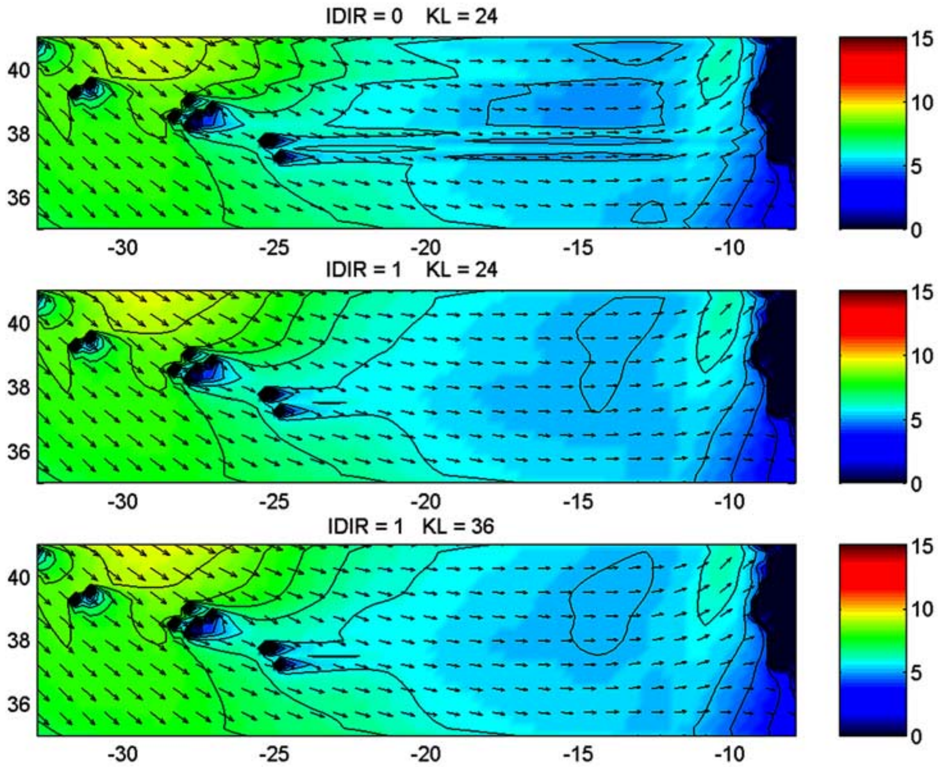

Figure 7. WAM-PRO significant wave height maps (9402260000, for 26 February at 0000 UTC) varying the parameter IDIR and directional resolution in the WAM-PRO model. Grid resolution is 0.25°.

parallel to the coast. The winter wave climate in the west adjacent coast of Portugal is swell dominated because of the frequent storms farther to the north. Winds are locally predominantly northerly to northwesterly (Figure 8).

[37] Table 1 shows some statistics from the comparisons of the calculated and measured significant wave height at that location during the whole month of February 1994 when using 24 and 36 directional bins. It can be concluded that the WAM-PRO model overestimates the significant wave height for both cases with and without Azores Islands, with negative values of bias around 0.5 m on the average. The correlation coefficients are very similar, indicating that the trends are very similar. The numbers in Table 1 are consistent with the wave model statistics found in the literature [*Zambresky*, 1989].

[38] The comparison between the *Hs* time series modeled and measured (Figure 9) shows a good agreement during the largest storm, which occurred around the 4th day of the simulation, and also for the one on the 19th day. However, for the other storms the wave model slightly overestimates the measurements.

5. Modeled Sheltering Effects of the Azores Islands

[39] This study shows how the Azores Islands, located in the middle of the open ocean, may contribute to the dissipation of the spectral wave energy under certain weather conditions. The attention was centered on those main situations that illustrate the phenomena: first, when the waves come from the southwest (Figure 5), and second, when coming from the northwest (Figure 6), associated with the storms that crossed over the Azores Islands.

[40] During February 1994 a strong sheltering effect to the east of the islands was observed associated with the passage of the *Hs* maximum across the Azores. Figures 10–12 present the results of calculating the three reference cases with a fine grid of 0.25° in which the nine islands are resolved. The strip with the fine grid shown in those figures is nested in the overall model shown in Figures 5 and 6.

[41] The zoom of the sheltering effect detected in Figure 5 is shown in Figure 10. In Figure 10a the nine Azores Islands that were missing in the 0.5° grid can be seen. For this reason, now the sheltering effect of Azores has changed by increasing the region of the shadow according (or associated) to the nine islands (Figure 10a). When the Azores Islands are ‘‘removed’’ from the bathymetry data set, the sheltering effect disappears (Figure 10b).

[42] When the wave field propagates from the west (20 February at 1200 LT), the sheltering effect delays the arrival of the high *Hs* wave front to the coast of continental Portugal (compare Figures 11a and 11b). Paying attention to the longitude −20°, it seems that the wave front advanced faster when the Azores Islands were missing. It is evident that the Azores archipelago contributed to the reduction of the *Hs* maximum when it entered into the region of the islands, reducing the wave energy. The basic effect of the islands is the blockage of the waves in the lee of the islands.

