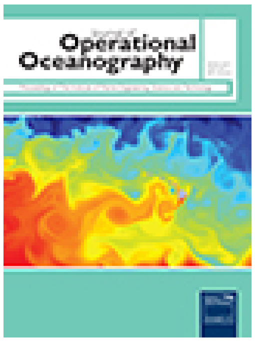

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Wave power estimation by means of spectral wave models and satellite records

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ABSTRACT
The aim of this work is to study different approaches for the estimation of the energy potential of sea waves. To this end, numerical models and remote sensing, especially satellites, are utilised for the regions of North Atlantic Ocean and the Mediterranean Sea. In particular, two methods are compared: one based on the full wave spectrum and a second utilising simplified formulas based on specific wave parameters and certain approximations. Moreover, an attempt for a qualitative assessment of the wave model WAM over areas of different wave climatology is made by the comparison of relevant wave spectra. The main outcomes of this work show that simplified calculation approaches of wave energy potential overestimate the energy rate of even 10% on average, varying in the cases of shallow or deep waters. Moreover, the performance of the wave model is satisfactory resulting to small statistical errors in the calculation of wave characteristics, a fact that proves the suitability of WAM model for reliable wave energy assessment.

ARTICLE HISTORY
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1. Introduction

The increasing energy needs worldwide are currently covered mainly by an exhaustive exploitation of fossil fuel. This process is strongly connected with certain environmental issues such as global warming, air and water pollution and the fact that oil deposits are not limitless. Apart from the environmental impact, recent economic crisis affects countries with limited availability of oil resources. As a result, research in the field of renewable energy resources gains significant interest, in order to develop methodologies and feasible technology to exploit alternative forms of energy such as solar, wind or sea waves energy.

Despite the fact that wave power seems to be of interest even during the nineteenth century (Clement et al. 2002), solar and wind energy dominate the market nowadays (Falnes 2007). Nevertheless, the potential of sea waves indicates some interesting advantages over other energy resources and it would be even suitable and profitable acting complementary to them. Low diurnal variability, ease and accuracy of prediction, variety of machine types suitable to local conditions and good ratio of area coverage over power produced by the machines are some of the key features characterising wave power. As a result, it is quite a promising candidate in terms of adaptation to large-scale energy demands once the overall cost of its production becomes competitive to other forms of energy (Thorpe 1999).

In order to study, analyse and forecast sea waves there are three major approaches: *in situ* measurements of waves characteristics with the help of buoys or other instruments, remote sensing observations from satellites and simulations using numerical modelling. As far as satellites are concerned, two of the instruments used to observe the sea state are altimeter sensors and Synthetic Aperture Radars (SAR). There are intrinsic difficulties in calculating wave characteristics utilising local or remote devices, as long as systematic errors have to be taken into account, yet they are easy to be removed. Numerical models, on the other hand, also have problems concerning their usage. Main issues are the duration of runs, accuracy and quality of initial conditions, required CPU resources and last but not least, the grid and time resolution of the model.

In this work, a combination of remote sensing observations and numerical modelling is used to obtain sea state information and study two different points of view in the estimation of wave power. At first, there is the analytic way of calculating energy by integrating the full wave spectrum given in terms of directions and frequencies. The alternative method is based on specific wave parameters and assumptions, providing a simplified formula. The second part of this study was focused on the results of WAM in terms of spectrum calculation, significant wave height and mean wave period

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estimation. These results were evaluated against available satellite records.

Geographically, this work was focusing on the North Atlantic Ocean and more specifically to coasts of Spain and Great Britain, while some tests were carried in Mediterranean Sea. The time period of study begins from August of 2009 and to the end of December of 2010.

In this framework, it is conducted a statistical analysis of sea waves data taken from satellite Envisat and numerical model WAM. The two main directions of this work lead to the conclusion that assumptions in wave power calculations are sources of systematic error thus overestimating power at a mean percentage of 10%. As far as the second part of this work is concerned, model WAM seems to provide accurate estimation of statistical wave characteristics since the statistical analysis performed lead to satisfactory results.

2. Models–methodologies

Numerical wave models provide access to information quite easy and with relatively low cost. They have the ability to simulate statistical characteristics of sea waves such as wave heights and periods as well as two dimensional (over frequencies and directions) wave spectra. Recent developments in computer infrastructure allow working with increased time and spatial resolutions in order to obtain higher quality analysis than in the past years.

2.1. WAM

The model used in this work is Wave Analysis Model (WAM) a third generation wave model which solves the wave transport equation explicitly without any assumptions on the shape of the wave spectrum (Komen et al. 1994). Particularly, the ECMWF version is utilised, which integrates some important updates, thus increasing the capabilities of the model. The advection scheme used is based on Corner Transport Upstream scheme and it takes into account contributions from corner points. In addition, shallow water effects are parameterised in a new manner, so time evolution of wave spectrum and the kurtosis of wave field are affected (ECMWF 2008). This model is expected to perform efficiently at varying bathymetry and sea states (Bidlot et al. 2007; Janssen & Onorato 2007a; Bidlot 2012).

2.2. Satellites

Our second source of wave information is satellite records from altimeter sensors or SAR. Altimeters utilise the echo of a pulse sent to the surface of earth in order to measure circulation, oceanic topography and bathymetry. Significant wave height and wind velocity are also parameters that can be calculated by the power and shape of echoed pulse. On the other hand, SAR instruments are more complex and offer a variety of information. They use the polarisation of light, various angles of incidence and reflection, along with variable spatial resolution, in order to achieve accuracy as good as few millimetres (https://earth.esa.int/web/guest/missions/esa-operational-eo-missions/envisat/satellite/space-segment).

Particularly, in this work, records from satellite Envisat and the accompanying instrument ASAR were used. Envisat was a satellite from European Space Agency (ESA) that was operational for 10 years from 2002 to 2012. It was launched in a Sun synchronous polar orbit at an altitude of approximately 800 km. It was able to orbit Earth at 101 min with a repeat cycle of 35 days (ESA 2002).

As a successor to the European remote sensing satellite (ERS) programme, more advanced imaging radar, radar altimeter and temperature-measuring radiometer instruments were used to enhance ERS data sets. This was supplemented by new instruments including a medium-resolution spectrometer sensitive to both land features and ocean colour. Envisat was also able to monitor trace gases with two atmospheric sensors. One of the remote sensing instruments was Advanced Synthetic Aperture Radar (ASAR). Operating in C-band of microwaves (4–8 GHz), it provided enhanced land and sea coverage, range of incidence angles, polarisation and modes of operation. Depending on the mode of operation, it offered a spatial resolution up to 30 × 30 m and swath width from 5 km in wave mode up to 400 km in global monitoring mode.

2.3. Wave power

In order to estimate wave power that can be produced by the local waves, one can use two techniques according to data availability or the need to speed up calculations in expense of probably less accurate results. To begin with, if the full spectrum of a wave is available and is given in directions θ and frequencies f, the following analytic formula determines the amount of power (Laing et al. 1998; Bridges 2008):

$$P = \rho_w g \int_0^{2\pi} c_g(f, h) E(f, \theta)\, \mathrm{d}f\, \mathrm{d}\theta \ , \qquad (1)$$

where ρ_w is the water density, g is the gravity acceleration and group velocity of the waves is taken into account as $c_g(f, h)$ and it can take two forms depending on water depth:

$$c_g(f, h) = \frac{g}{4\pi} f^{-1} \text{ deep water}, \quad (2)$$

$$c_g(f, h) = \sqrt{gh} \text{ shallow water}. \quad (3)$$

A more simple formula than Equation (1) can be used with certain assumptions. The amount of energy carried by a wave of certain frequency is

$$E = \frac{1}{8} \rho_w g H_{1/3}^2, \quad (4)$$

where $H_{1/3}$ is the significant wave height. Significant wave height is defined as the average of the largest one-third of wave heights. This statistical parameter of the wave corresponds well to visual estimates of wave height. So wave power can be determined by the product of the energy in formula (4) and the propagation speed of energy in waves, meaning the group velocity $P = c_g E$. In the majority of cases, wavelengths are smaller than the depth of water in the area, Equation (2) is utilised and the result is the following simple formula for wave power:

$$P = \frac{\rho_w g^2}{64\pi} T H_{1/3}^2, \quad (5)$$

where T is the mean period of the wave. The derivation of the latter formula is based on linear wave theory, the assumption that we are dealing with deep water and that energy in sea waves propagates with the group velocity of the wave. This final assumption is correct mainly for narrow-banded wave fields (Soomere & Eelsalu 2014).

3. Data processing

This work focuses on the North-East Atlantic Ocean as well as the Mediterranean Sea. Specifically, tests were performed at the locations presented in maps of Figure 1. The assumptions made in order to use the simplified formula do not hold in all sites, since depths vary, along with wave characteristics. For instance, there are sites at the western coast of G. Britain which are swell dominated but water depth is small.

The time of the tests cover a period of 17 months from August 2009 till December 2010. The areas were selected taking into account the fact that satellite data available were covering mostly Atlantic Ocean and some parts of Mediterranean Sea. Despite the fact that a set of 10 years data would be ideal to cover a climatic approach, this exceeds the target of this study.

Model WAM simulations were conducted with the following configuration. Geographically, it covers Northern hemisphere from latitude 20° to 75°, while longitude limits are 50° W and 30° E. Spatial resolution is 0.05° × 0.05° and it consists of 1601 × 1101 points. Furthermore, the version of WAM model utilised in the presented study (ECMWF CY36R4) have a new advection scheme accounting also for the corner points of the grid and, therefore, providing a more uniform and accurate simulation of the wave energy distribution even in complicated coastlines (Janssen & Onorato 2007b; Bidlot 2012). Moreover, the setup and specific options enabled the model to take into account bottom friction, wave breaking, refraction, diffraction and wave currents interaction during the integration, while the spatial analysis of 0.05° ensures a valid simulation over coastal areas (Galanis et al. 2012; Zodiatis et al. 2014). Spectral data are available at certain points of the grid, while minimum frequency that can be simulated

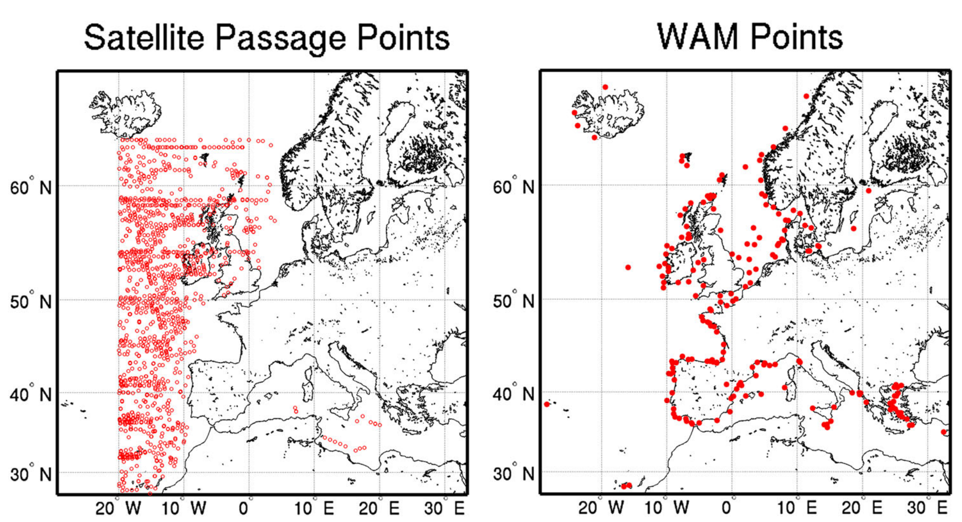

Figure 1. (a) Map of the points where satellite data are available and (b) locations where wave spectrum was available from WAM.

is 0.055 Hz and the forecast is analysed in 25 wave frequencies and 24 wave directions.

