WIND ENERGY
Wind Energ. 2006; **9**:251–266
Published online 28 November 2005 in Wiley Interscience
(www.interscience.wiley.com) DOI: 10.1002/we.169

Research Article

Offshore Wind Climatology over the Mediterranean Basin

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Key words:
offshore;
modelling;
wind climatology;
Mediterranean Sea

To obtain the offshore wind climatology over the whole Mediterranean region, European Centre for Medium-range Weather Forecasts (ECMWF) 6-hourly wind data over a grid resolution of 0·5° × 0·5° for a period of 24 years have been retrieved. Data sets at 850 and 700 hPa pressure levels and 10 m above the surface were downloaded. For each grid point, mean wind speeds and Weibull probability density function parameters have been computed. As the wind field of ECMWF at 10 m is less accurate near the coast and in narrow basins, e.g. the Adriatic Sea, owing to the size of the mesh and land–sea mask smoothness, these statistics have been corrected, for each grid point, with the statistics produced using 2 year runs of a limited-area model with a grid size of 10 km. Results have been compared with experimental data from buoys, islands and ships in various regions of the basin. Maps of mean wind speeds and Weibull parameters are shown here for the whole Mediterranean Sea to illustrate these results. Copyright © 2005 John Wiley & Sons, Ltd.

Received 27 November 2004; Revised 12 May 2005; Accepted 10 June 2005

Introduction

In the last few years, large wind farms with wind turbines up to 2·5 MW have been erected offshore, especially in North Europe, where the high mean wind speed is suitable for profitable wind energy applications. In North European areas, only a few studies[1–3] have been performed for predicting wind climatology in offshore regions, i.e. Denmark, based on the WAsP[4] model of Risø National Laboratory (Roskilde, Denmark), which is the most widely used tool for wind energy assessment. Some of these methods used to evaluate wind resources at Danish offshore sites[2] rely on the comparison of long-term measurements at nearby land sites with offshore short-term records and have been shown to give promising results there.

In Mediterranean areas there is a lack of such studies, mainly linked to the difficulty of meteorological monitoring in deep waters, to the sea breeze wind regimes, to local winds such as Bora, Mistral, Sirocco or Etesian and to the complex orography of the coastline. The performances of the WAsP model and the above-mentioned methods for estimating wind resources have been evaluated in the North Adriatic area.[5,6] In particular, in Reference 6 the wind climatology at a platform located 15 km offshore of Venice was estimated using five different methods and wind climatologies produced using long-term data from four coastal meteorological stations located at coastal sites along the Venice Gulf. The applicability of those methods was discussed and it was found that the WAsP model is still the best tool for wind climate estimates, provided that one looks for the

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scale parameter A (m s^{-1}) and shape parameter k of the Weibull probability density function for the total wind distribution over all directions:

$$f(u) = (k/A)(u/A)^{k+1}\exp\left[-(u/A)^{k}\right] \quad (1)$$

where u (m s^{-1}) is the wind speed. On the other hand, if we consider the A and k parameters for each sector, the WAsP program is able to reproduce the wind climatology of the platform only if the coastal reference station is in the same wind breeze regime. This is because, in Mediterranean coastal areas, wind climatology is influenced by local sea breeze circulation, especially during summer. In this case, WAsP tends to reproduce the sea breeze statistics of particular coastal stations also at distances where this phenomenon disappears or changes in direction because the orientation of the coastline has changed.

Offshore Mediterranean wind climatology, derived from a new methodology based on WAsP (GeoWAsP) developed within the EU POWER project Predicting Offshore Wind Energy Resources,[7] has also been investigated in a previous article.[8] GeoWAsP is independent of surface measurements of wind speed. Near-surface wind speed profiles were derived in two steps: (1) geostrophic wind speeds were calculated from a sea-level pressure data set for the period 1985–1997; (2) WAsP was applied at each 0·5° × 0·5° grid of the seas of the European Union to transform geostrophic wind to surface wind profiles for the centre of each grid at heights between 10 and 150 m. The assumptions made were that any nearby land had roughness length z_o = 0·03 m and no orography was used.

Offshore wind climatology from GeoWAsP was compared with wind climatology obtained from the reanalysis data set of the European Centre for Medium-range Weather Forecasts (ECMWF) presented in the next section. It was found that, in general, mean wind speed U (m s^{-1}) produced with the ECMWF data set is lower by about 10%–20% than U produced using GeoWAsP along the East African coast and in the Adriatic Sea and northern Aegean Sea, whereas it is higher by 5%–10% in the centre of the Mediterranean basin. As discussed in Reference 8, the overestimate of GeoWAsP in coastal areas is likely due to the lack of orography and thermal forcing in the methodology.

Our purpose is to improve knowledge of sectorwise wind distributions at geostrophic and surface levels and to obtain the wind climatology at 10 m above the surface of the Mediterranean Sea by following a different approach described in this article.

The methodology adopted here and the climatological data used are presented in the next section. Section three illustrates the comparison between our results and experimental data.[6,9–12] In section four, maps of mean wind speed U and of scale coefficient A and shape coefficient k of the Weibull distribution function over the whole Mediterranean basin are shown.

Models and Methodology

Reanalyses of ECMWF

Since 1979, ECMWF has been running a global model to produce forecast data. This model has been improved in both resolution and the parametrization of physical processes and updated regularly at various times over the years. To produce a long time series of consistent meteorological analyses using a single version of the ECMWF model for the period 1 January 1979–28 February 1994, the ERA-15 project was started in 1993. We retrieved the horizontal wind components from the ECMWF reanalysis for the period January 1979–February 1994 and the operational analysis for the period 1994–2002 at a grid resolution of 0·5° × 0·5° over the whole Mediterranean area. We must point out that, during the latter period, the grid resolution has been improved and the number of vertical levels has been increased; however, tests on the wind climatology over the two periods, conducted considering both offshore and overland wind climatology, have shown that those changes did not modify the offshore wind climatology, and few changes have been found in coastal areas. The analysis data we have retrieved represent the initial condition field for the ECMWF numerical weather forecast model. This field is produced using an advanced analysis procedure to assimilate observations i.e. the ‘four-dimensional variational data’, where the concept of a continuous feedback between observations and

DOI: 10.1002/we

model was put on a mathematical foundation in the so-called Kalman filter.[13] The analysis is performed by comparing the observations directly with a very short forecast, using exactly the same model as the operational medium-range forecast. The differences between the observed values and the equivalent values predicted by the short-range forecast are used to make a correction to the first-guess field in order to produce the atmospheric analysis.[13] In such a procedure, atmospheric physics processes are not directly built into the analysis but are included through the comparison with the forecast model.

Longitude and latitude co-ordinate pairs, with respect to Greenwich, of the lower left corner and upper right corner of the domain are (−7·5°,30°) and (36°,47°) respectively. Surface data (10 m above the sea) and data at two pressure levels (850 and 700 hPa) were retrieved. We confined ourselves to the latter because, in an earlier article,[14] no differences in frequency distribution were found above that pressure level in all available radiosounding measurements; concerning wind speed, at 500 hPa, its mean value was higher than at 700 hPa, but spatial variation over the whole area was around 10%, with a minimum wind speed value of 15 m s^{-1} above the Po valley area.

For each grid point and each pressure level, mean wind speed U and Weibull parameters A and k have been calculated for 12 directions of 30° each.