[43] The comparison of the nested wave field with and without the Azores (22 February at 0000 UTC) shows (Figure 12) that close to the Portuguese coast, the 5 m significant wave front appears extended over a big area,

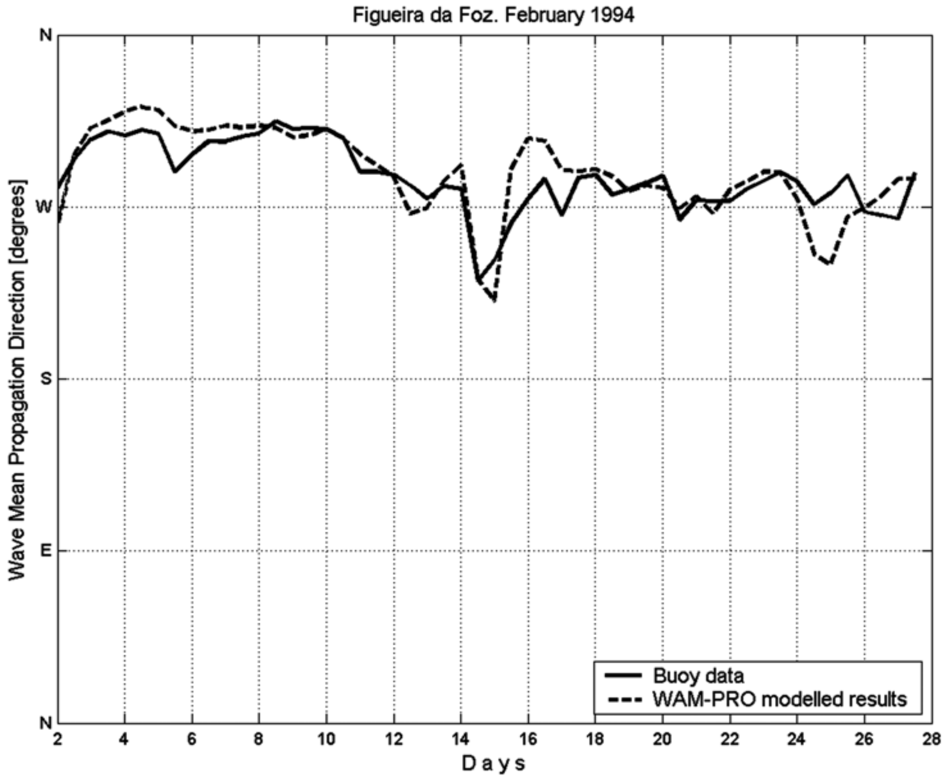

Figure 8. Figueira da Foz WaveRider and WAM-PRO modeled mean propagation direction time series for winter 1993–1994. Data plotted every 12 hours.

reaching the coast of Portugal faster than when the islands are taken into account in the simulations. When islands are absent in the simulation (Figure 12 (bottom)), the "green area" of about 7.5 m (green color in the bar scale) penetrates southern up to 36° latitude coming from the north. The high *Hs* wave front is reduced, indicating that the effect of shadowing phenomena due to wave front is trapped and blocked in the Azores archipelago, losing the energy.

[44] According to the wave simulations performed with and without islands, it seems that close to the Terceira Island (see location in Figure 1 as a black square), the comparison of the modeled *Hs* time series shows clearly that the Azores archipelago blocks the propagation of the strong swell wave energy, reducing the *Hs* on the leeside. In some storms the reduction at that point can be about 4 m (20 February 1994 at 1200 UTC), as shown in Figure 13.

[45] To asses how the sheltering effect changes with the distance from the islands, various traces of the resulting *Hs* were determined along a track coinciding with the main wave propagation direction. To have more significant values, the individual spatial traces have been averaged, and Figure 14 shows monthly mean curves of *Hs* taken over a track in the typical winter wave propagation direction that for this region, which is from northwest to southeast. This shows that at the end of nested grid, which is about 800 km away from the islands, the sheltering effect is attenuated.

[46] Other *Hs* curves were taken along the track from west to east (see Figure 4) up to the Portuguese continental shelf along 1700 km (Figure 15). As can be seen, differences between simulations with and without islands are being reduced when the distances increase away from the islands. Small average differences of about 20 cm can be

Table 1. Statistical Parameters for Differences of the Significant Wave Height *Hs* at the Figueira da Foz Between Measurements and the WAM-PRO Model Nested 0.25° of Resolution Fine Grid for February 1994 for 36 and 24 Directional Bands and IDIR = 1[a]

	KL = 36		KL = 24	
Figueira da Foz	With Azores Islands	Without Azores Islands	With Azores Islands	Without Azores Islands
Correlation coefficient	0.85	0.84	0.85	0.84
Bias	−0.46	−0.51	−0.43	−0.48
RMS error	0.92	0.97	0.89	0.94
Standar deviation	0.79	0.82	0.78	0.81
Slope	0.88	0.86	0.88	0.87
Scatter index	22.9	23.6	22.7	23.4
Hs mean	3.70	3.75	3.65	3.71

[a]Wave height *Hs* is in meters.