The statistical analysis of the data sets was based on the following parameters:

$$\text{Mean bias} \quad (\text{MB}) = \frac{1}{N}\sum_{i=1}^{N}(M_i - O_i), \tag{6}$$

$$\text{Mean normalized bias} \quad (\text{MNB}) = \frac{1}{N}\sum_{i=1}^{N}\left(\frac{M_i - O_i}{O_i}\right) \times 100\%, \tag{7}$$

$$\text{Mean normalized gross error (MNGE)} = \frac{1}{N}\sum_{i=1}^{N}\left(\frac{|M_i - O_i|}{O_i}\right) \times 100\%\,, \tag{8}$$

$$\text{Root mean square error} \quad (\text{RMSE}) = \sqrt{\frac{1}{N}\sum_{i=1}^{N}(M_i - O_i)^2}\,, \tag{9}$$

$$\text{Standard deviation} \quad (\sigma) = \sqrt{\frac{1}{N}\sum_{i=1}^{N}(M_i - O_i - MB)^2}. \tag{10}$$

In the expressions above, N is the number of data, M_i is the value given by WAM and O_i are satellite records. The above statistical parameters provide various information concerning the data set. In particular, mean bias is the standard mean value of the difference between satellite records and WAM estimation, so considering satellites as correct, this value should be expected near zero. On the other hand, mean normalised bias indicates the error relatively to observation values as a percentage but sometimes is biased due to small values in the denominator. RMSE is a frequently used measure of the difference between values predicted by a model and the values actually observed. RMSE is utilised to aggregate the differences into a single measure of predictive power. Finally, standard deviation is indicative of the average amount that each number in a data set varies from the centre value.

4. Results

This work is focused on the subject of calculating wave power. Two of the wave statistical parameters that affect directly the estimation are significant wave height and mean wave period. Before proceeding with the comparison of the analytic formula and the simplified one, a validation of the data taken from the model WAM is necessary. Aiming to perform this qualitative control, the relevant wave spectra are checked in terms of capturing the correct wave direction and the accuracy of predicting the proper amount of wave energy as it is calculated by spectrum integration with respect to directions and frequencies. These results were compared against satellite records of GDR (Geophysical Data Records-Delayed Time) as following (ESA).

The data of the significant wave height and mean wave period refer to the areas of G. Britain and the Atlantic coast of Spain. Two data sets, one by the simulation of the spectral model and the second from the records by the ASAR instrument, are studied here focusing on the statistical comparison between the two data sets and conducting quality control to spectra plots. Statistical fitting as long as statistical parameters mentioned earlier are used.

4.1. Statistical comparison

To investigate the correlation between satellite records and model results, correlation diagrams are given in Figures 2 and 3 for each variable and area of interest.

The two areas in consideration are G. Britain and Spain. For the case of G. Britain geo-graphic boundaries are taken from 50.25°N to 60.07°N and from 22.21°W to 0.12°W. Accordingly, the area of Spain was set with limits 34.22°N to 46.96°N and from 22.66°W to 2.05°E. Each pair of data was created by parsing model results from the relevant database that coincide both in time and space with the passage points of the satellite.

In order to provide a better understanding of these diagrams, linear fitting was attempted with least square method. The value of parameters A, B in $y = Ax + B$ is presented in Table 1.

In addition, a series of statistical indexes for the data in study are provided in Table 2.

A general conclusion that can be made here is that the wave model WAM tends to overestimate significant wave height, while mean wave period data are a statistically better match. In particular, overestimation of significant wave height in G. Britain has a constant behaviour, whereas in Spain overestimation seems to be significant at larger waves.

4.2. Spectra comparison

A further evaluation of WAM is achieved by comparing wave spectra data at certain geographic locations as calculated by the model and the records provided by Envisat. The choice of each location is made by taking into account spatial and time limitations. Data combination from each of the two sources is made in a way that these points are inside a square with a side of size 0.3°

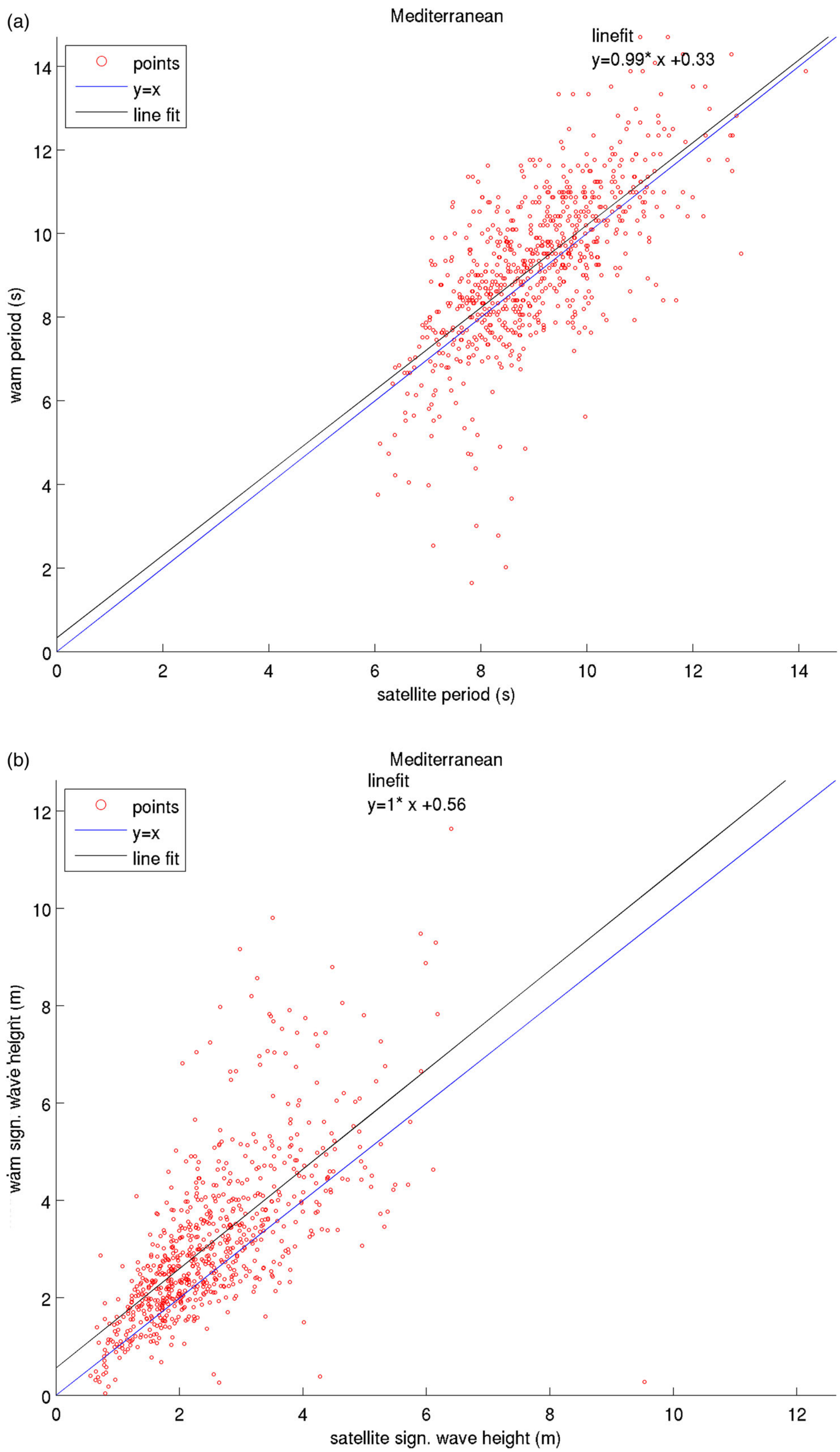

Figure 2. Correlation diagrams for mean wave period and significant wave height for the area of Great Britain for the entire time period.