Limited Area Model Q-BOLAM

The ECMWF data set presents the advantage of being over a long-term period and therefore suitable for meaningful climatological analyses. However, this data set has limits ascribed to various reasons: as discussed above, the physics of the atmospheric processes is not directly built into the analysis, and the ECMWF forecast model has too low spatial resolution of the orography so it is unable to reproduce typical meso-scale processes. These limits lead to errors in forecasting wind profiles in the first hundreds of metres overland; furthermore, owing to the 0·5° × 0·5° land–sea mask, we expect also large errors at the surface over the sea near the coast and in narrow basins. As an alternative, we considered a limited area model (LAM) called QBOLAM, which is a parallel version of the finite difference, primitive equation, hydrostatic model BOLAM (Bologna limited area model).[15] The model runs operationally on a 128-processor parallel computer (QUADRICS), getting the initial and boundary conditions from ECMWF. The model domain covers the whole Mediterranean Sea (including part of the Atlantic Ocean) with a horizontal grid step of 10 km and 40 vertical levels in terrain-following σ co-ordinates (Figure 1). Unfortunately, a QBOLAM long-time series over the same period as the time series of ECMWF does not exist, since the model only became operational in late 2000. Thus a 2 year data set of QBOLAM operational runs (from 01/10/2000 to 30/09/2002), for a total of 730 runs, has been used to obtain wind speed and direction every 6 h (2920 time samples). The model runs operationally at the Italian Agency for Environmental Protection and Technical Services as part of the POSEIDON sea wave and tidal forecasting system,[9] getting the initial and boundary conditions from ECMWF analysis and forecast respectively.

A 60 h forecast with 0·3° horizontal grid spacing starts daily at 12:00 UTC. The first 12 h forecasts are neglected (spin-up time). This low-resolution forecast provides boundary conditions to the high-resolution 48 h forecast run. Outputs are available every 3 h and are considered here only up to 24 h. The model inner domain covers the whole Mediterranean Sea (including part of the Atlantic Ocean) with a horizontal grid step of 0·1° and 40 vertical levels in terrain-following σ co-ordinates (Figure 1). Equations are discretized on a rotated horizontal Arakawa-C grid. Some parametrization schemes are simpler than in other BOLAM versions owing to massive parallelization issues. Postprocessed QBOLAM output is provided on a 0·1° longitude–latitude grid. For this study, each ECMWF grid point has been associated with the coincident postprocessing QBOLAM grid point. To compare the climatology from the two models, we have considered the outputs of QBOLAM and ECMWF for the 2 years overlapping period. We believe that those 2 years include all different meteorological conditions characteristic of the Mediterranean area.

For each grid point we have estimated values of mean wind speed U and Weibull parameters A and k for 12 30° sectors and compared those with the values estimated at the same grid point using the ECMWF data. The procedure is described below and is based on the concept of modifying the Weibull parameters of the long-term data series of ECMWF wind fields in order to improve accuracy in areas where some typical meso-

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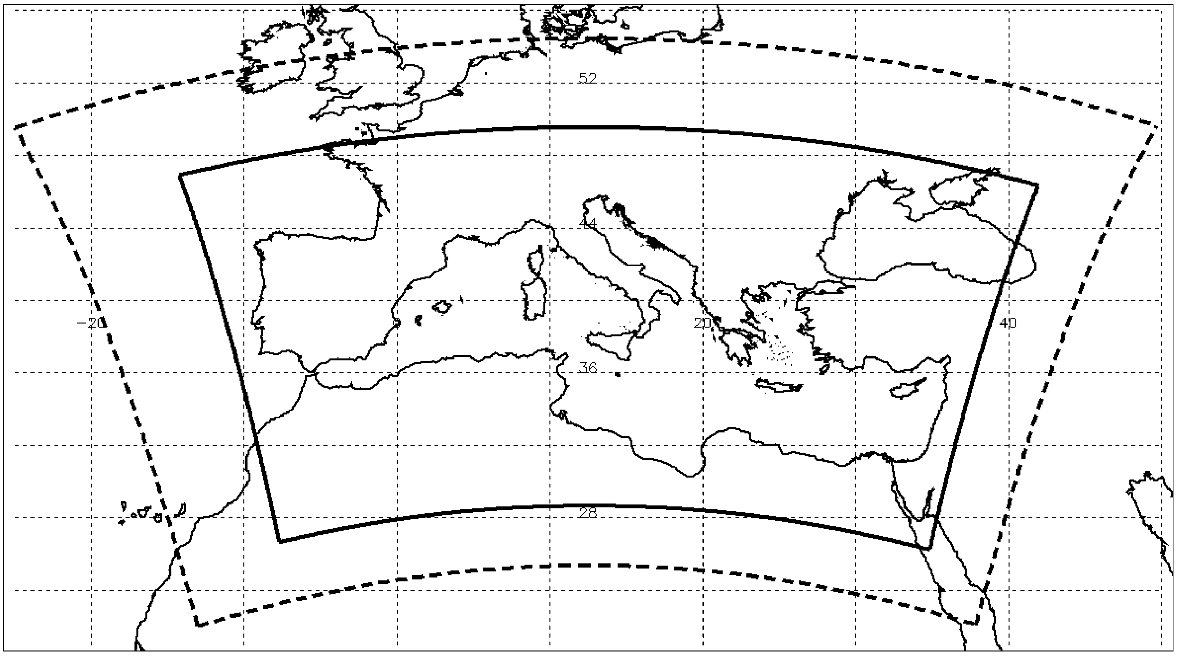

Figure 1. Domain of QBOLAM (grid step: 30 km at the borders and 10 km over the Mediterranean area)

scale processes occur, i.e. in the coastal areas, as discussed above. This method is similar to the Weibull correction method described in Reference 1 and is outlined as follows.

1. Weibull parameters A and k and mean wind speed U are determined for each of the 12 sectors at each grid point of the ECMWF and QBOLAM domains for the overlapping 2 years period. To compare the QBOLAM climatology with the climatology from ECMWF, we averaged U, A and k from a number of QBOLAM grid points surrounding the ECMWF grid within an area of 0·1°.
2. Differences between the two models at each ECMWF grid point are expressed in terms of the ratios A_{QBOLAM}/A_{ECMWF} and k_{QBOLAM}/k_{ECMWF} for each sector, which we call correction factors.
3. These correction factors are applied to the Weibull parameters calculated for the long-term data set of ECMWF.

Limitations of this method will be discussed in section three.

In Figure 2, we present the ratio between the mean wind speed U from QBOLAM and U from ECMWF, calculated over the common 2 years. We note that U_{ECMWF} is less than U_{QBOLAM} along the northern and south-eastern coasts of the Mediterranean Sea and in its small basins, whereas U_{ECMWF} is larger that U_{QBOLAM} in small areas located along the Mistral stream.

Upper-level Climatology from ECMWF Reanalyses

Concerning wind climatology at higher pressure levels, we chose 850 and 700 hPa to represent geostrophic wind climatology. In mountainous areas, these pressure levels cross the orography and therefore the wind field is meaningless there.