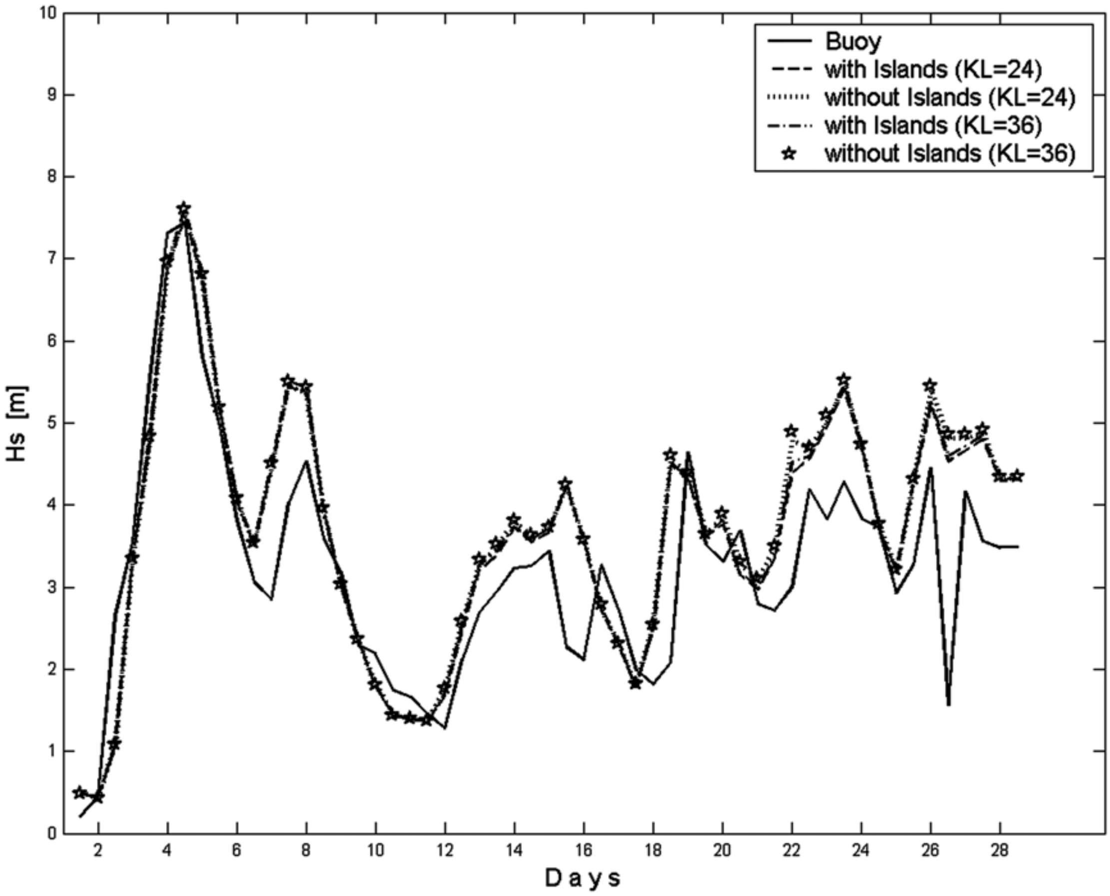

Figure 9. Comparison of time series of significant wave height between the WAM-PRO model results and buoy data starting in February 1994 at location Figueira da Foz (latitude 40.25°, longitude 9.25°). Simulations were first performed for 24 directions (KL) with/without islands and then for 36 directions with/without islands.

observed near the Portuguese continental shelf, showing that the sheltering effect, although small, is persistent far away from the Azores archipelago.

[47] At specific times the sheltering effect can be larger, as shown in Figures 16 and 17, which present the curves for 19 and 25 February 1994 at 1200 UTC, respectively. The *Hs* traces in Figures 14–17 show that instantaneous differences can be larger than the mean values and can also be felt at larger distances. If the waves come from the southwest, west, and northwest, the modeled sheltering effect of the islands can affect the *Hs* that reaches some regions of the coast of Portugal. The islands seem to be ‘‘protecting the coast,’’ reducing the value of significant wave height that would reach the coast if they were not there.

6. Effects on the Modeled Wave Spectrum

[48] The presence of the Azores Islands, while reducing *Hs*, also induces a spread of energy and induces changes in the directional wave spectrum. In this section the attention is addressed to the influence of the Azores Islands shadowing effect on the wave energy distribution, in particular, in the changes induced in the directional wave spectrum.

[49] Considering a location close to Terceira Island (see Figure 1) and comparing the directional wave spectra obtained for 13 February 1994 at 0000 UTC, shown in Figures 18a and 18b, a three-peaked spectrum can be seen in Figure 18a, with *Hs* = 2.1 m. Two swell systems are present with the sea wave component. However, when the Azores Islands are absent in the geographical domain (Figure 14b), the spectrum exhibits only one component, centered over the low-frequency region over 0.1 Hz, with *Hs* = 4.1 m, i.e., twice of the value of the first case when Azores Islands are ‘‘acting’’ like an obstacle contributing to the dissipation or attenuation of the wave energy. The swell is affected by the sheltering of the Azores Islands, reducing the significant wave height by 2 m in this instantaneous event case.

[50] For instance, the shadow effect of Azores contributes to the attenuation or smoothing of the wave energy field in the North Atlantic Ocean, before approaching the Iberian peninsula. The wave directional spectra given in Figure 19 show the complexity of the monthly mean spectrum when the wave field enters into the region of the islands, experimenting probably different dissipative physical processes that reduce the spectral wave energy. The *Hs* is reduced by 1.97 m if the islands are taken into account in the simulation.

[51] In order to find if the shadowing effect of the Azores is noticeable on the Portuguese coast, the mean spectrum