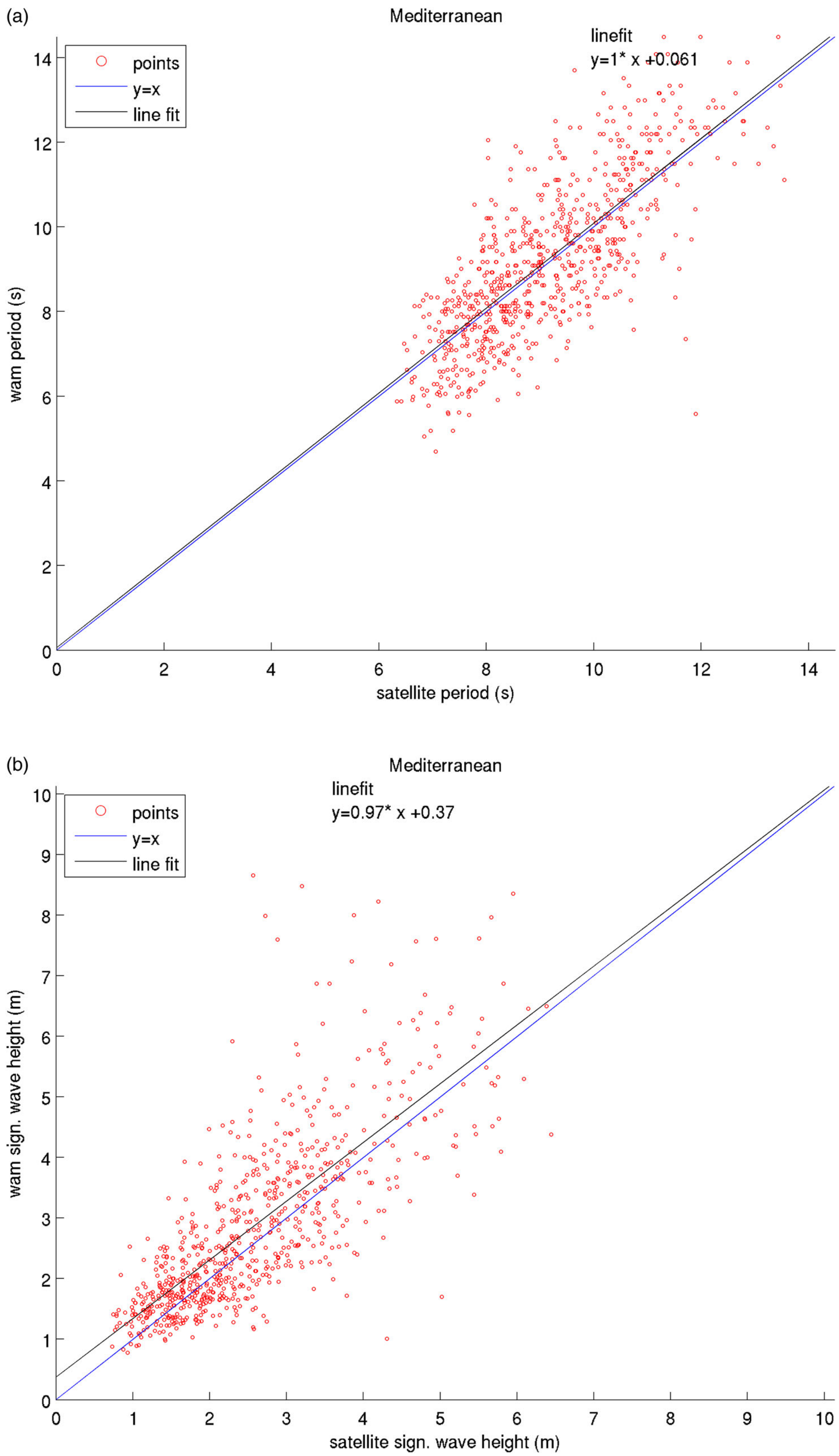

Figure 3. Correlation diagrams for mean wave period and significant wave height for the area of Spain for the entire time period.

Table 1. Table of least square method parameters.

	Significant wave height data	
	G. Britain	Spain
A	1.02 ± 0.08	0.97 ± 0.06
B	0.6 ± 0.2	0.37 ± 0.17
Mean wave period data		
	G. Britain	Spain
A	0.99 ± 0.07	1.00 ± 0.06
B	0.3 ± 0.7	0.1 ± 0.6

Table 2. Table of statistical parameters.

	Significant wave height data			
	MNB	MNGE	RMSE	σ
G. Britain	25%	36%	1.3	1.2
Spain	12%	28%	1	0.97
Mean wave period data				
	MNB	MNGE	RMSE	σ
G. Britain	11%	11%	1.3	1.3
Spain	10%	10%	1.2	1.2

or 33 km and the time difference is less than half an hour, with the majority of combinations to be 10 min away. The above limitations are adequate in off-shore, open sea areas, where sea state and weather conditions vary slowly in time and space.

Polar plots of spectra are provided for comparison purposes where the radial direction represents frequency variable f, polar direction θ is the usual wave direction in space and colour contours correspond to wave power. Moreover, diagrams of cumulative wave power over θ direction and frequency f offer another qualitative index of comparison.

From Figures 4–9 the results are presented as pairs of satellite records and WAM data that refer to points within a spatial radius of 0.3° and a 10 min window.

The first set of Figure 4 refers to an area in North Atlantic Ocean, to the west side of G. Britain. A qualitative comparison between satellite and WAM shows that the model succeeds to predict the frequency and the direction with maximum power, but the integral of two spectra differs 80%.

More cases are presented in Figures 5–9. They all refer to the Atlantic Ocean, as access to satellite records from Mediterranean Sea was limited.

In Figure 5, waves in a sea area 50-km North of Scotland are presented. Once again, model WAM successfully predicts direction and frequency of maximum wave power but not its value. The total amount of wave power is very well predicted, while there is a certain dispersion of power over directions mainly and frequencies secondarily.

The wave presented in Figure 6 was recorded 200 km west of Northern Ireland. Although, there is dispersion of wave power in frequencies, the results do not differ from those of Figure 5.

Another case of a wave that is dispersed over frequencies but not in directions is presented in Figure 7. The location in which this wave is recorded was near the western coast of Ireland.

The two final cases 8 and 9 show the presence of waves with multiple directions and frequencies. Figure 8 shows wave spectra and cumulative diagrams that refer to the area south of the Faroe Islands.

In Figure 9 the case of an area that is not situated in open ocean is presented. Specifically, it refers to the middle of eastern G. Britain, in North Sea.

In the last two figures it is verified that there is a good behaviour of the model in predicting multiple waves.

As an extra test for the evaluation of the model, areas with specific wave characteristics were taken into account. Particularly, mean wave period and significant wave height were studied in terms of the statistical frequency of the appearance of larger values over smaller ones.

In the case of the Mediterranean Sea, it is confirmed that mean wave period present a tendency to values indicating wind-sea and significant wave height corresponding to smaller effect of fetch, as shown in Figure 10.

The exact opposite behaviour is found at British coasts. For a more accurate comparison, data were separated in east and west coast of G. Britain, as Atlantic Ocean affects primarily the western part. The results are presented in Figures 11 and 12.

4.3. Energy estimation

The purpose of the second part of our work is the comparison between the two methods of estimating the wave power. In order to perform this analysis, the entire set of available data was used. On one hand there is the analytic formula that needs wave spectrum expressed in terms of frequency and direction. On the other hand, the simplified expression of the analytic formula is used making necessary the knowledge of statistical parameters of wave such as mean wave period and significant wave height.

The results from both methods are studied using the normalised difference between them at each point, that is

$$\text{Bias} = \frac{(E_{\text{spec}} - E_{\text{simp}})}{E_{\text{spec}}} \times 100\% \quad . \tag{11}$$

In Figure 13, the differences are separated in classes with range 10% and the results show that the simplified formula seems to overestimate wave power no more than 10% for the majority of points.

In order to use the spectral formula, one has to characterise each point according to its sea depth. The selection of a value of 40 m for this limit seems

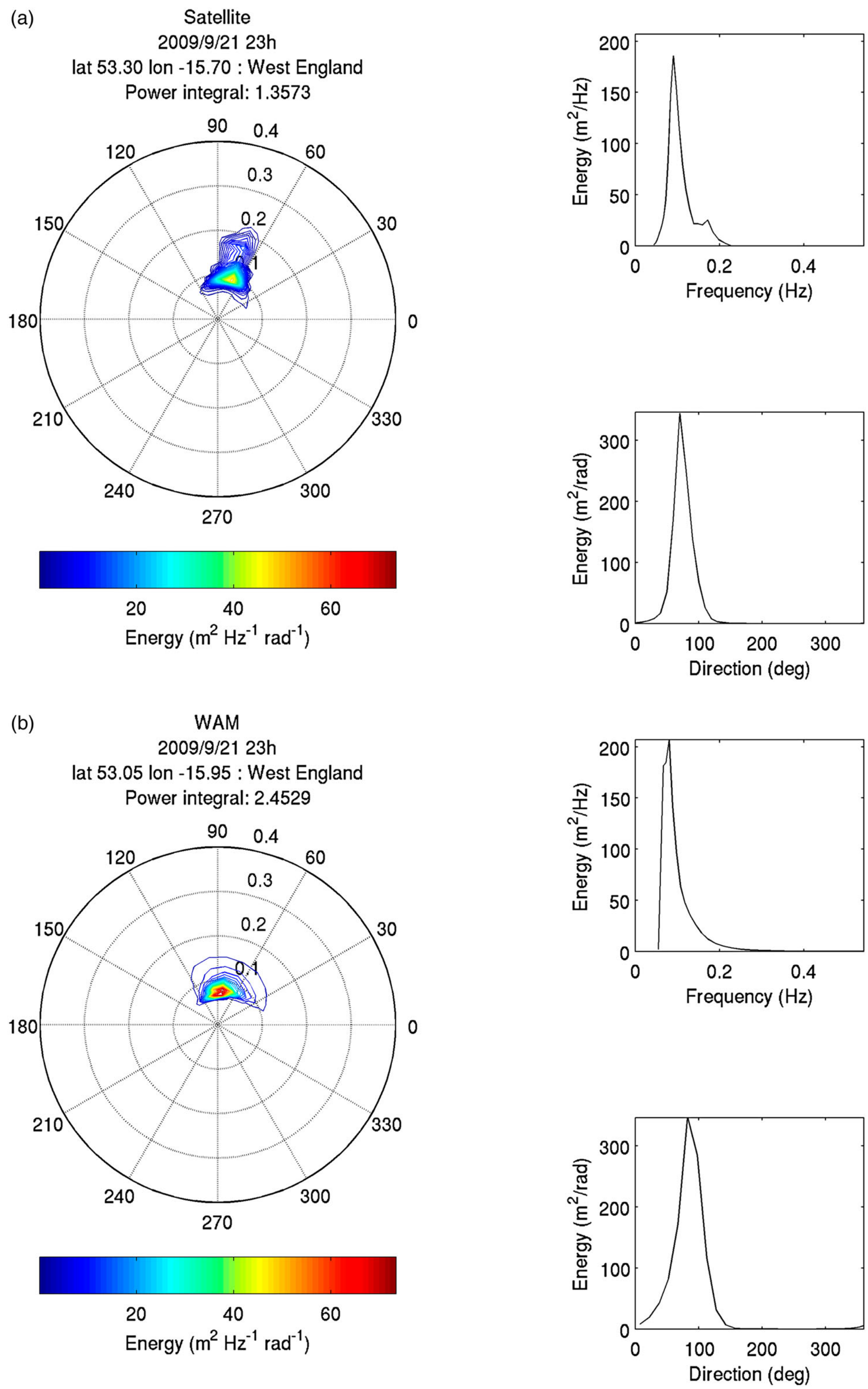

Figure 4. Spectrum and cumulative diagrams over direction and frequency as recorded by Envisat (a) and the according data provided by WAM. Area in consideration: N. Atlantic Ocean.

reasonable for the majority of cases. The total amount of data is presented in Figure 14.

Figures 15 and 16 offer a more detailed view of the results as they are separated in the cases of shallow and deep water.