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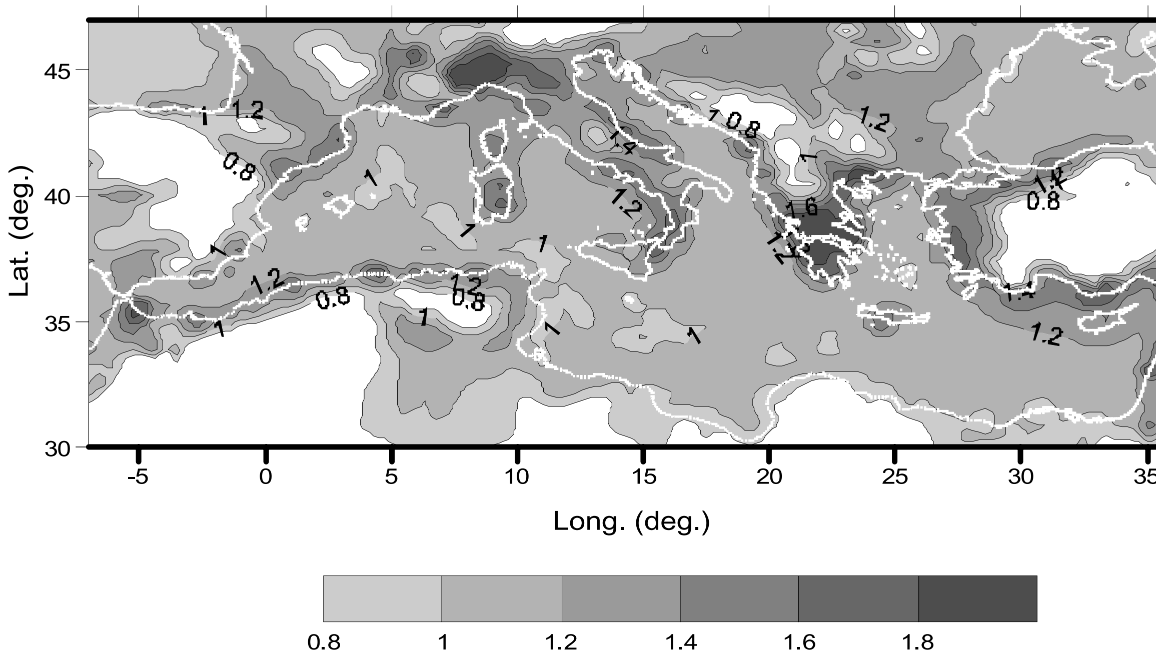

Figure 2. Ratio U_{QBOLAM}/U_{ECMWF} at 10 m over the period 01/10/2000–30/09/2002

Comparison with Experimental Data

Data from Buoys and Islands

To evaluate our results, we have compared U, A and k obtained from ECMWF corrected with QBOLAM runs with U, A and k estimated using observed wind data collected at buoys and islands located in different Mediterranean regions. Parts of these data sets were collected within the FP5 EU project Net for Offshore Sustainable Technologies, Resources and Use in the Mediterranean Sea (NOSTRUM) ALTENER-2002-065.

Here:

- data from the model are retrieved at the grid point nearest to the measurement site;
- the comparison of buoys/islands and model is limited to the period covered by the observations.

Figure 3 show the position of islands (rectangles) and buoys (triangles). Table I displays the geographical coordinates of the stations, the values of U, A and k estimated from the model and (a) islands or (b) buoys and the percentage difference ΔU defined as

$$\Delta U(\%) = 100\,(U_{\text{model}} - U_{\text{data}})/\mathrm{U}_{\text{data}} \tag{2}$$

where U_{model} is the mean wind speed from the model and U_{data} is the mean wind speed from data.

The comparison between model and island data is not straightforward, because we miss the information on how obstacles and vegetation are located around the sensors, so we cannot clean the raw data by removing the effects of these elements in order to obtain the regional climatology.[8] Nevertheless, even though we could not expect to have good quantitative agreement between model and island data, we must observe that the results are consistent. In fact, U_{model} is larger than U_{data} when the islands are large (Mallorca, Ibiza, Menorca), while U_{model} is smaller than U_{data} when the wind is measured at the top of smaller and mountainous islands (Ustica, Limnos, Andros). Results from the comparison between model and islands are shown in Table I. The percentage differences ΔU are very high, varying from –31·8% to 53·1%.

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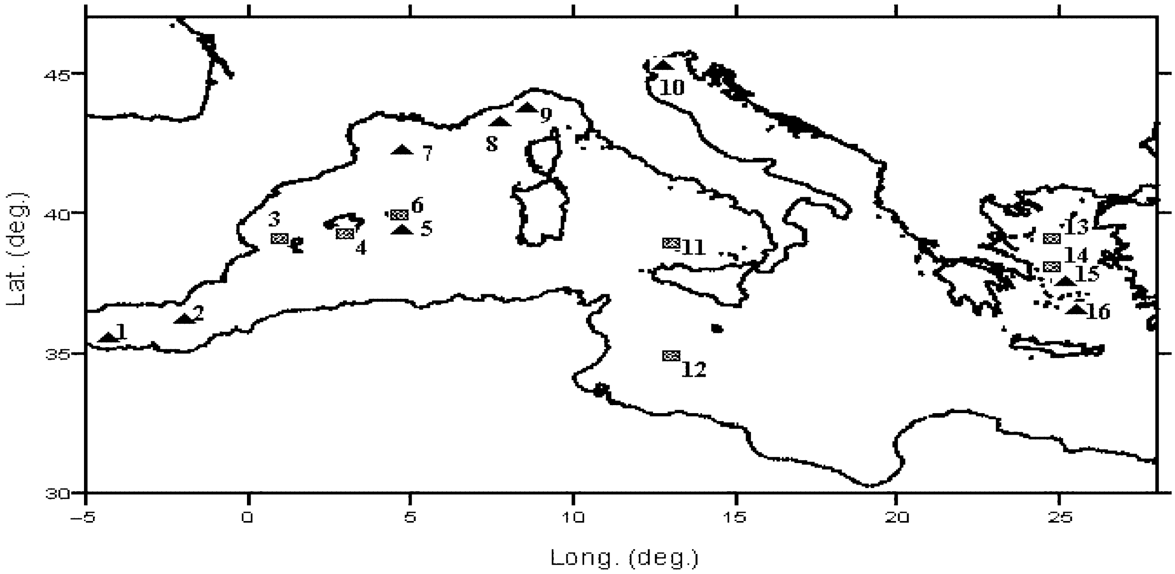

Figure 3. Location of islands (rectangles) and buoys (triangles)

The buoy anemometers are installed on poles at heights ranging from 4 m (Mykonos, Santorini[10]) to 13 m (Ligurian Sea[11]) above the sea surface, so wind flow measured at buoys can be considered unperturbed; however, buoy observations represent local conditions, whereas U_{model} is representative of an area of at least 100 km^2. Taking this into account, we observe that the agreement between model and buoys is satisfactory: ΔU lies between −14·2% and 8·8%. The model not only estimates in a satisfactory way the Weibull parameters for the total wind frequency distribution but also gives good results per sector. In Figure 4, frequency distributions and Weibull parameters of 3- or 6-hourly experimental and simulated data are shown for six of the nine buoys. The Spanish buoys could not be compared, since only annual values of U, A and k were provided.

Data from Ships

Wind measurements from ships sailing in the Ionian Sea and Aegean Sea and connecting the innumerable islands that populate this region of the Mediterranean are less accurate than the measurements from buoys. Generally, the anemometers are positioned on the bows of ships, and correction methods are applied to take into account the speed of the ship and its pitch and roll. Accurate descriptions of the applied methods are available in Reference 12. Another important source of uncertainty is ascribed to the long routes of these ships, which result in a wind distribution that does not correspond to specific meshes of the model domains. Despite these limitations, we also show the comparison between wind statistics from the model and ships. Figure 5 shows 37 zones covering the main part of the eastern Mediterranean Sea. Wind statistics of these zones are published in Reference 12 in the form of experimental frequency distributions for eight sectors of 45° each. The comparison for these 37 areas is synthesized by the histograms showing percentage differences of U (Figure 6(a)), A (Figure 6(b)) and k (Figure 6(c)). In general, the model underestimates the mean wind intensity and overestimates the k parameter. Looking at the different zones of the eastern Mediterranean Sea, the underestimation of mean wind speed is concentrated in zones I04 (ΔU = −18·6%), I07 (−19·7%), A05 (−24·0%), A09 (−14·6%), A10 (−21·6%) and A11 (−18·3%). The best agreement between measurements and model is from zone A13 to zone A20 and from zone K01 to zone K06, with differences not exceeding ±12%. No quantitative comparison has been made for the frequency distributions in each sector, but the accordance ships/model is not dissimilar from that shown in Figure 4.