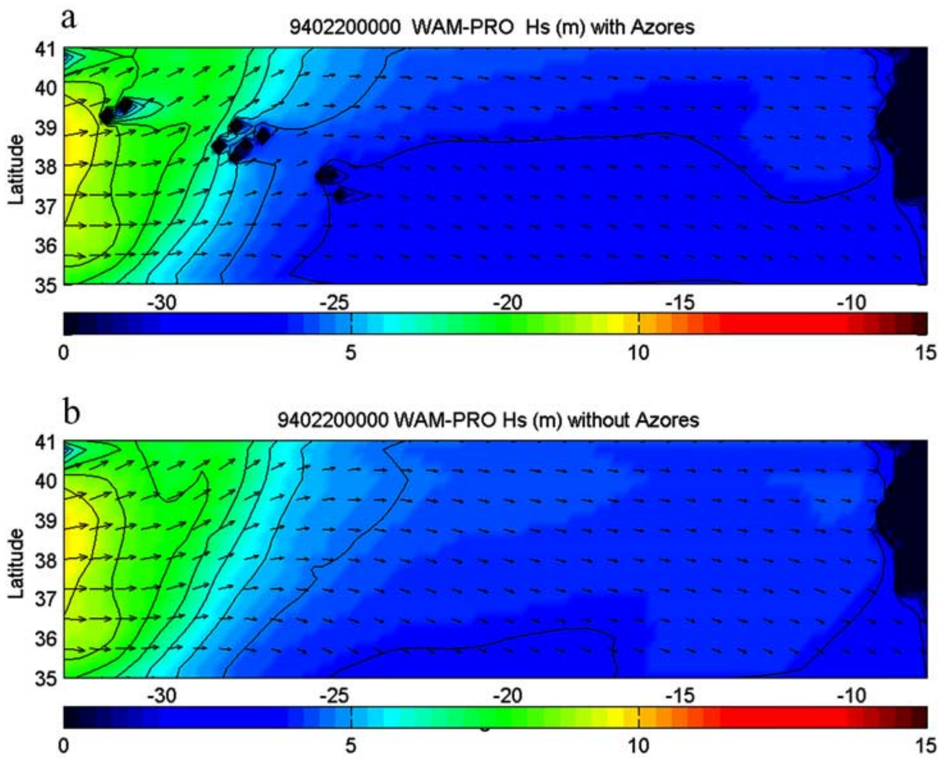

Figure 10. (a) Shadow effect of the Azores is reflected in the WAM-PRO *Hs* map at the same date as Figure 5 (20 February 1994 at 0000 LT), but this is a nested wave field in the 0.25° grid ("zoom"). (b) Shadow drastically disappears when the Azores Islands are missing in the bathymetry input data set. IDIR = 1.

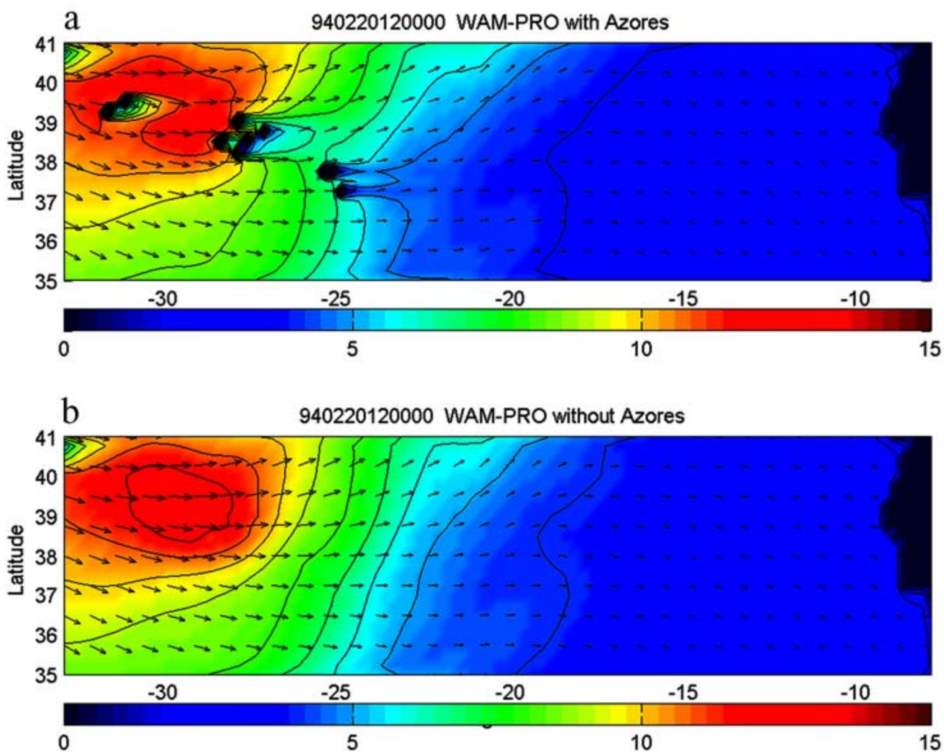

Figure 11. (a) Shadow effect of the Azores Islands, but 12 hours later (20 February 1994 at 1200 UTC). (b) Sheltering effect of the nine islands disappears when the Azores Islands are missing in the bathymetry input data set. IDIR = 1.

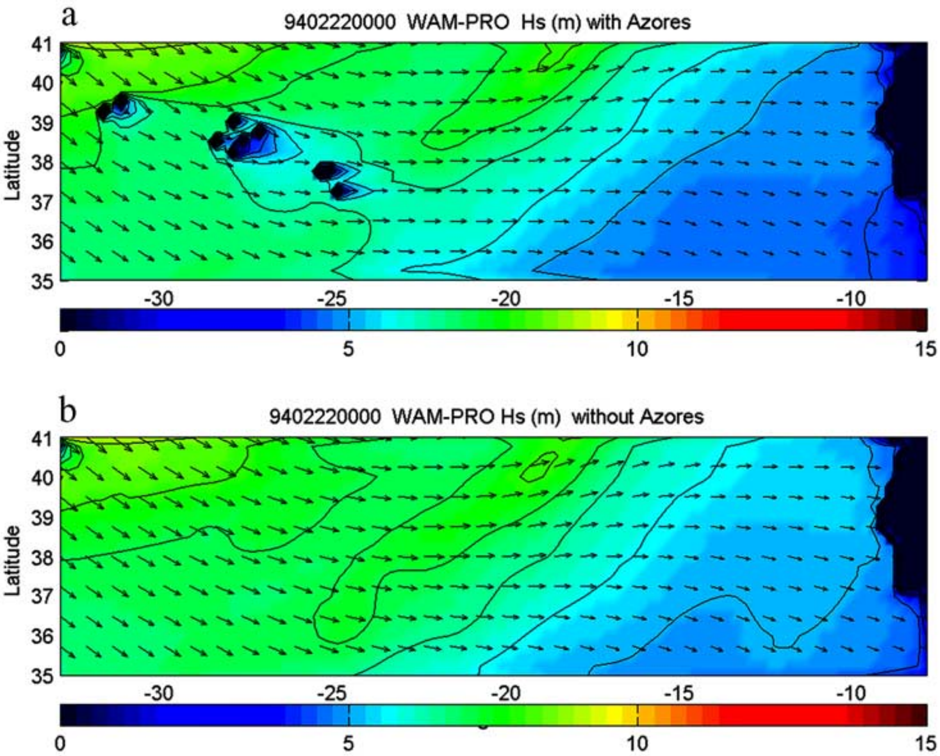

Figure 12. (a) Shadow effect reflected in the 0.25° resolution WAM-PRO *Hs* map for date 22 February 1994 at 0000 LT. (b) Without the Azores Islands, the shadow effect is reduced. IDIR = 1.