Reviewing Figures 14–16 it is obvious that for cases characterised as deep water, the simplified formula overestimates wave power constantly, while in shallow depths results vary from 90% to −100% differences. Specifically, the mean value of the normalised difference for the

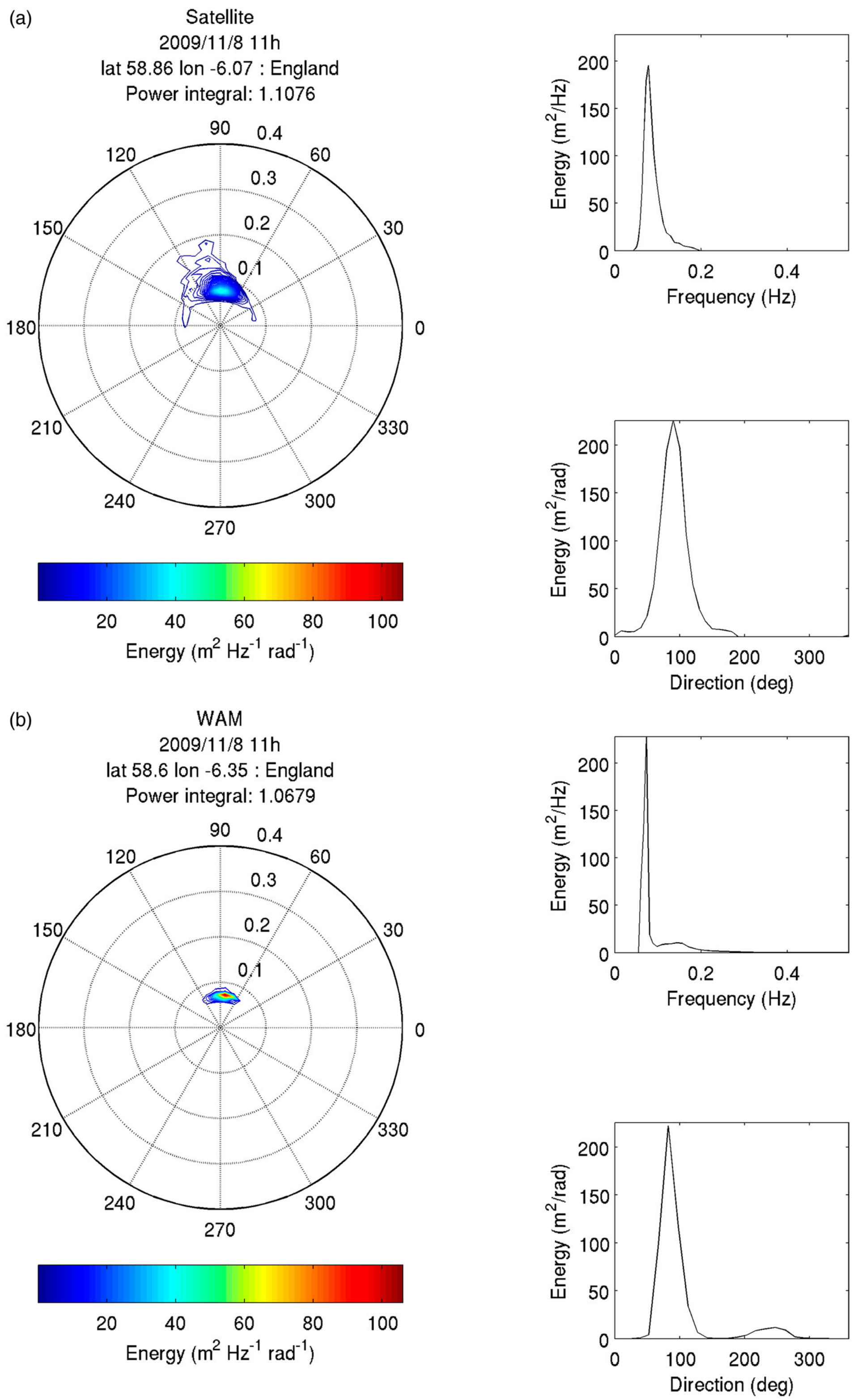

Figure 5. Spectrum and cumulative diagrams over direction and frequency as recorded by Envisat (a) and the according data provided by WAM.

entire data set is 16%, whereas in shallow water case is 57% and −5% for deep sea.

Furthermore, we tried to investigate whether the choice of the limit with value 40 m affects the results. Figure 17 is created using values of the limit from 10 to 70 m with a step of 10 m.

The different distribution at each figure is due to the cases where depth is close to the value of the limit to

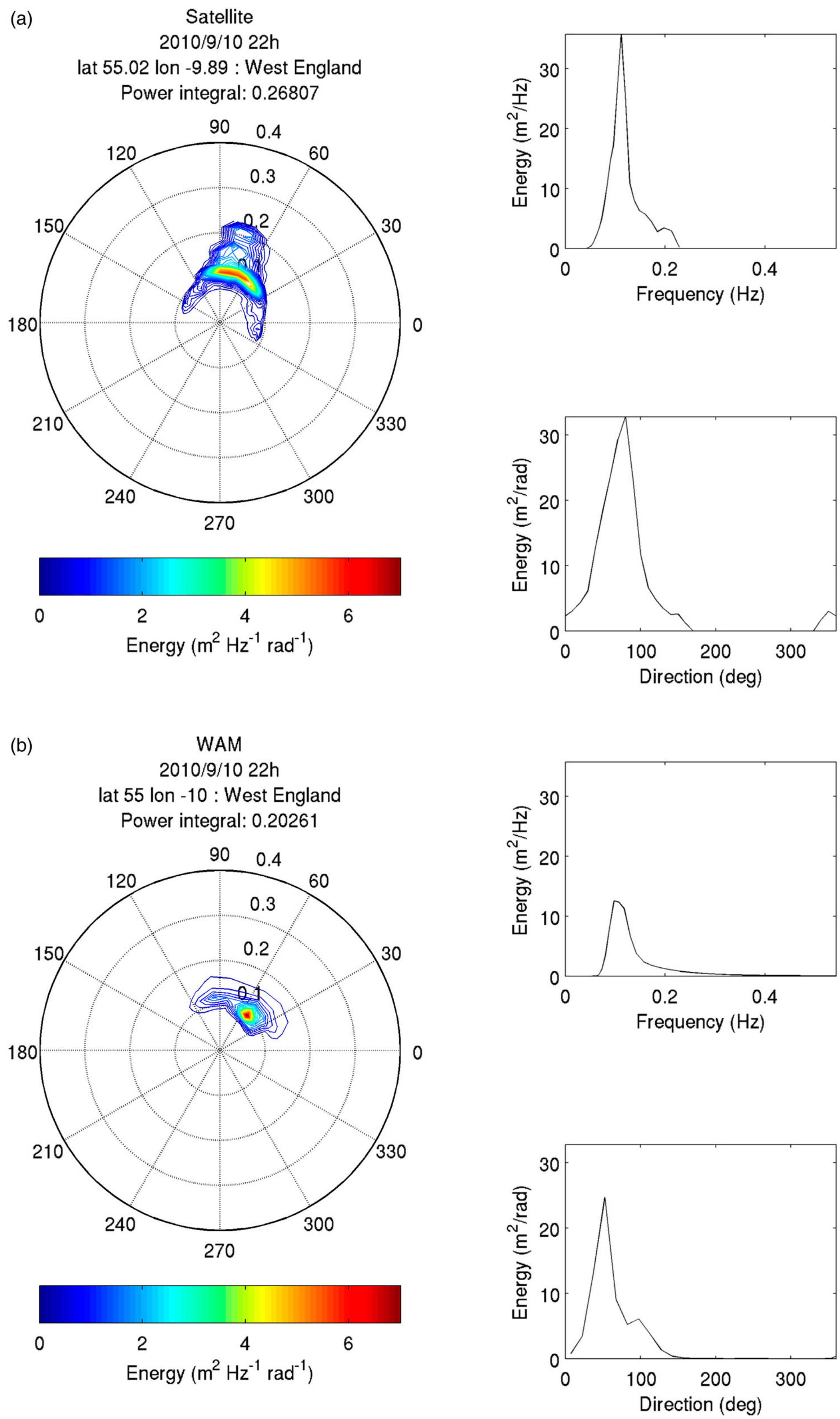

Figure 6. Spectrum and cumulative diagrams over direction and frequency as recorded by Envisat (a) and the according data provided by WAM.

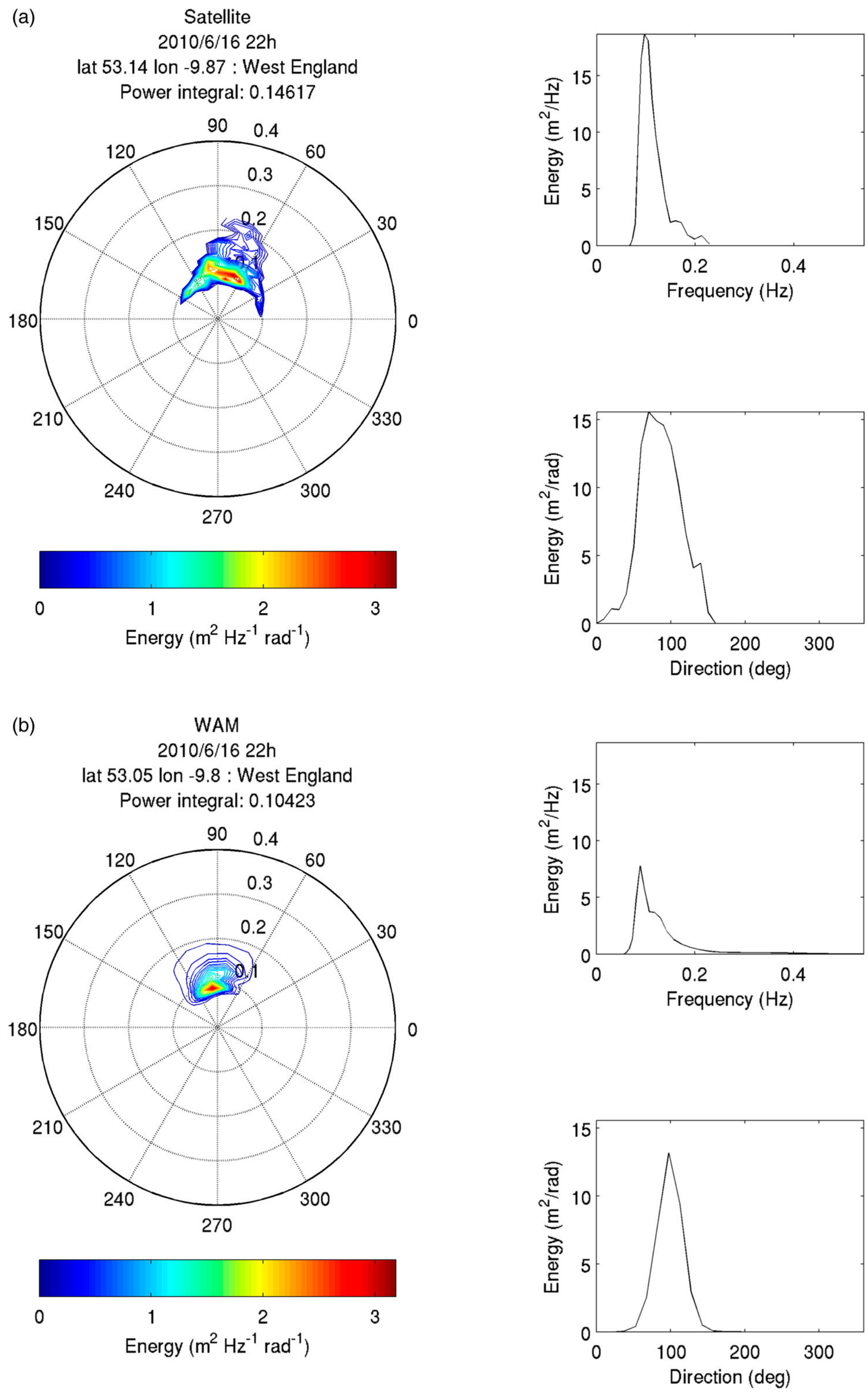

Figure 7. Spectrum and cumulative diagrams over direction and frequency as recorded by Envisat (a) and the according data provided by WAM.

change the characterisation between deep and shallow water. Figure 18 provides a better view of this situation.