DOI: 10.1002/we

Table I. Comparison of mean wind speed U and Weibull coefficients A and k between (a) islands or (b) buoys and model

(a) Island	Country	Latitude (deg)	Longitude (deg)	Altitude (m)	Period	Data			Model			
						U (m s^{-1})	A (m s^{-1})	k	U (m s^{-1})	A (m s^{-1})	k	ΔU (%)
Mallorca	Spain	39·55	2·73	8	1974–1989	2·8	2·6	0·91	4·2	4·6	1·68	50·0
Ibiza	Spain	38·86	1·38	12	1974–1989	3·2	3·6	1·15	4·9	5·4	1·77	53·1
Menorca	Spain	39·86	4·23	82	1974–1989	4·2	4·6	1·31	4·6	5·2	1·80	9·5
Lampedusa	Italy	35·50	12·58	40	1959–1990	4·9	5·8	1·60	5·7	6·5	1·93	16·3
Ustica	Italy	39·25	13·00	243	1951–1996	6·2	7·0	1·40	5·1	5·7	1·65	–17·7
Limnos	Greece	39·94	25·11	260	09/99–08/00	6·9	7·8	1·81	5·4	6·1	1·97	–27·8
Andros	Greece	37·96	24·75	303	09/99–08/00 + 2002	8·3	9·4	2·31	6·2	7·1	2·57	–31·8
(b) Buoy		Coast distance (km)										
Côte' d'Azur	France	43·40	7·80	53	19/10/00–30/09/02	5·6	6·1	1·39	4·8	5·0	1·34	–14·2
Golfe du Lion	France	42·10	4·70	170	07/12/01–30/09/02	7·4	8·3	1·82	7·2	8·0	1·87	–2·7
Mar de Alboran	Spain	36·23	–5·30	25	12/96–11/01	5·2[a]	5·8[a]	1·61[a]	4·6	5·1	1·72	–11·5
Cabo de Gada	Spain	36·57	–2·34	20	12/97–11/01	5·3[a]	5·9[a]	1·52[a]	5·3	6·1	1·97	0·0
Mahòn	Spain	39·75	4·42	15	1993/4/6/8/9	5·3[a]	5·9[a]	1·72[a]	5·5	6·2	1·81	3·8
Venice platform	Italy	45·50	12·52	16	1976–1982	4·3	4·7	1·19	3·8	4·4	1·86	–11·6
Ligurian Sea	Italy	43·50	9·00	65	01/02/00–31/12/00	4·5	4·8	1·26	4·7	4·9	1·41	4·4
Mykonos	Greece	37·51	25·46	4·3	01/06/00–30/10/00	7·5	9·0	2·76	6·9	8·0	2·59	–8·0
Santorini	Greece	36·25	25·50	10·4	01/01/00–31/12/00	5·7	6·6	1·87	6·2	7·0	2·32	8·8

[a] Calculated from annual values.

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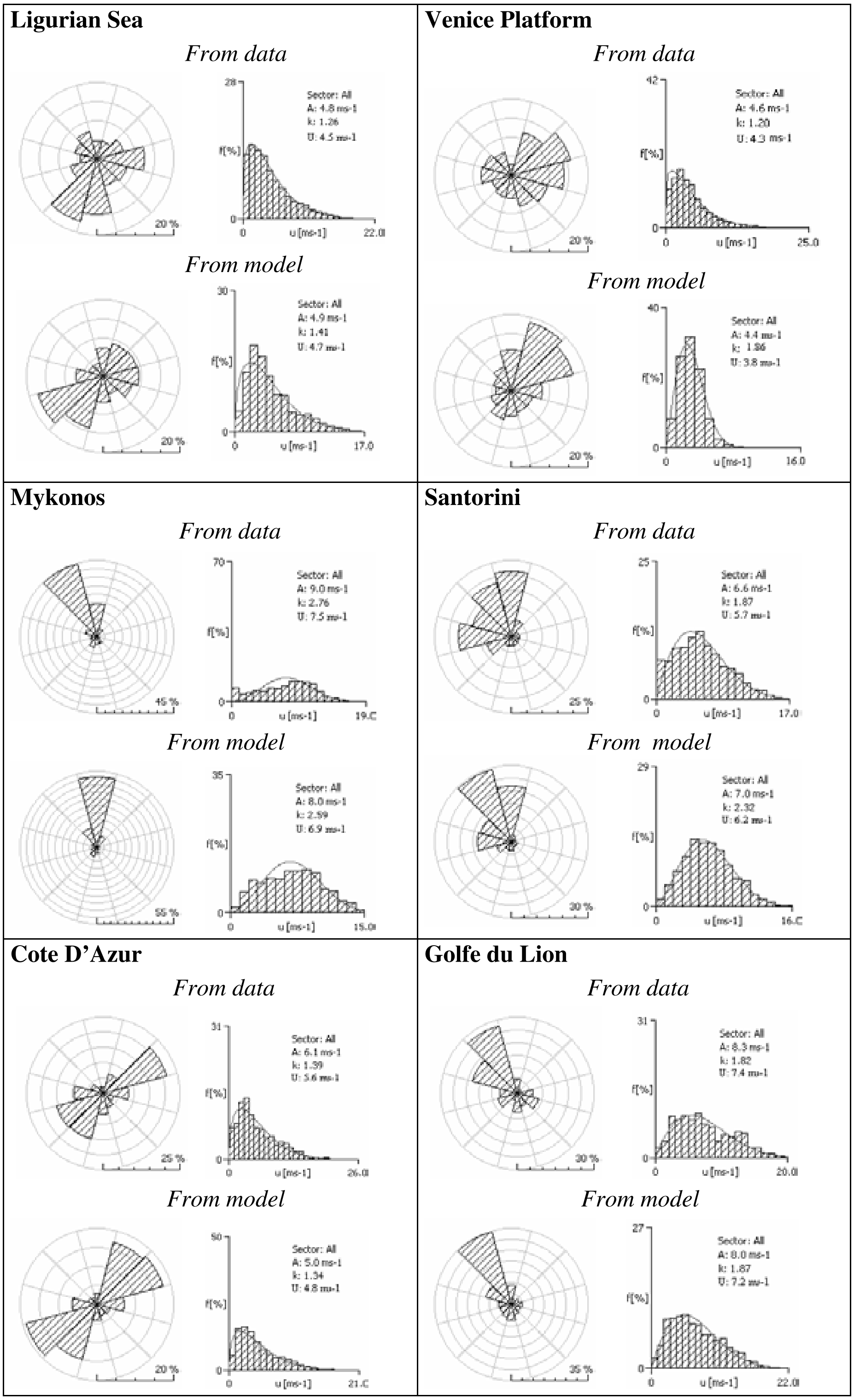