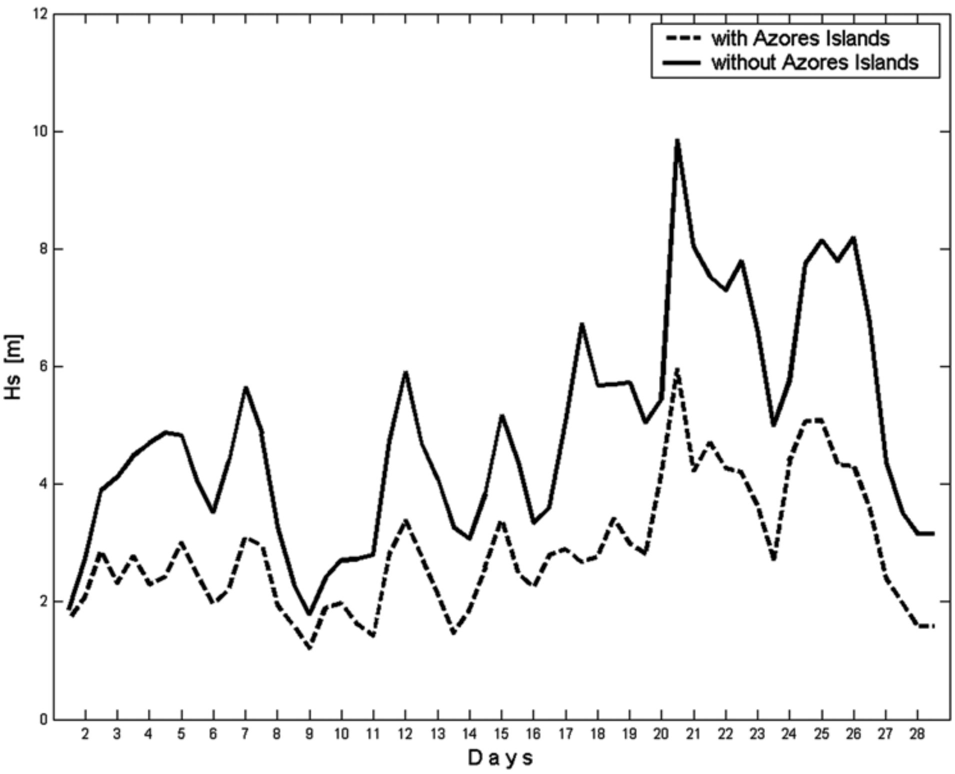

Figure 13. Comparison of modeled time series of significant wave height WAM-PRO model results during February 1994 at location Terceira (latitude 38.25°, longitude −27.25° (see Figure 1)). Simulations were first performed for 24 directions with/without islands.

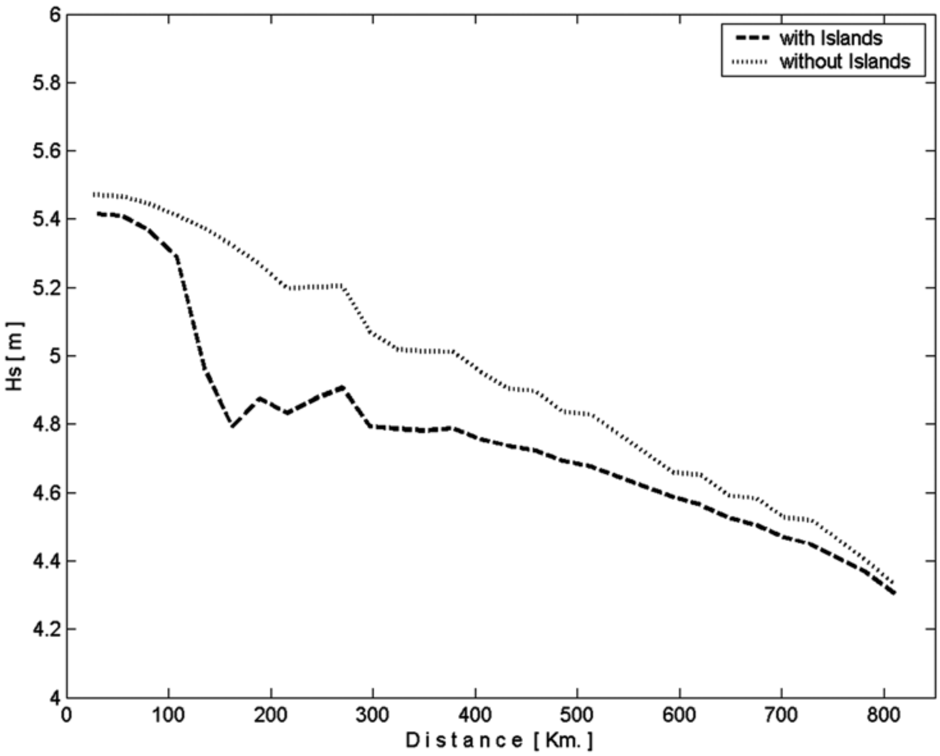

Figure 14. Monthly mean curve for *Hs* for February 1994 as a function of the distance along the track northwest-southeast to the south of the Azores Islands.