Another observation concerning Figure 17 is the appearance of a secondary maximum at the class of 70–80%. This can be explained by the fact that simplified expression of wave energy is created with the assumption of deep water. Therefore, increasing the value of the limit, more and more cases are considered shallow and the difference between the two methods rises.

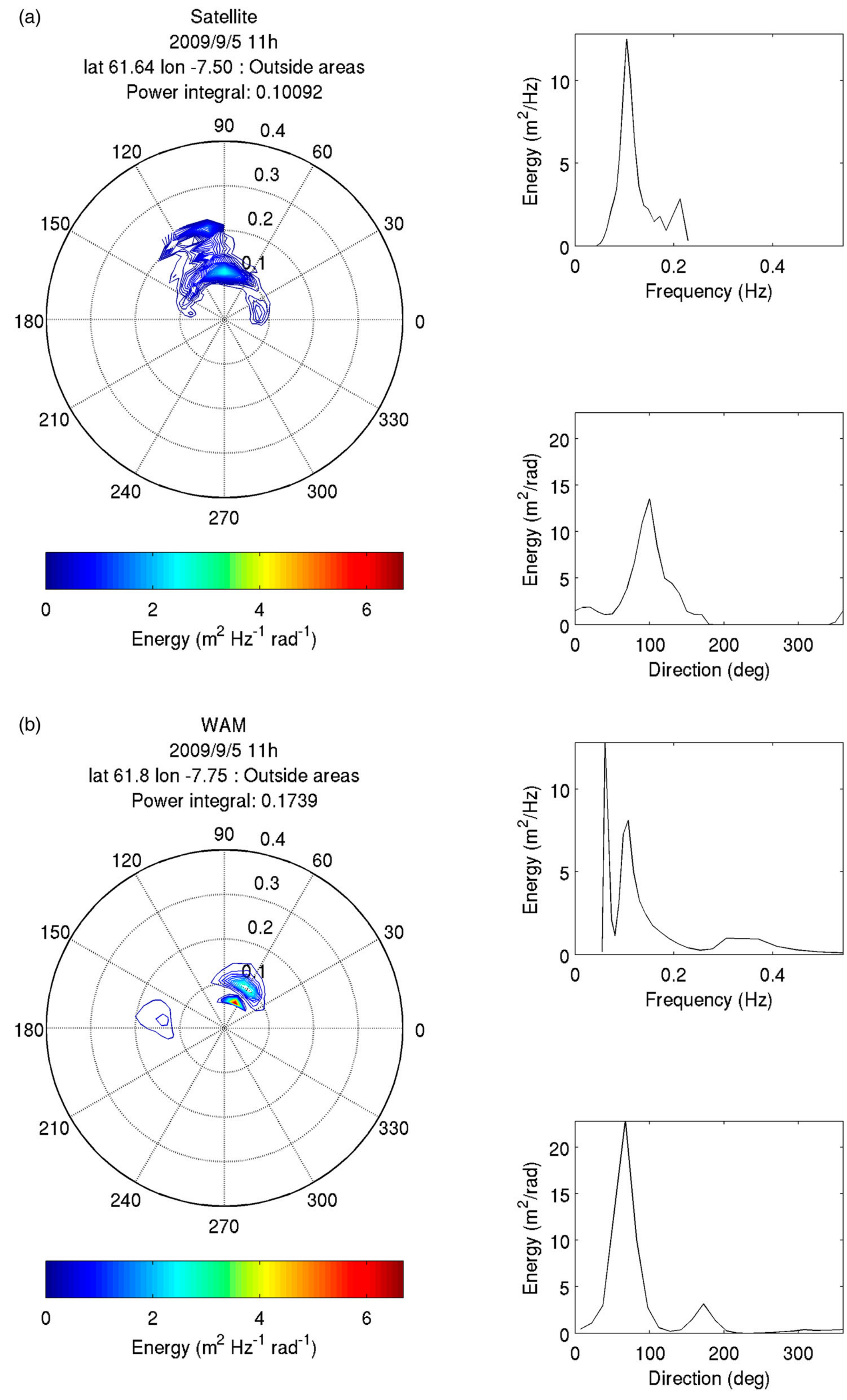

Figure 8. Spectrum and cumulative diagrams over direction and frequency as recorded by Envisat (a) and the according data provided by WAM.

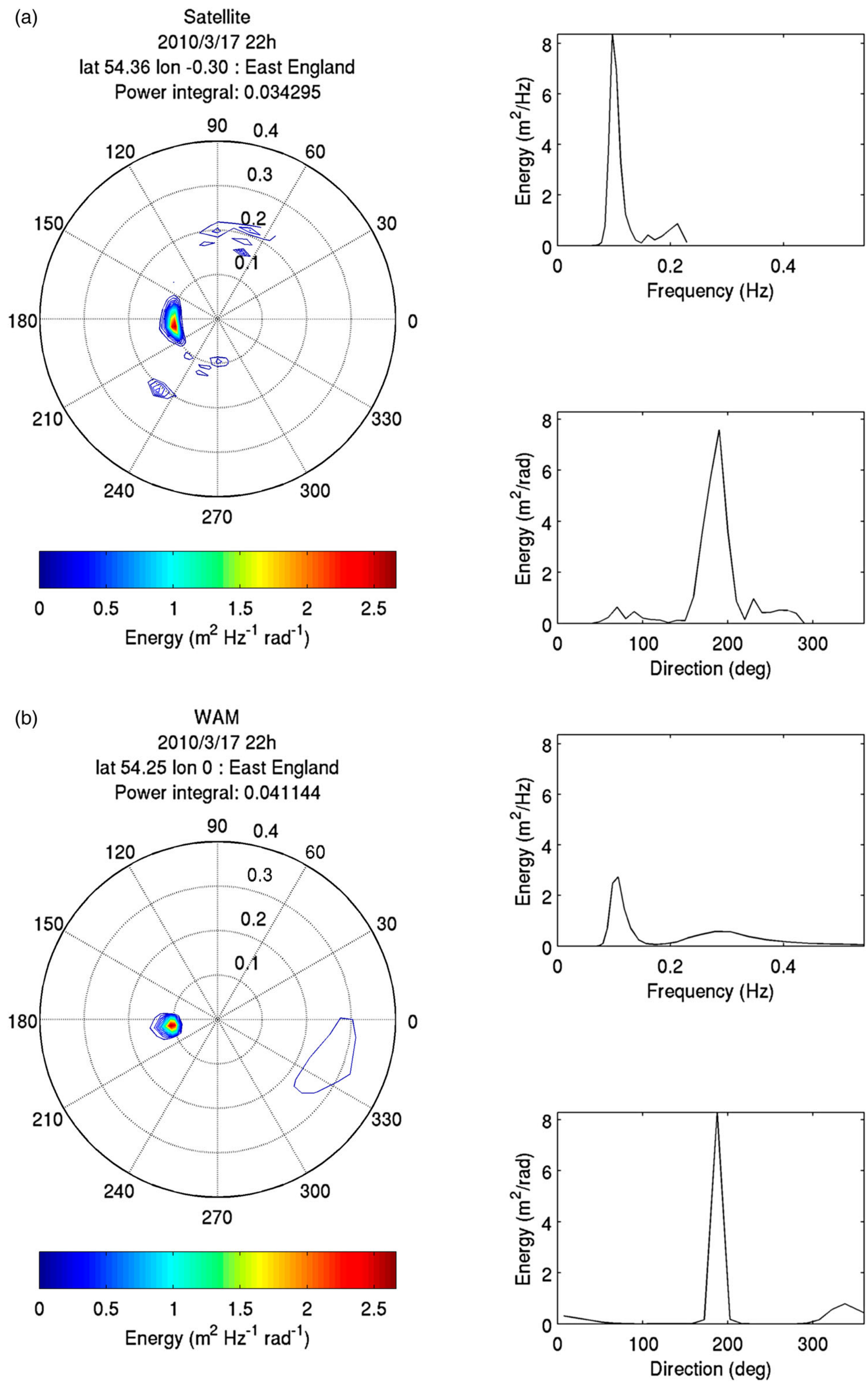

Figure 9. Spectrum and cumulative diagrams over direction and frequency as recorded by Envisat (a) and the according data provided by WAM.