Figure 4. Experimental and modelled wind distributions at six buoy locations

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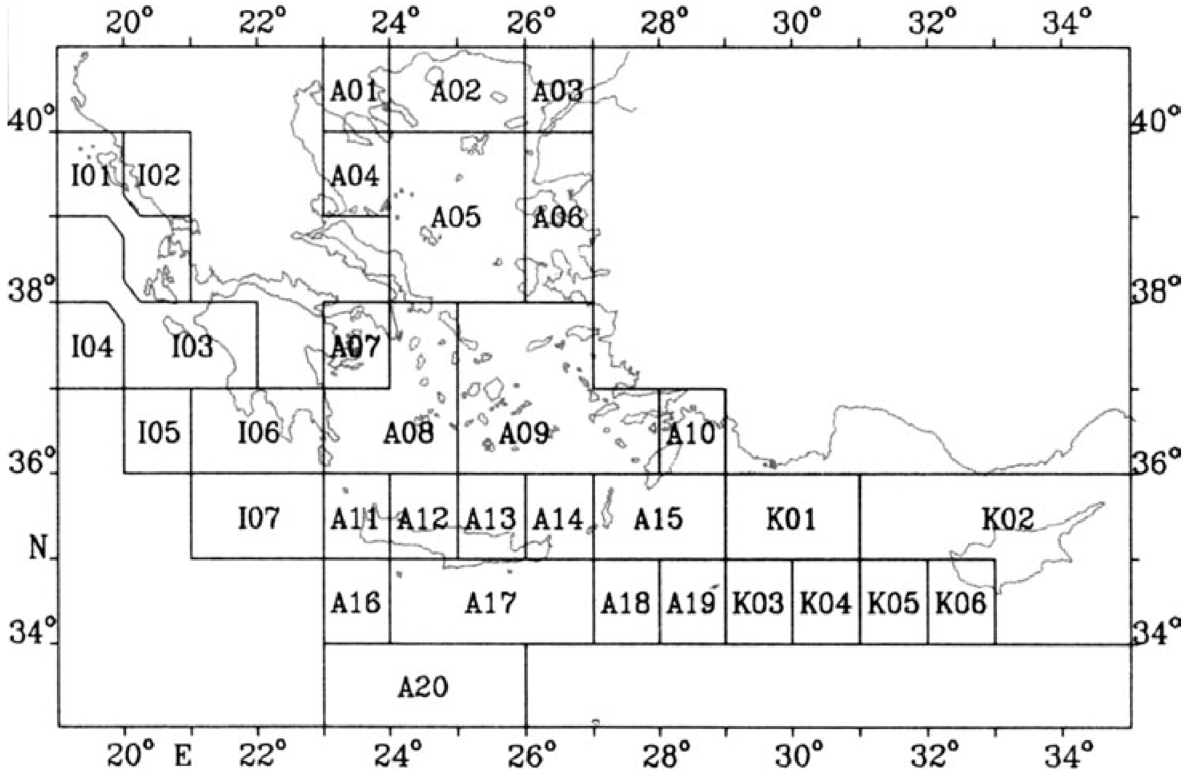

Figure 5. Ship measurement zones located in the Ionian Sea and Aegean Sea used for the comparison

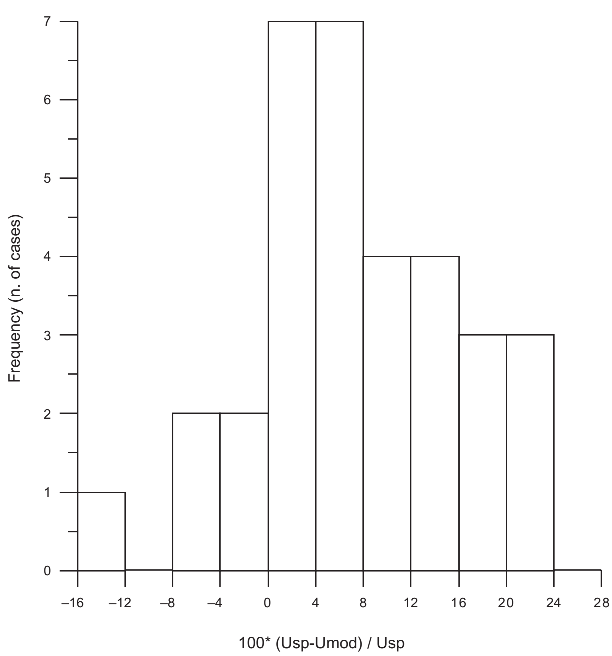

Figure 6(a). Histogram of differences between experimental and modelled mean wind speed over all zones

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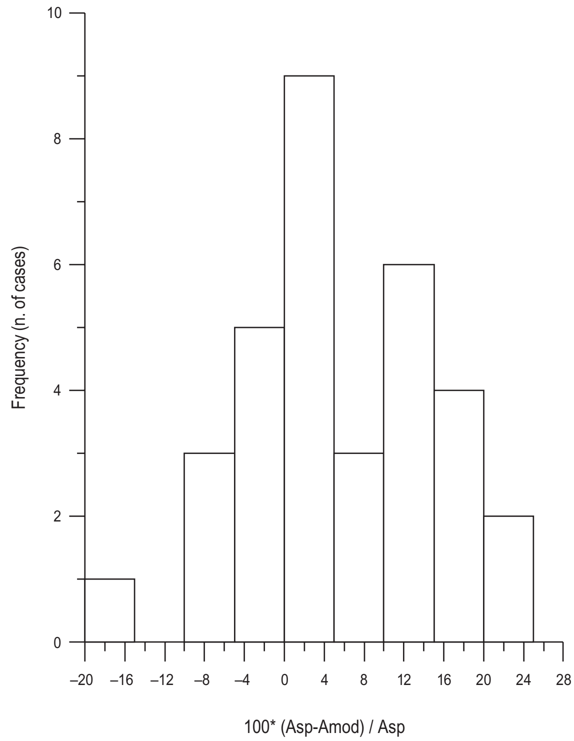

Figure 6(b). Histogram of differences between experimental and modelled A factor over all zones

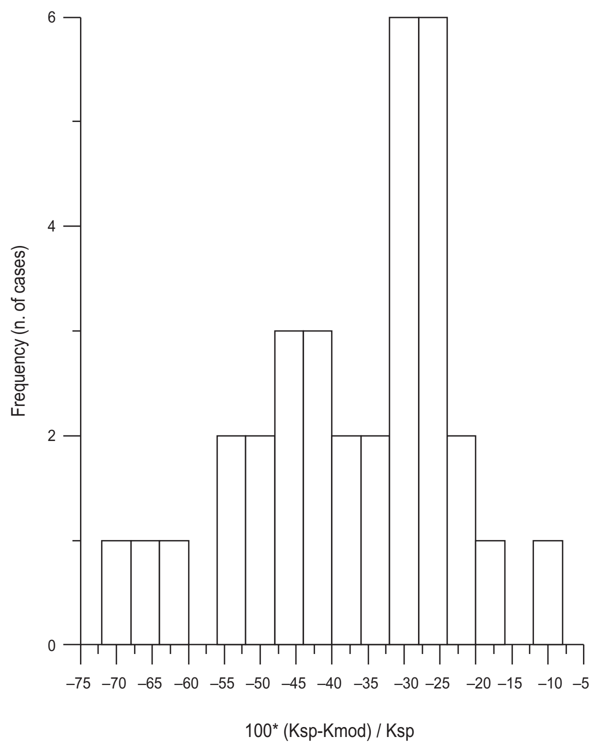

Figure 6(c). Histogram of differences between experimental and modelled k factor over all zones

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Wind Atlas over the Mediterranean Area

In this section we present the maps of A, k and U over the whole Mediterranean Sea at 850 and 700 hPa and 10 m a.s.l. We acknowledge the limitations of the model in coastal areas because of its coarse resolution; however, we believe that these maps will give an indication of the best areas to take into consideration for a more careful investigation of wind energy application offshore.

Geostrophic Level

Figures 7(a) and 7(b) show the horizontal variation of U and of the wind roses at 850 hPa for a period of 24 years from 1979 to 2002. Figures 8(a) and 8(b) show the corresponding results at 700 hPa. The variability of U is shown also overland. In fact, these maps are useful tools to determine the areas with the same wind climatology at geostrophic level. Examining both wind speed and direction, we can localize areas where the wind climatology changes rapidly. Generally, the extension of these areas is determined by the features of the orography and limited by mountainous chains. The areas with higher horizontal gradients of wind speed are:

- zones close to the Alps mountains and to the borders of the Golfe du Lion, with gradients of about 1·5 m s^{-1} per 100 km;
- part of Greece, Turkey, Corsica and Sardinia, with gradients from 0·5 to 0·75 m s^{-1} per 100 km;
- Italian coastal areas where the 850 hPa isolines cross the Italian Peninsula, showing discontinuity and sudden changes in direction.