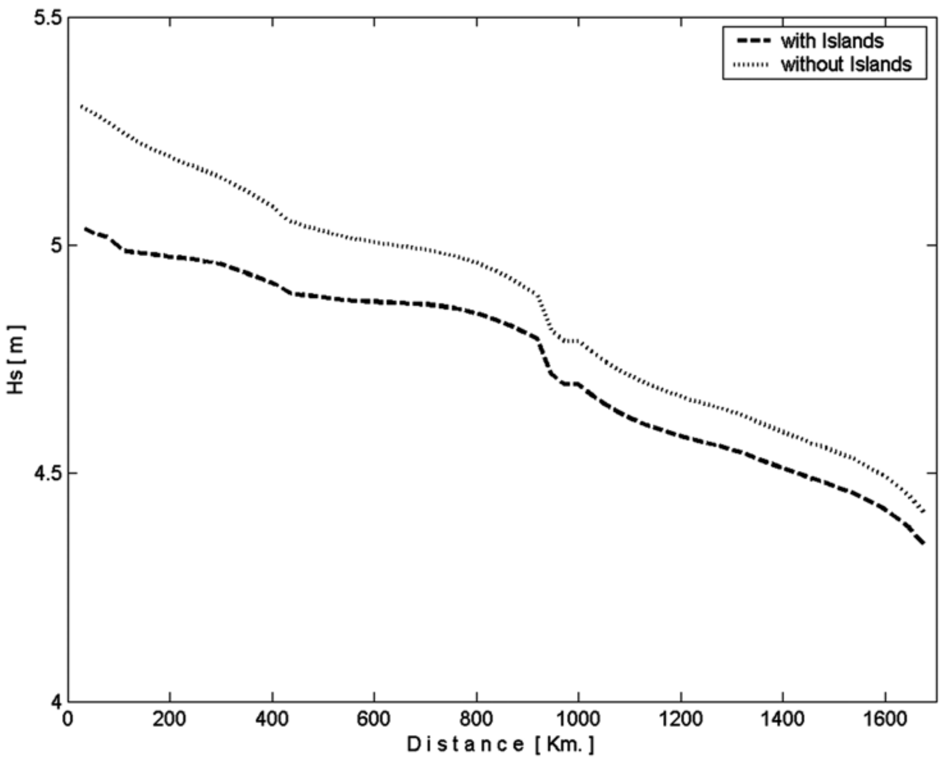

Figure 15. Monthly mean curve for *Hs* for February 1994 as a function of the distance taken from west to east up to the Portuguese continental shelf.

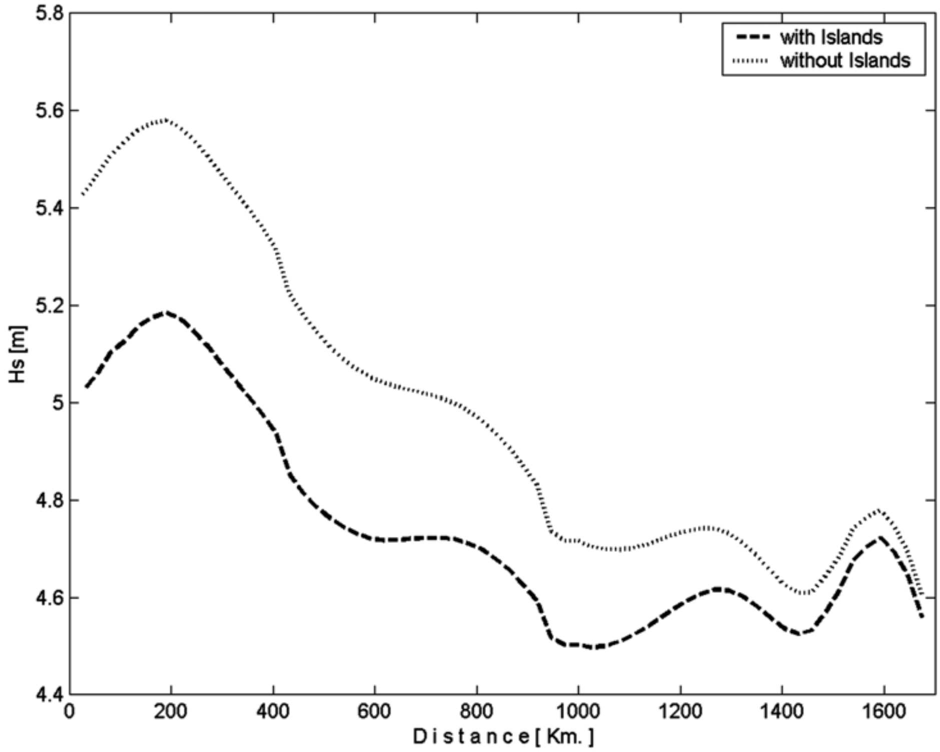

Figure 16. Curve of significant wave height as a function of the distance taken from west to east for 19 February at 1200 UTC.