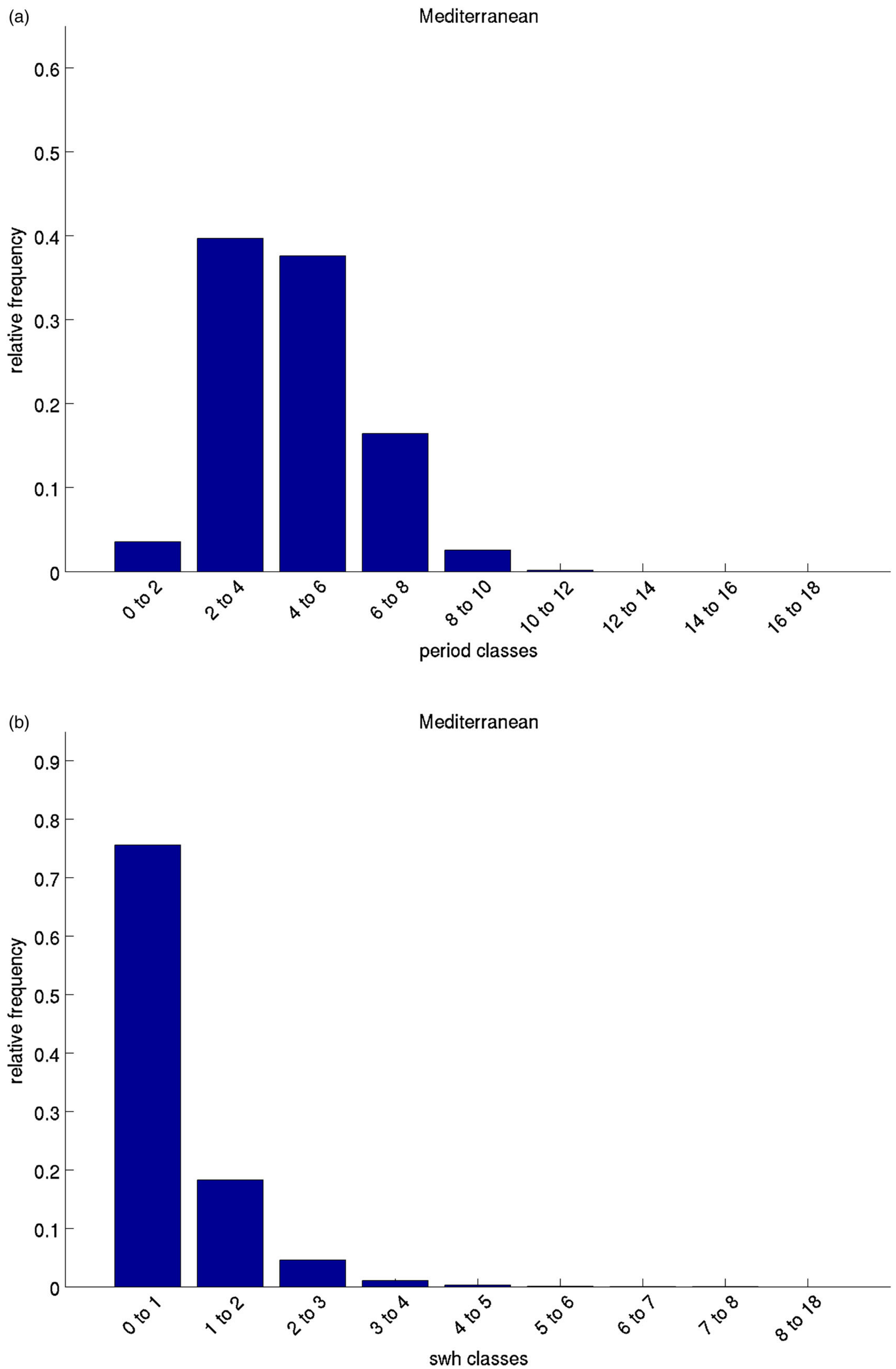

Figure 10. Distribution of mean wave period (a) and significant wave height (b) data provided by WAM from August 2009 to December 2010 in Mediterranean Sea.

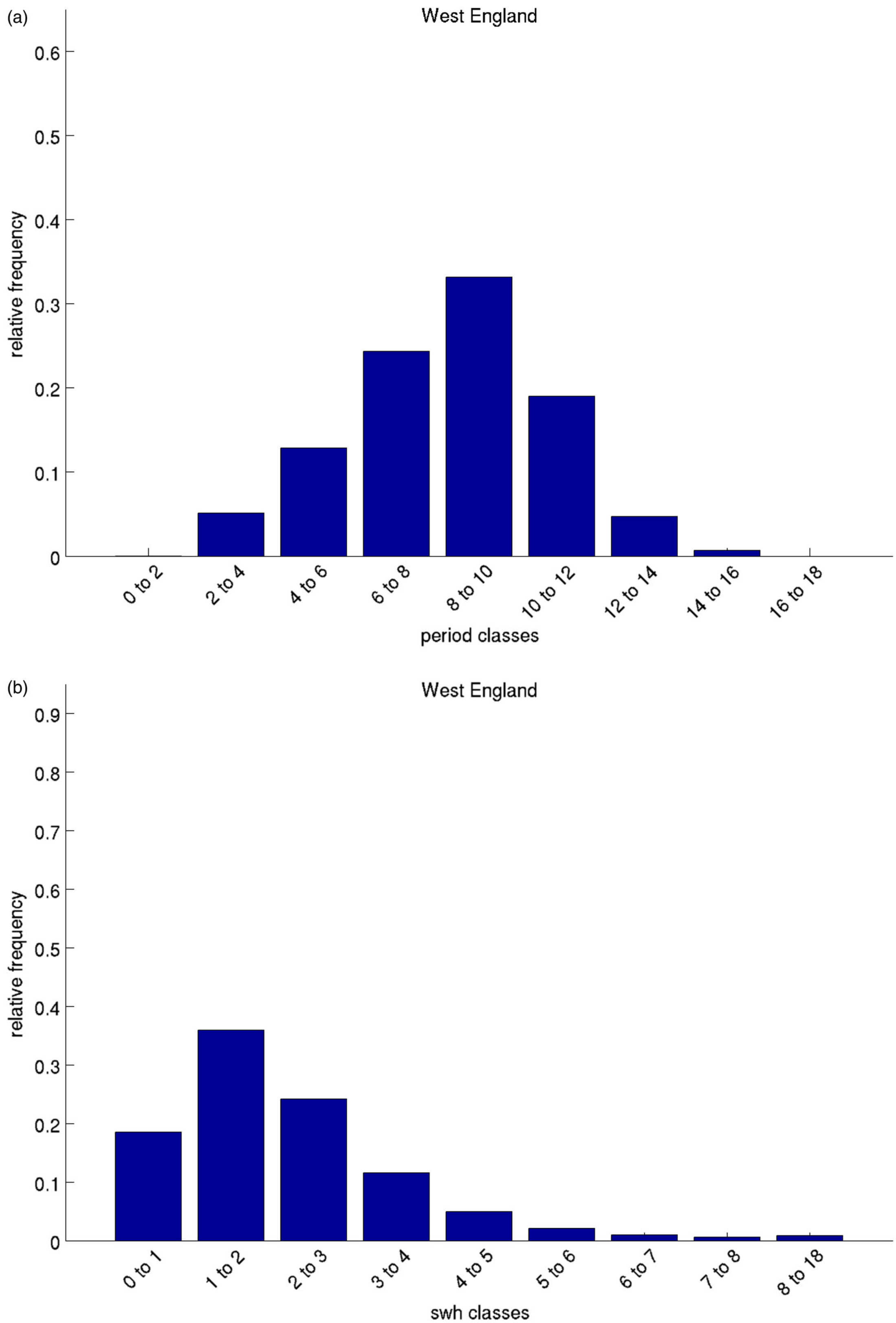

Figure 11. Distribution of mean wave period (a) and significant wave height (b) data provided by WAM from August 2009 to December 2010 for West England.

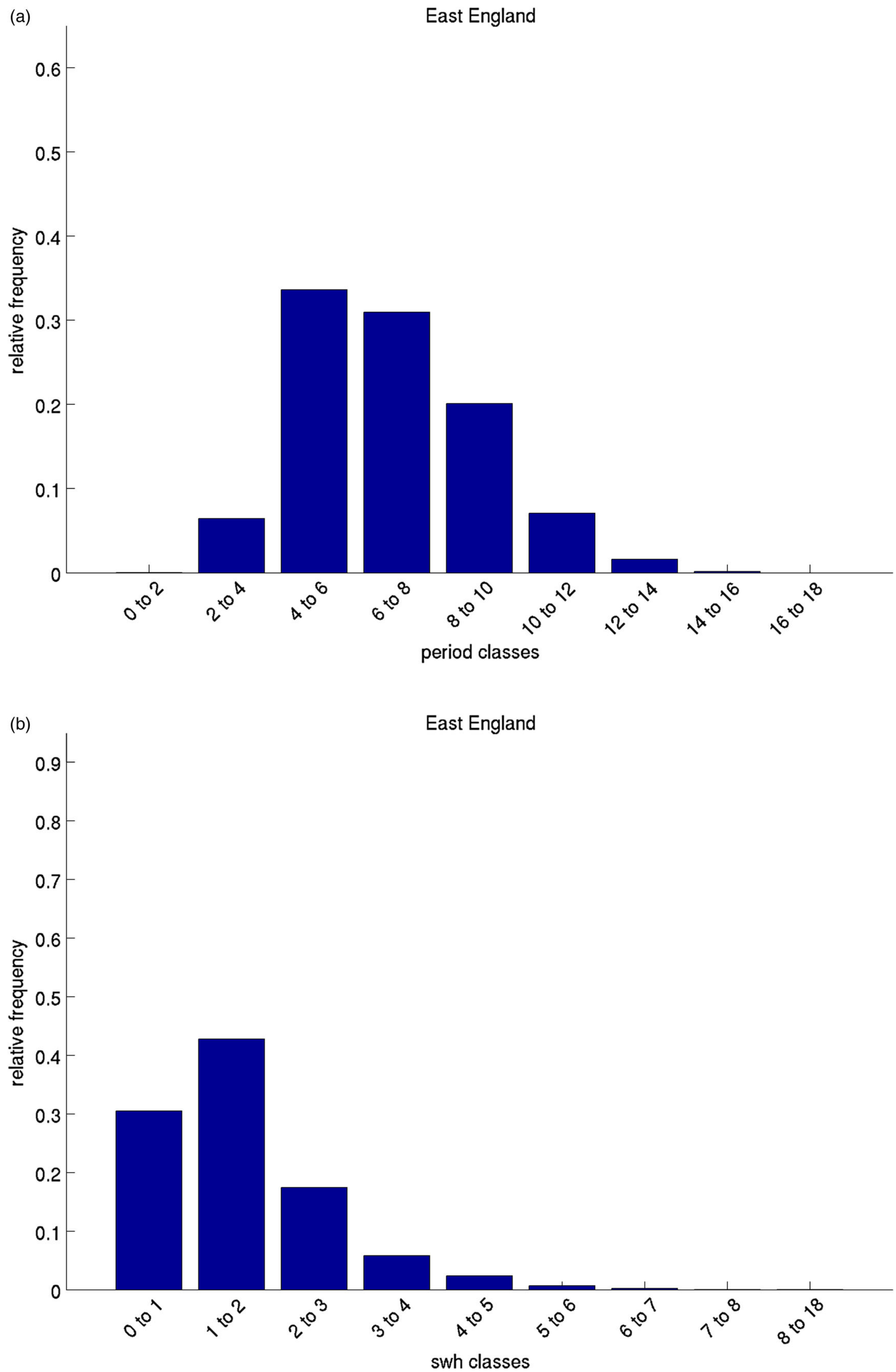

Figure 12. Distribution of mean wave period (a) and significant wave height (b) data provided by WAM from August 2009 to December 2010 for East England.