Looking at the general features, we see, as expected, the main wind blowing from the northwest. We note also that the central part of the basin is dominated by a mean wind speed between 7·5 and 8·5 m s^{-1} at 850 hPa, extending from the Golfe du Lion to the Aegean islands (and part of the Black Sea), while at 700 hPa this area is smaller, ending west of the island of Crete, with values between 10·5 and 11·5 m s^{-1}.

Considering the spatial variation of the wind rose, we can observe distinct regions influenced by channelling effects, i.e. Gibraltar or the Sicily Channel, or large-scale wind regimes such as Mistral or Tramontana, i.e. the North Adriatic, west of Sardinia and the southeastern part of the Mediterranean. These local winds do not always appear at geostrophic level. In fact, some of them, e.g. Mistral and Etesian, at 850 hPa exert their influ-

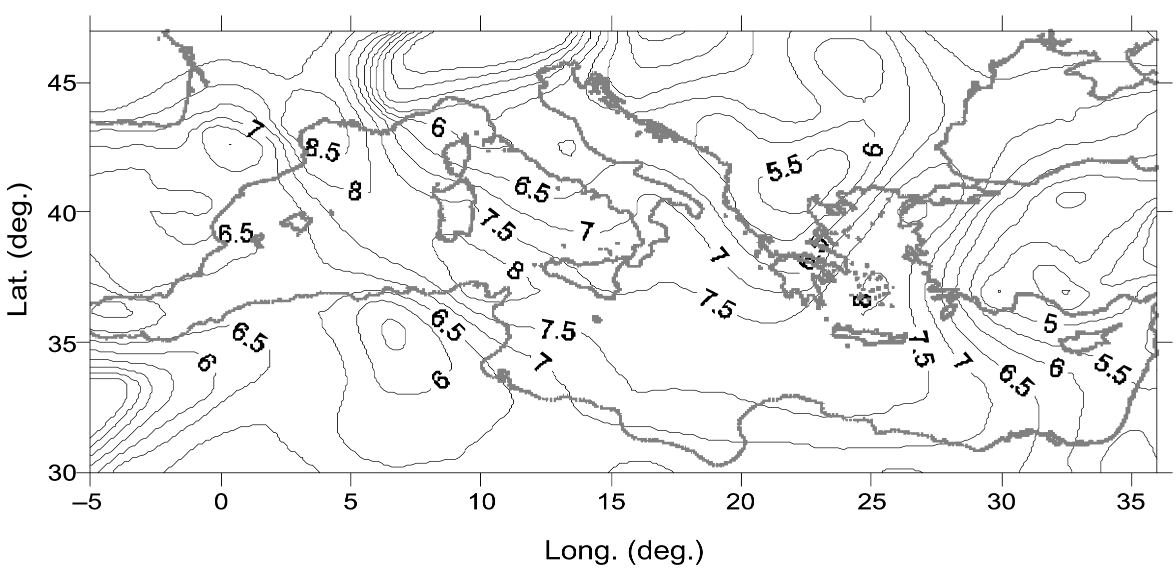

Figure7(a). Mean wind speed U (m s^{-1}) from ECMWF at 850 hPa over 24 years

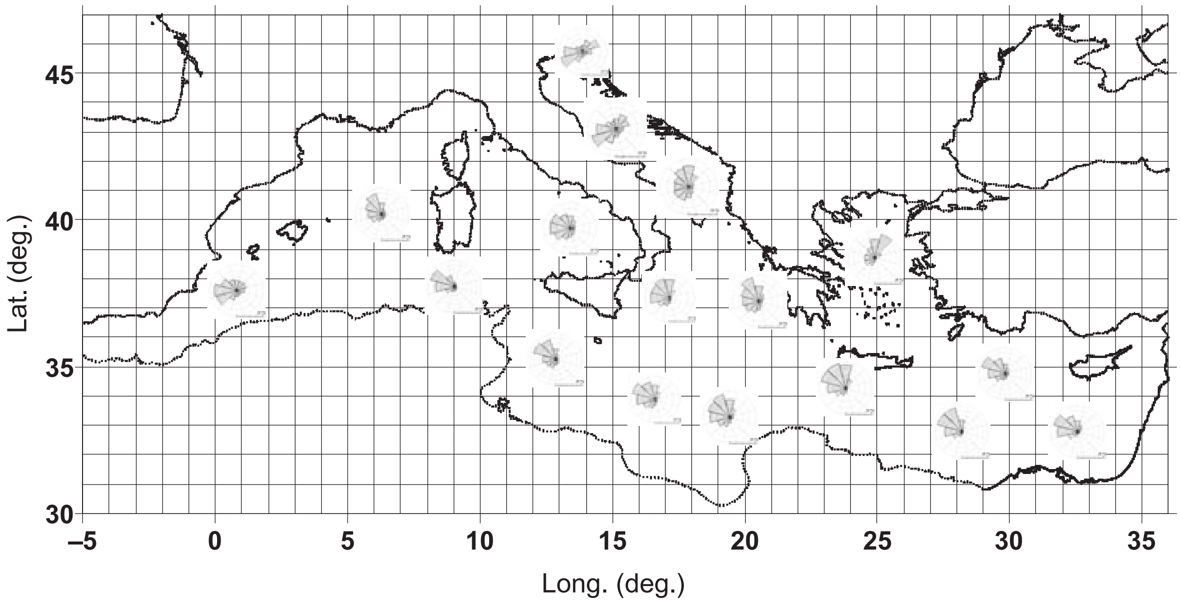

Figure 7(b). Wind frequency distributions from ECMWF at 850 hPa over 24 years

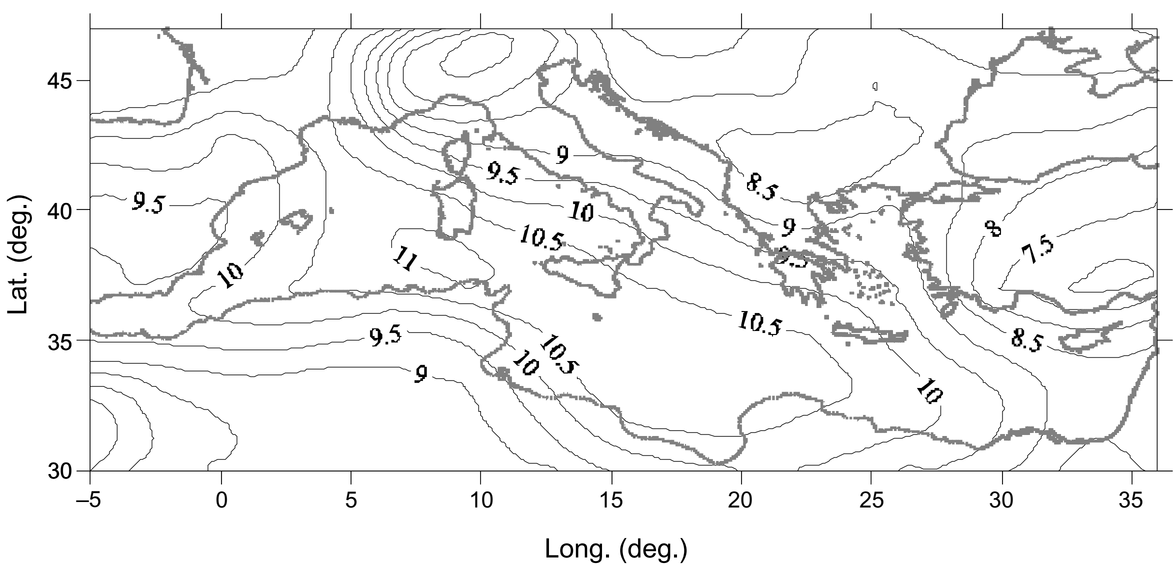

Figure 8(a). Mean wind speed U (m s^{-1}) from ECMWF at 700 hPa over 24 years

ence over most of the Mediterranean; others, e.g. Bora, blowing from the Balkans to Trieste and Venice, are just visible up to 850 hPa and disappear at 700 hPa, where the westerly component prevails over the whole North Adriatic basin.