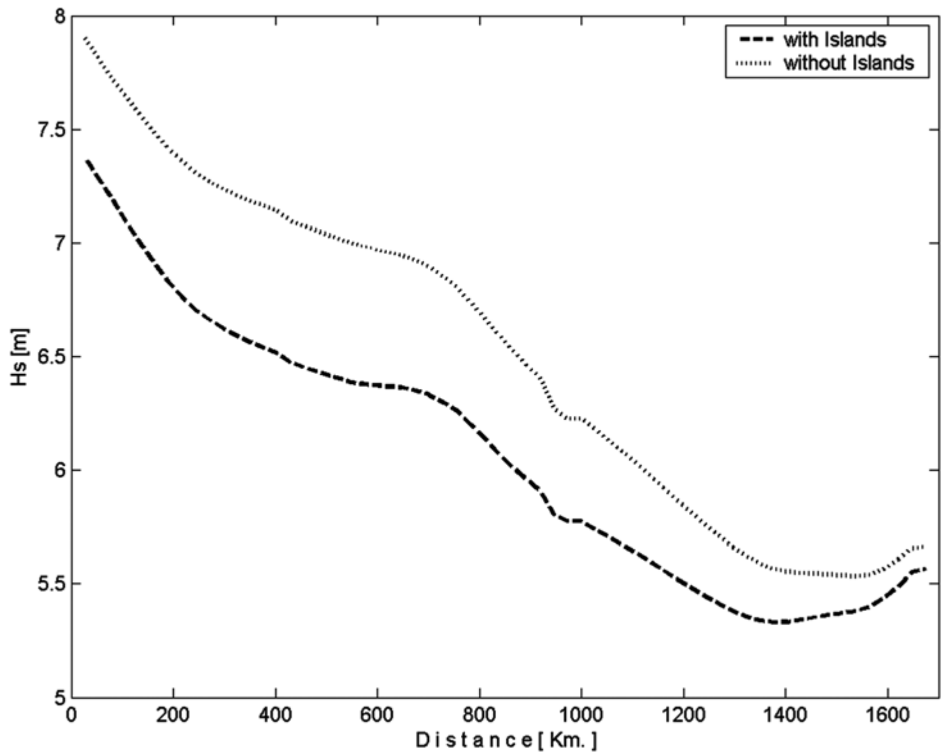

Figure 17. Curve of significant wave height as a function of the distance taken from west to east for 25 February at 1200 UTC.

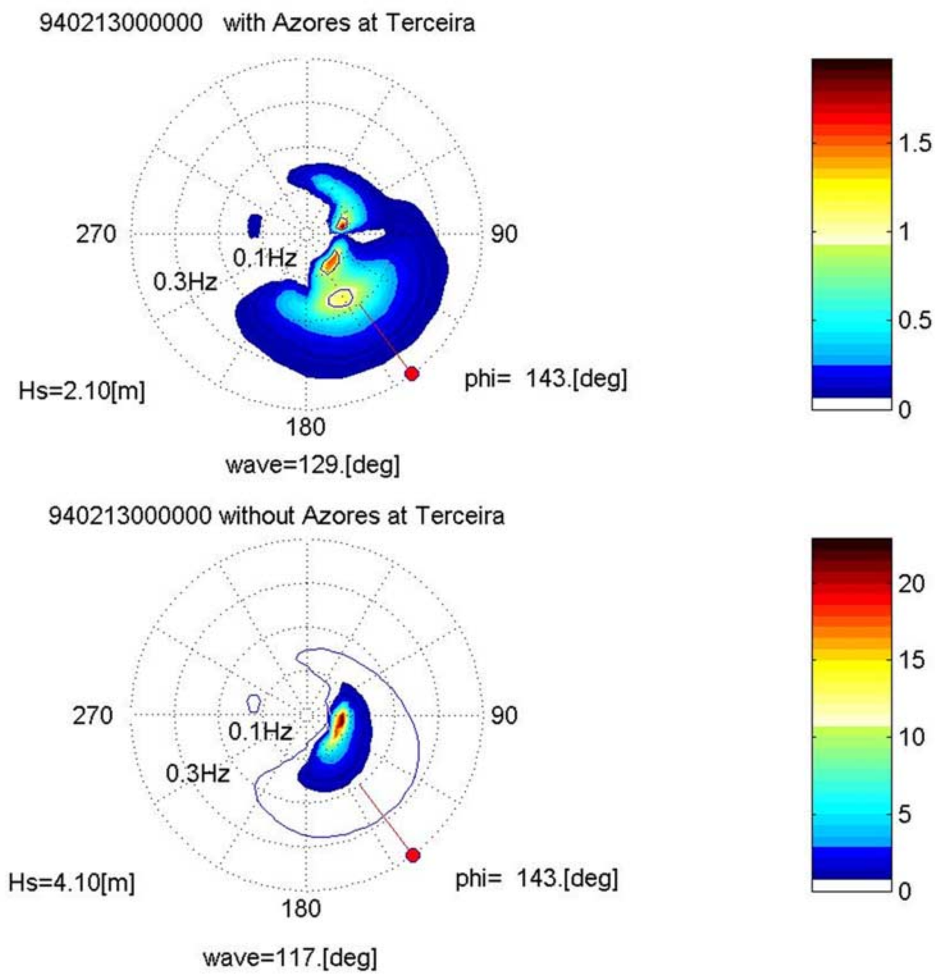

Figure 18. Directional wave spectra obtained by WAM-PRO model for 13 February 1994 at 0000 UTC at the location shown in Figure 1, close to Terceira Island (one of the Azores) (marked by a black box). Values for significant wave height (in meters) and wave = mean wave propagation direction relative to north (degrees) are given at left; phi = wind direction, and in both cases the direction is given to where the waves were propagating and to where wind was blowing (the wind direction was indicated by solid line with circle). The circles indicate the wave frequency from the center out at 0.1 Hz intervals. Spectral density contours are at 0.05 m^2 Hz^{-1} $degree^{-1}$ intervals, with color scale provided at right.