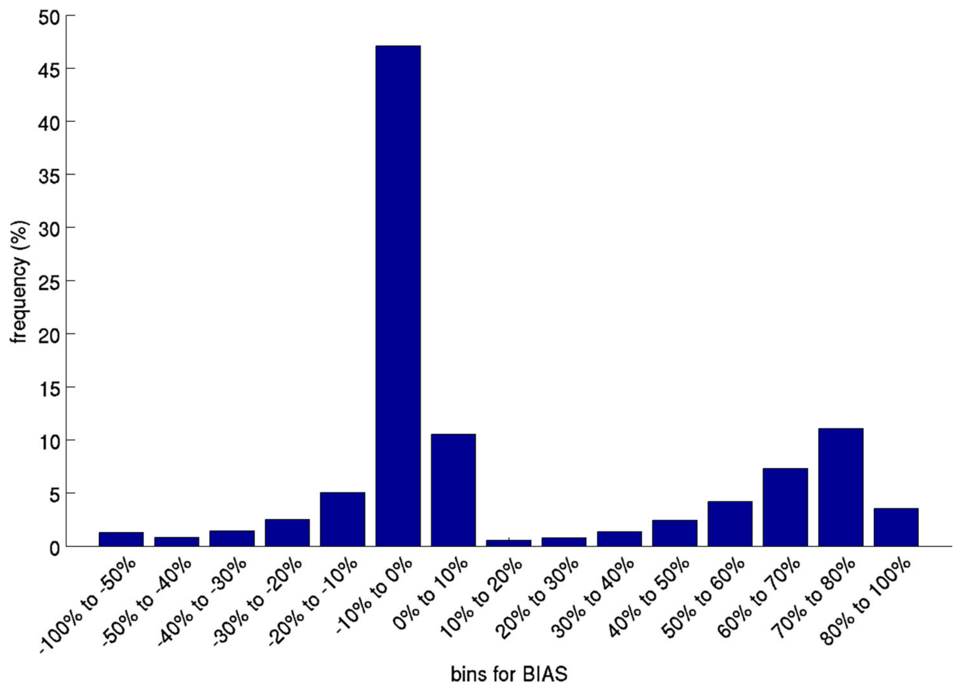

Figure 13. Results of normalised difference (%) between the two methods of calculation.

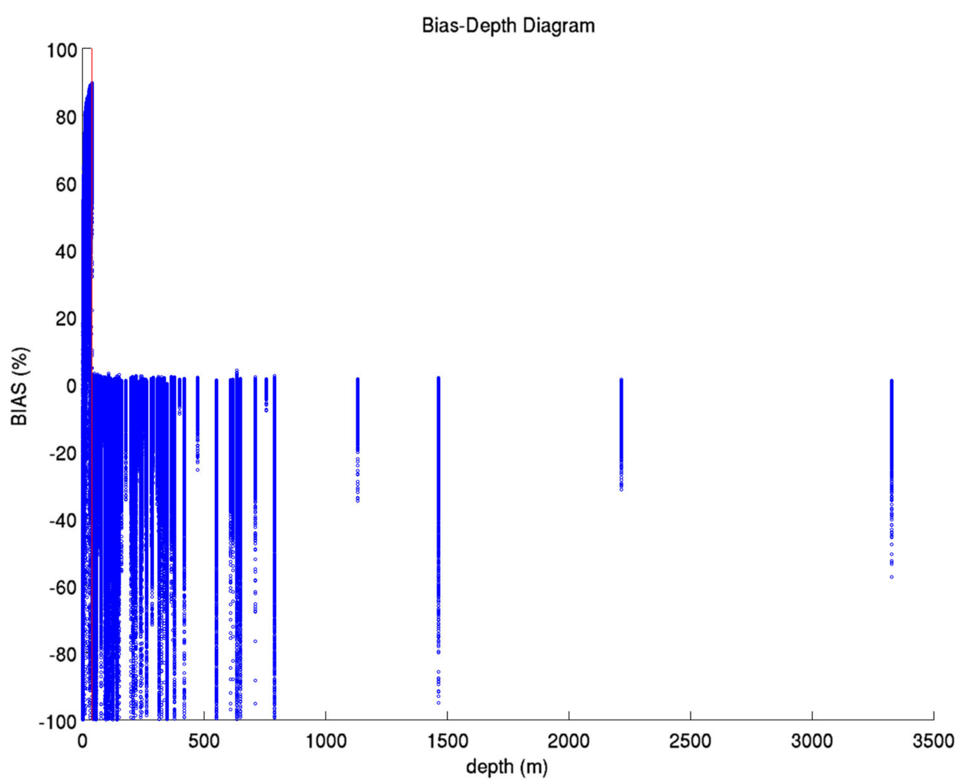

Figure 14. Normalised bias over bathymetry.

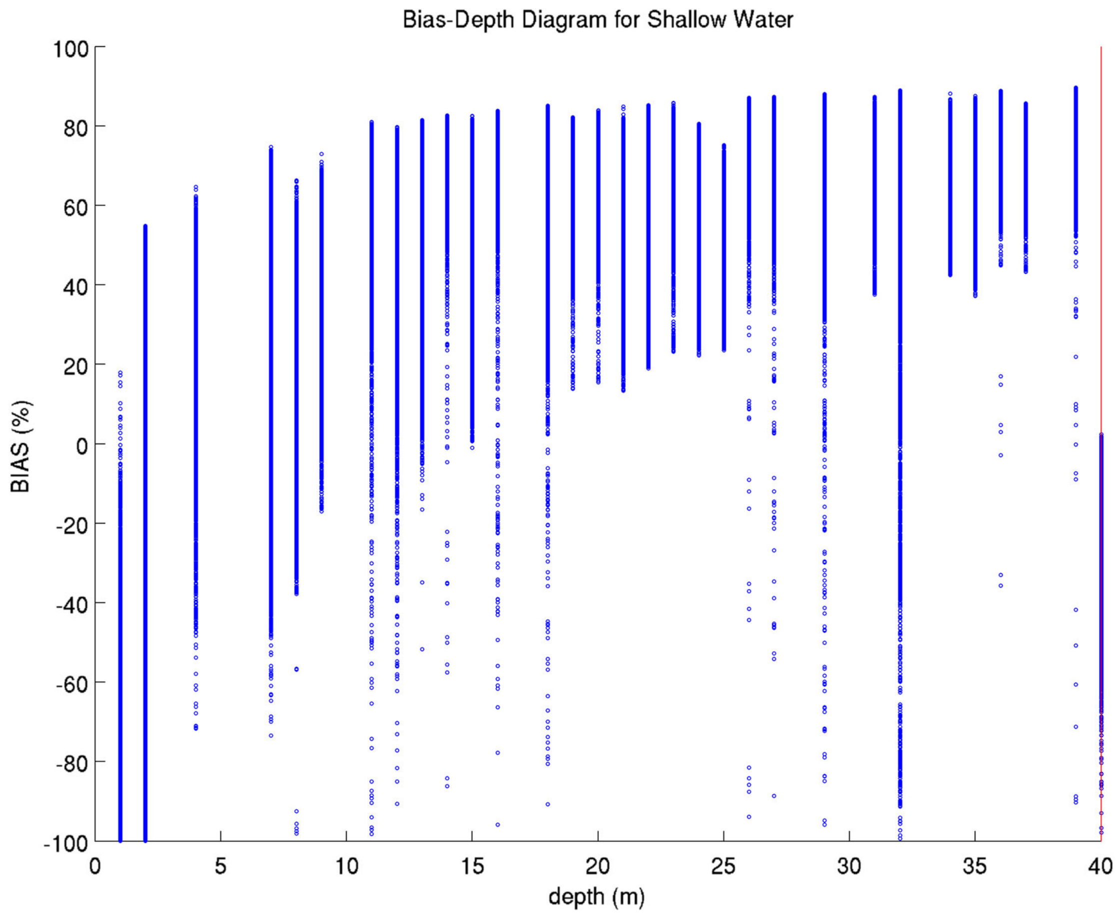

Figure 15. Normalised bias over bathymetry for shallow water.

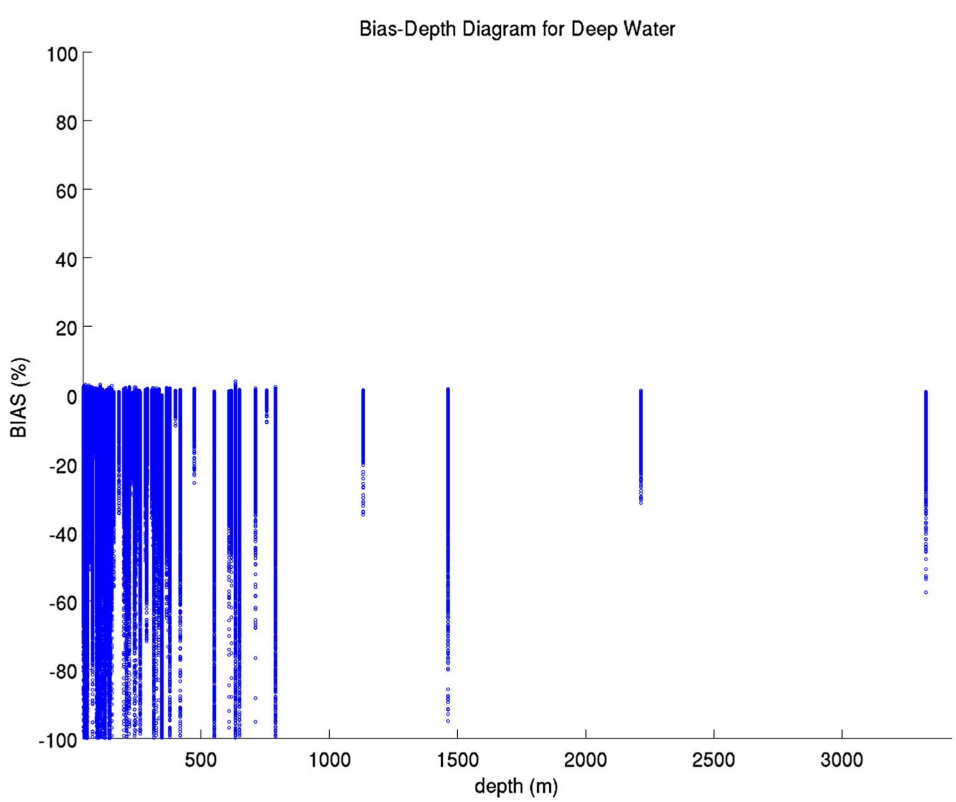

Figure 16. Normalised bias over bathymetry for deep water.