Surface Wind at 10 m

The spatial variation of wind speed U and Weibull parameters A and k at 10 m a.s.l., calculated with the method presented in section two, is shown in Figures 9(a) 9(c) respectively. In general, we note that the points

DOI: 10.1002/we

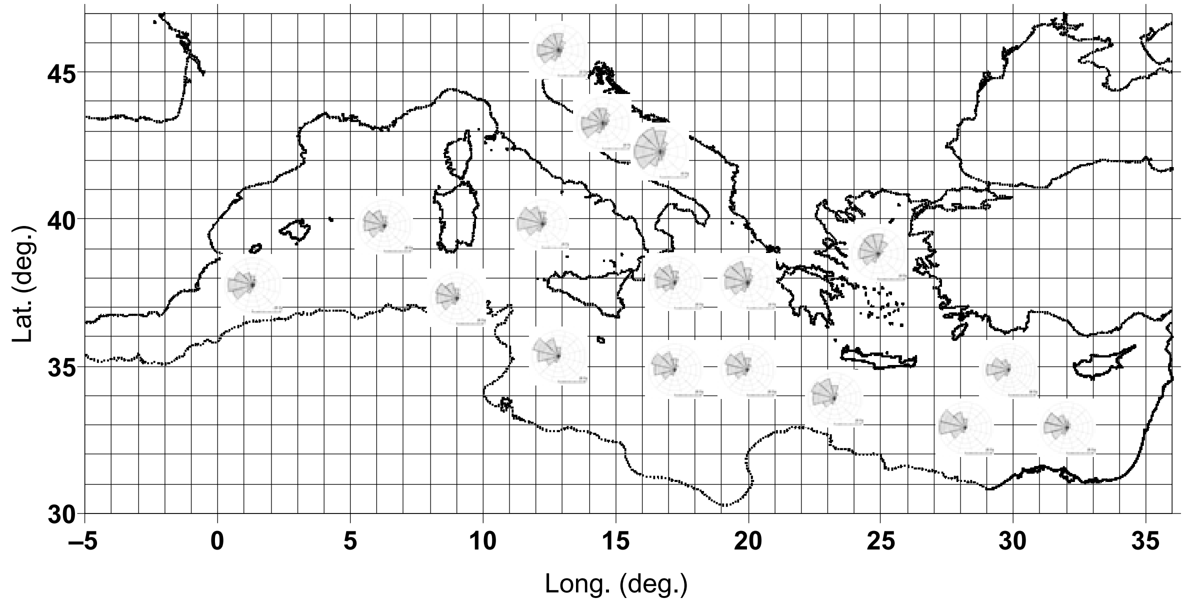

Figure 8(b). Wind frequency distributions from ECMWF at 700 hPa over 24 years

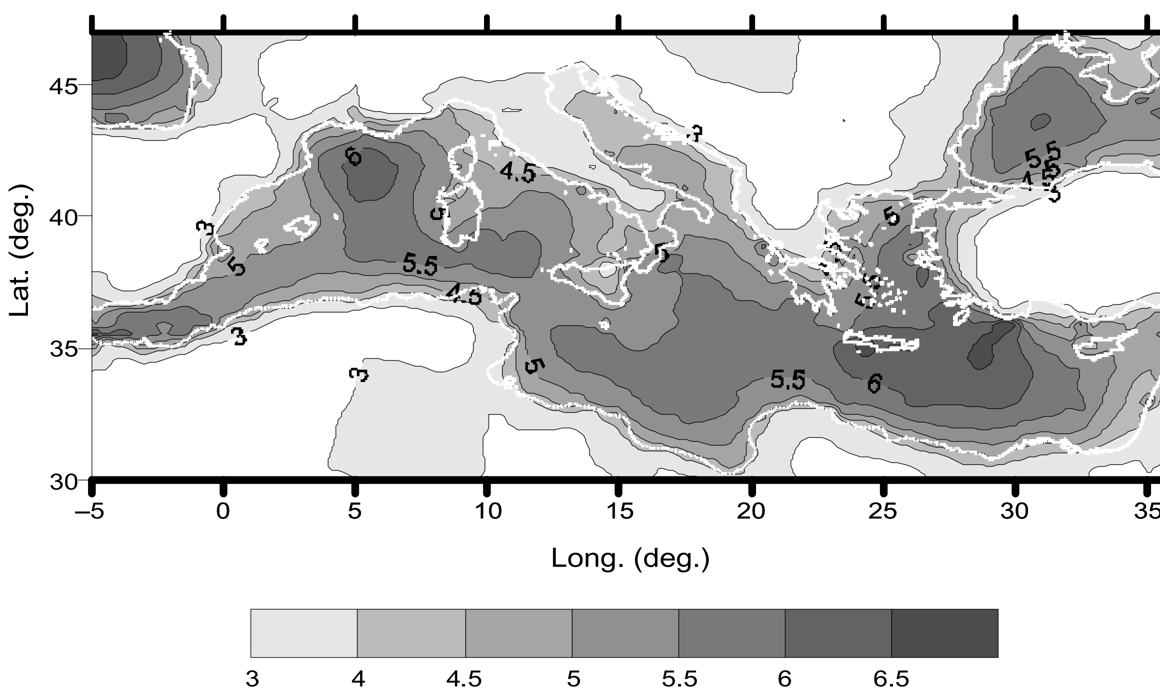

Figure 9(a). Mean wind speed U (m s^{-1}) at 10 m above the Mediterranean Sea

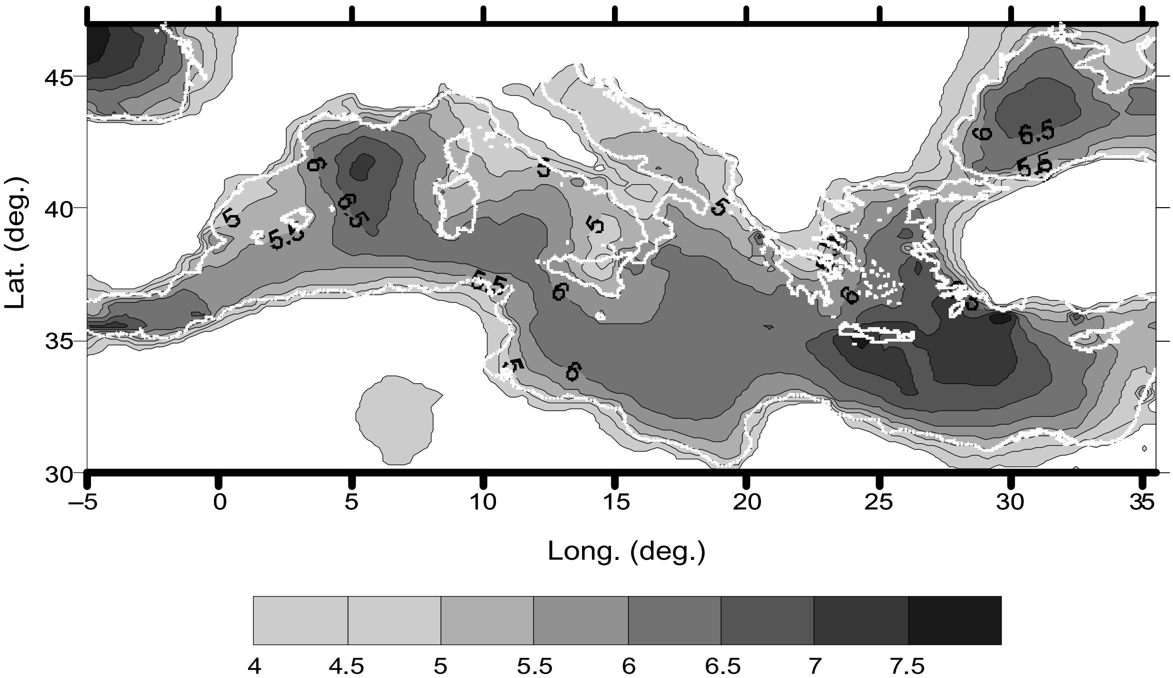

Figure 9(b). Scale parameter A (m s^{-1}) at 10 m above the Mediterranean Sea

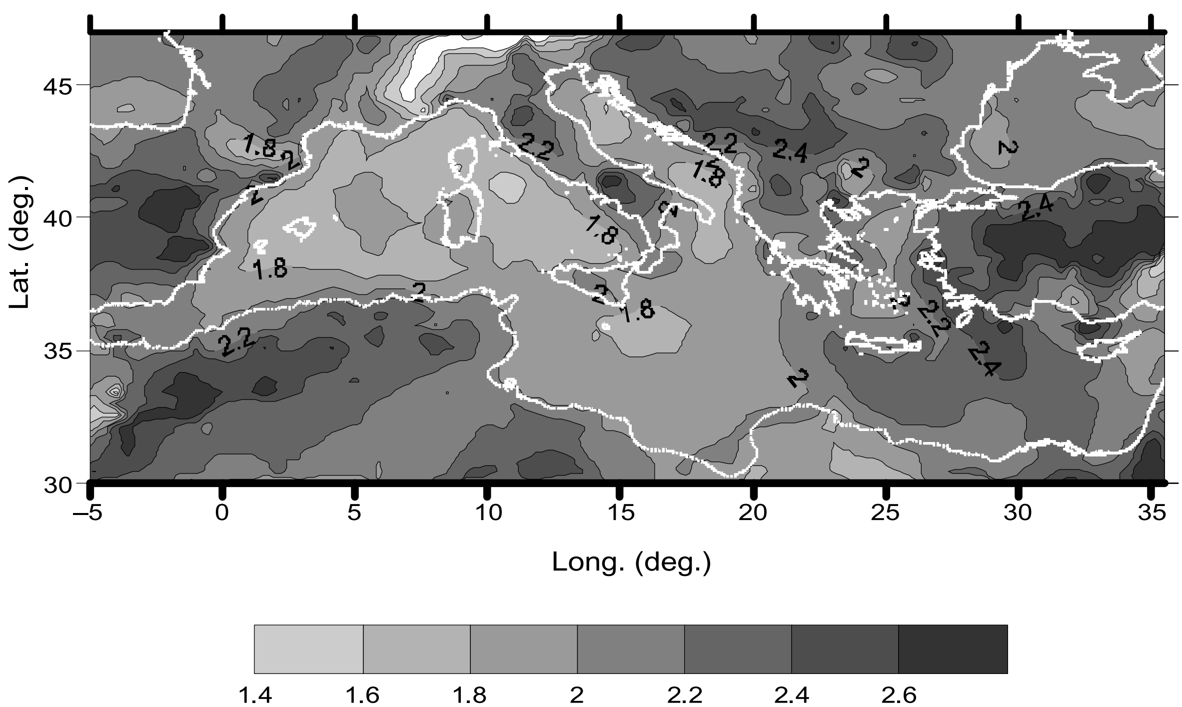

Figure 9(c). Shape parameter k at 10 m above the Mediterranean Sea of highest wind speed are found offshore, far from the coast in the middle of the various basins of the Mediterranean Sea, with maximum speeds reaching 6·5–7·0 m s^{-1}. Furthermore, if we focus on coastal areas, the most interesting places for wind energy application are located, from west to east, close to the Gibraltar strait, in the Golfe du Lion, west and south of Sardinia, south of Sicily, in the Greek archipelago with its *ca* 2000 islands and in the southwest part of the Turkish coast.

West of Sardinia, the horizontal variation of the main directions is from the northwest, due to the Mistral, which maintains its influence down to south Sicily. East of Sardinia the wind rose is characterized by the Tramontana and Sirocco regimes as well. The channelling effects are evident not only approaching the narrow straits, i.e. Gibraltar, Messina and Bonifacio (between Sardinia and Corsica), but also in large water channels such as the Sicily Channel (between Tunisia and Sicily). Along the coast of Africa these directions turn following the orography. In the Adriatic Sea the effect of the Bora (in the northern part) and Tramontana winds from the north-northeast sectors becomes predominant.

Final Remarks

Maps of U, A and k presented in this article show that the areas more suitable for wind energy application in the Mediterranean basin are located close to the Gibraltar strait, in the Golfe du Lion, western Sardinia, south of Sicily, the Greek islands, the southwestern part of the Turkish coast and most of the North African coast.