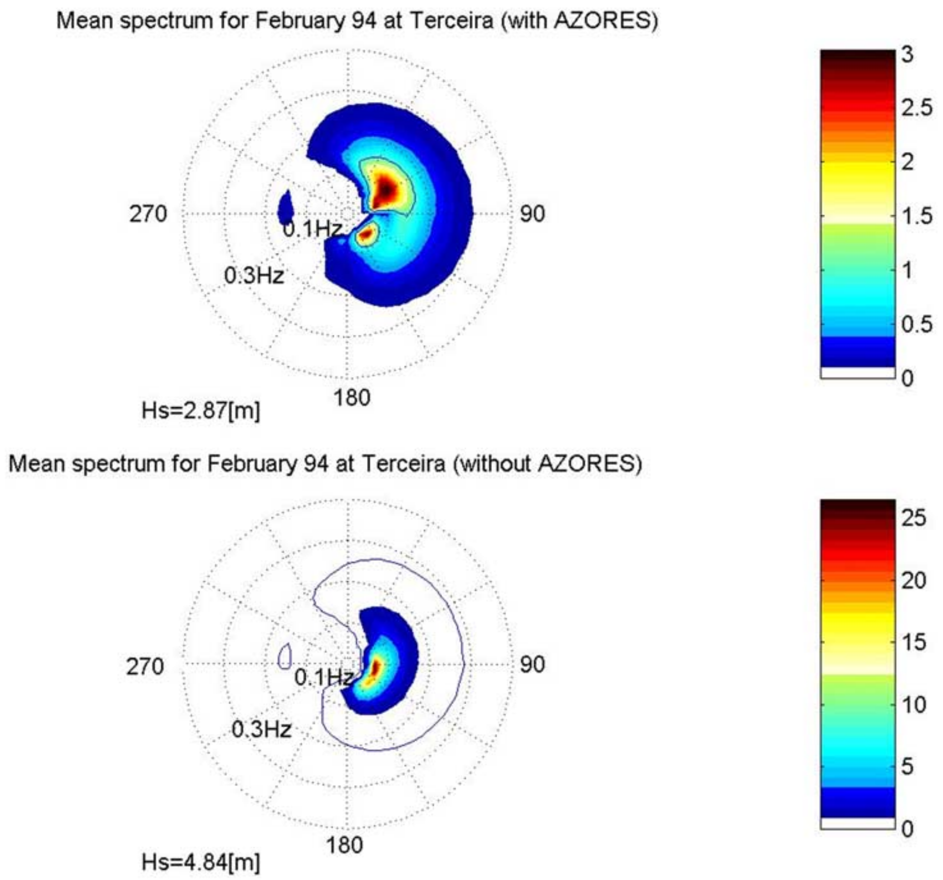

Figure 19. Mean directional wave spectra obtained by WAM-PRO model for February 1994 at the same location in Figure 1, close to Terceira Island (black box).

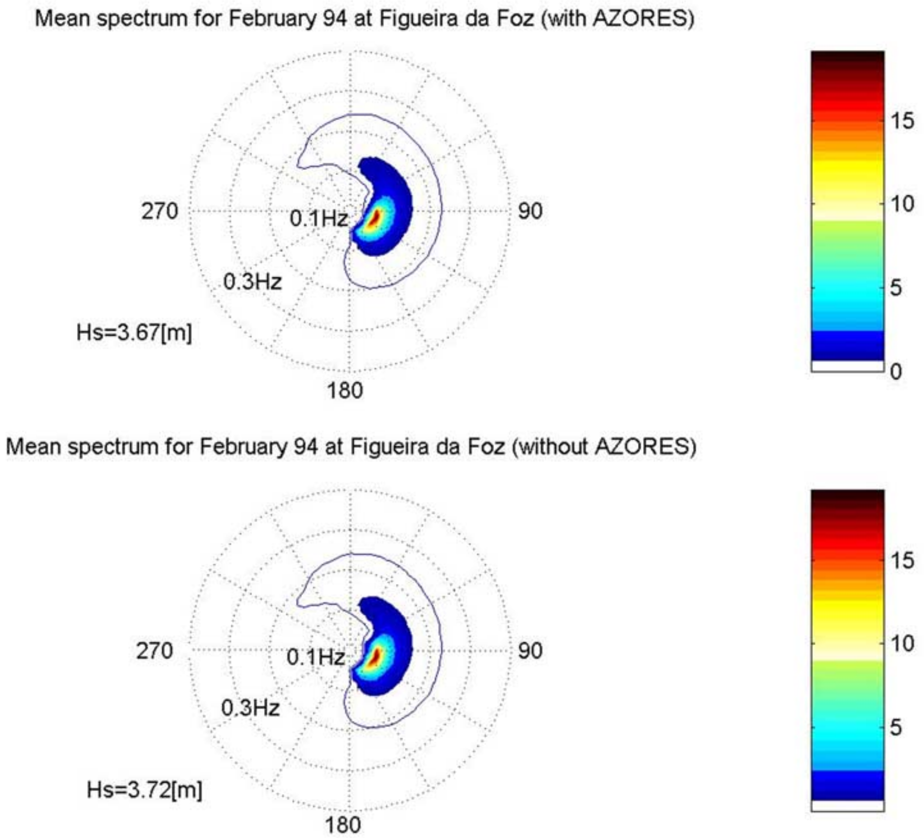

Figure 20. Mean spectra for February 1994 at the Figueira da Foz in deep waters (150 m depth).

was calculated for the month of February 1994 at Figueira da Foz (Figure 20), showing that swell is dominant with a northwest mean wave propagation direction and that the mean *Hs* does not increase noticeably when the Azores Islands are not taken into account in the simulations. For this location far away from the Azores the shadowing effect in the *Hs* wave field is not important (i.e., resolving the islands in the calculations), as was already shown in the *Hs* time series (Figure 9).

7. Concluding Remarks

[52] This study has shown that the sheltering effect of the islands can be felt locally, and it was demonstrated that wave models could represent this effect as long as a very fine grid is used. With the coarse grid normally used in ocean wave models, these islands will be unresolved, and the resulting predictions can induce a wrong spatial wave field distribution and should be treated with caution, especially in the vicinity of the islands. In the particular example calculations it was shown that in some storm conditions the Azores Islands could have an important sheltering effect felt in various directional sectors and at relatively large distances from the islands.

[53] From the 3 months of wave simulations (December 1993, January 1994, and February 1994), it was observed that a strong sheltering effect has occurred when the maximum of the storm area passed across the Azores. When the waves come from the west, southwest, or northwest, the shadow effect appears as an area protected from the high waves in the direction toward continental Portugal.

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