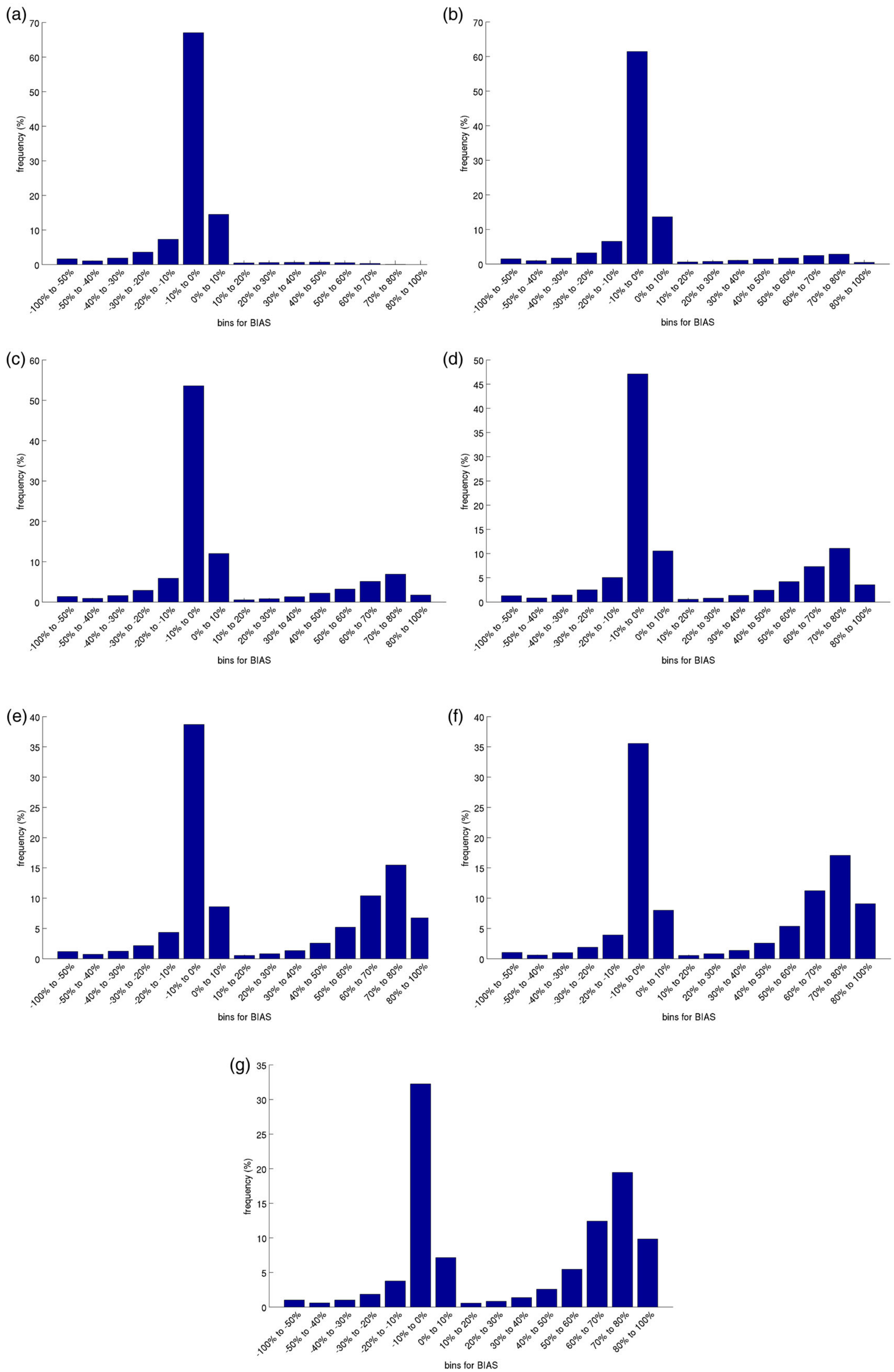

Figure 17. Normalised bias (%) over depth for various values of the separating limit.

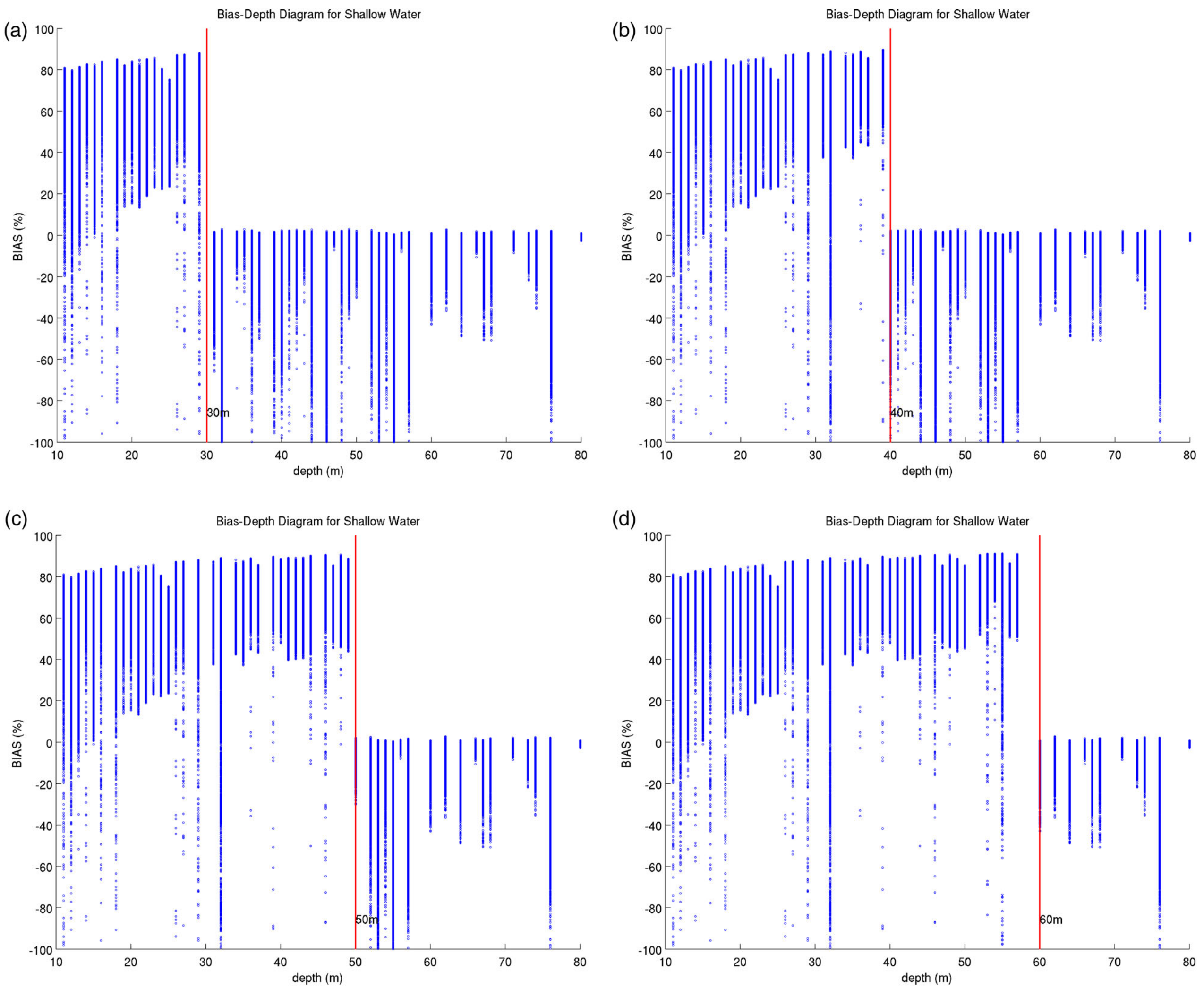

Figure 18. Normalised bias over depth, zoom to depth values close to the limit.

5. Conclusions

Wave models are considered to be useful tools in the study of sea waves where *in situ* observations, satellite records or any other source of information is difficult or expensive to acquire. Furthermore, simplified formulas provide fast calculations with minimum knowledge of the state of the system. The goal of this work is the analysis and study of two methods of calculating wave power:

(1) Analytic formula using wave spectrum
(2) Simplified expression of the preceding formula using mean wave period and significant wave height

To this end, wave data were analysed from the areas of North Atlantic Ocean and the Mediterranean Sea during a time period of 17 months beginning from August 2009 till the end of December 2010. From the analysis presented, it is concluded that the simplified formula tends to overestimate wave power potential by 10%, a behaviour that is enhanced at larger depths. In addition to this, the analytic formula depends on the value of the criterion used to characterise water as shallow or deep. Obviously, there is no standard value for this criterion as even the same area can be affected by different kind of waves. Hence, the bathymetry is an insufficient way to determine a deep or shallow water situation and the dominating wave length is needed to be taken into consideration. A brief part of the results shows this issue and the differences produced by the various choices of the critical value. With these in mind, the simplified formula is not suitable for shallow water as it could considerably underestimate the wave potential of an area, while for deep water a correction coefficient would be enough to compensate for any discrepancy.

Besides the analysis of wave power formulas, an evaluation of the model WAM was attempted using data provided by satellites. Generally, there is a statistical coincidence of wave parameters recorded by satellite and those calculated by WAM. Significant wave height is overestimated at the areas of interest, effect that is enhanced at extreme values. This discrepancy can be at least partially due to the intrinsic difficulty of satellite instruments to correctly record these values. On the other hand, mean wave period data differences are restricted to less than 10%, so the estimation is more accurate. Of course, one could notice that the theoretical wave energy potential is never reached and after the adaptation of a specific wave converter technology, it is the device power curve that will be used. However, the wave energy potential is a good first indicator for wave energy assessment studies especially when combined with the analysis of the joint wave height – period distribution that may critically support the appropriate technology for the area under study.

Furthermore, the tests conducted at areas with specific wave characteristics confirm that the model provides accurate estimation of significant wave height and mean period. Particularly, significant wave height in Mediterranean Sea tends to be smaller than that of the Atlantic Ocean due to little effect of fetch. Additionally, mean wave period achieves values of smaller scale in Mediterranean Sea compared to those of Atlantic Ocean because open seas are swell dominated and subjected to larger scale phenomena. It is therefore a sensible result that the overall behaviour of the model makes it a suitable tool for reliable wave energy analysis.

Disclosure statement

No potential conflict of interest was reported by the authors.

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