Comparisons of U, A and k between time series from the model and from buoys are more reliable with respect to observations from islands or from sensors installed on ships; on islands because of local effects around the anemometer influencing measurements and on ships because of missing information on different ship heights and on the methods used to correct the motion of the ship. However, this study shows that, if we take into account the total wind distribution and the total mean wind speed, comparisons between U, A and k from model outputs and from islands and ships show satisfactory agreement.

Even though the horizontal representativeness of the outputs from simulations is about 100 km^2, the model predicts mean wind speed and Weibull parameters A and k measured at the buoy locations with an error between –14·2% and 8·8%. In more detail, the model underestimates U from buoys if they are placed in the vicinity of mountainous coastal zones (Côte d'Azur) or in small basins (North Adriatic) and especially if the location is near to the coast (Venice platform).

Concerning ship observations, the model underestimates U from ships in small basins within islands (zones A05, A08, A09, A10) or close to open coastal areas (zone I04, I05). Furthermore, we observe that in areas close to islands such as Rhodes and Crete the model underestimates the mean wind measured from ships by around 20%. The opposite happens in adjacent zones, i.e. zones A10, K01, A11 and A12. This means that the model cannot properly reproduce the mean wind when large horizontal gradients are present. We believe this is due to the fact that ships measure offshore and in straits, while the model sees a combination of land and sea.

It is important to note that it is not advisable to use the A and k parameters presented in this study for estimating the real wind potential energy offshore, because the model is too coarse for proper wind potential assessment at specific sites.

Acknowledgements

We are very grateful to Dr C. A. Martin (BESEL Company, Madrid, Spain), Dr N. Hernigou (Espace Eolien Development, France), Dr K. Rossis (CRES, Athens, Greece) and Dr T. H. Soukissian (HCMR, Athens, Greece) who kindly provided Spanish, French and Greek experimental data used for the comparison. We thank Dr Rebecca Barthelmie from Risø National Laboratory, Denmark for useful discussions and comments. Data from Italian islands were kindly provided by the Italian Meteorological Service. Data from the Venice platform were kindly provided by Dr Luigi Cavaleri from ISMAR-CNR, Section of Venice, Italy. Data from the Ligurian Sea buoy were kindly provided by Dr Bozzano from ISMAR-CNR, Section of Genoa, Italy.

DOI: 10.1002/we

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DOI: 10.1002/we