CHAPTER 4 : Transforming geostrophic winds to turbine hub heights using WAsP

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4.1 Introduction

The second step of the POWER methodology (see Section 2.2) is to transform geostrophic winds to the sea surface layer by applying the Wind Atlas Analysis and Application Program (WAsP).

4.2 The Wind Atlas Analysis and Application Programme (WAsP)

WAsP [Mortensen *et al*., 1993] is a linear flow model that can be used to transform geostrophic winds to the surface layer. The model is well-established and commonly used throughout the wind energy community to perform wind resource assessments.

The WAsP model calculations are based on the geostrophic drag law combined with models of stability and development of an internal boundary layer (IBL). The standard version of the software allows coastal effects to be modelled assuming differences in mean onshore and offshore stability and using internal boundary layer theory to modify wind speed profiles over the width of the coastal zone. Within the model adjustments to the wind speed profile offshore are based on the assumption that the wind speed profile in the surface layer (up to approximately 100m) is slightly stable.

WAsP takes as input wind data from one site and estimates the wind regime at another nearby site. Simply put, the model operates in two steps:

step 1) The input wind data is used to calculate the corresponding “high level” geostrophic wind conditions for that time and location. In doing so, the model “subtracts” local effects such as zones of shelter from local obstructions (e.g. buildings or trees), acceleration or deceleration of air flow due to the shape and form of the surrounding landscape (e.g. if the site is on the brow of a hill, air flow from some directions could be accelerated compared to a flat open location) and the characteristics of the local vertical wind speed profile formed by a combination of internal boundary layers, each spawned by boundaries between zones with different surface roughness e.g. lakes, open grassland, crops, forests, urban areas etc..

step 2) The geostrophic wind conditions are transformed down to the second site. This time the model “adds” the local effects associated with the new location. Thus in estimating the wind regime at the second site WAsP takes account of differences in orography, surface roughness, obstructions, height above ground etc. between the two site.

In most cases, the wind data used as input to model will have been measured by instruments mounted on a meteorological mast installed at the site of a proposed wind farm, or at a nearby meteorological monitoring station. However, within POWER the input data is the geostrophic wind speed and direction data calculated from the sea level pressure data (see Chapter 3) and so, in effect, only step 2 of the WAsP model operations is being used. This method is also sometimes referred to in this report as GEOWAsP.

4.3 WAsP 5 versus WAsP 6.0

Plans to use an upgraded version of WAsP software (WAsP version 6.0, first released in March 1999) for POWER were abandoned because:

1. Use of upper air (geostrophic wind) data as input to the model has not been implemented entirely.
2. The ability to run the model remotely, in batch mode, is not supported in this release. This feature is essential for its application in the POWER project as there are a very large number of model runs to perform.

Therefore it was decided that the most recent release of WAsP 5 (version compiled in February 1999) would be used for the POWER project instead. This version of the WAsP model supports both features highlighted above.

4.4 Application of WAsP throughout European waters

The WAsP model was used to transform the calculated geostrophic winds (see Chapter 3) to the surface layer, at each point in the 0.5° x 0.5° latitude/longitude grid that lies over the sea. In practice this means that WAsP analyses were performed at over 3700 grid locations.

Coastline data was extracted from the *Digital Chart of the World* CD-ROM (distributed by PhD Associates Inc.). The *Digital Chart of the World* data contains over 164,000 latitude/longitude coordinate pairs that describe the position of the coast in the area of interest. Where a grid point was situated far offshore (>10km), a constant surface roughness value of 0.0002m was assumed. Alternatively, where a grid point was close to the coast (<10km) a roughness value of 0.0002m was assumed over the sea area and 0.03m over the land.

Mean wind conditions for the period 1985-1997 have been estimated at eight hub heights at each grid point over the sea. The hub height levels (10m, 30m, 50m, 70m, 90m, 110m, 130m and 150m above mean sea level respectively) were chosen to cover the range of expected hub heights of wind turbines that are likely to be sited offshore in the coming years.

In addition, the monthly and inter-annual variability of the wind conditions in European waters were also investigated by performing WAsP model runs estimating the mean monthly and mean yearly wind conditions at all offshore grid points

Finally, some additional WAsP runs were performed to obtain offshore wind predictions at specific locations and heights, which could be compared directly against observed data for validation purposes. (see Chapter 10 for more details).

4.5 Variable sea surface roughnesses

The components of the surface terrain (such as built-up areas, forests, hedges and crops) disturb the air flow close to the ground and generally act to slow down the wind at ground level. This in turn influences the vertical wind speed profile. This aerodynamic "drag" characteristic of a terrain is referred to as its surface roughness and is commonly parameterised by an aerodynamic roughness length, z_0. It is important to understand that "aerodynamic roughness" can be very different to the perception of roughness of a particular surface obtained by sight or touch. Values of z_0, for a selection of terrain types are given in the scientific literature (including [*Troen et al*, 1989]).

In general, the surface of the sea is aerodynamically very "smooth", with correspondingly small z_0 values (typically of the order of 10^{-4} to 10^{-3} m). However, whereas the roughness of land features can be thought of as essentially constant, the sea surface geometry and roughness alter continuously with varying wind speed. Unfortunately, despite decades of work on wind-wave interactions, a conclusive parameterisation of z_0 in terms of wind speed and/or sea state has not yet been identified [*Taylor (ed.),* 2000].

The distribution and variability of estimates of sea surface roughness throughout the POWER project area was investigated using a new parameterisation for z_0 suggested recently by researchers from the Southampton Oceanographic Centre [*Taylor and Yelland,* 2000]. It is proposed that sea surface roughness, z_0, can be predicted from the height and steepness of the waves at the site:

$$\frac{z_0}{H_s} = A\left(\frac{H_s}{L_p}\right)^{\mathrm{B}} \tag{4.1}$$

where H_s and L_p are the significant wave height and peak wavelength for the combined wind sea and swell (resultant) spectrum, and the best estimates for the coefficients are A=1200, B=4.5. This approach has the advantage that it takes into account the effects of not only locally generated wind waves, but also swell waves that have travelled into the area from more remote sites. In addition, it models changes in roughness due to wave shoaling in shallow water and fetch dependency is automatically accounted for within the wave input data. The formulation has been shown to explain the characteristics of a wide range of data sets, however Taylor and Yelland also point to certain weaknesses in the definition of the coefficients and some potential difficulties with its application. Nevertheless, it was decided that this was the most appropriate parameterisation of z_0 available for the task.

Values of z_0 were calculated using Equation 4.1 based on data from the UK Meteorological Office (UKMO) European Wave Model. The values of H_s were taken directly from the UKMO data, however values of peak wavelength, L_p, were determined from the dispersion relationship:

$$\frac{\omega^2}{g} = k\tanh(kh) \qquad (4.2)$$

where ω is the angular wave frequency ($2\pi/T_p$), g is the acceleration due to gravity, k is the wave number ($2\pi/L_p$) and h is the water depth. Figure 4.1 illustrates the water depths throughout the European Wave Model area used in these calculations.

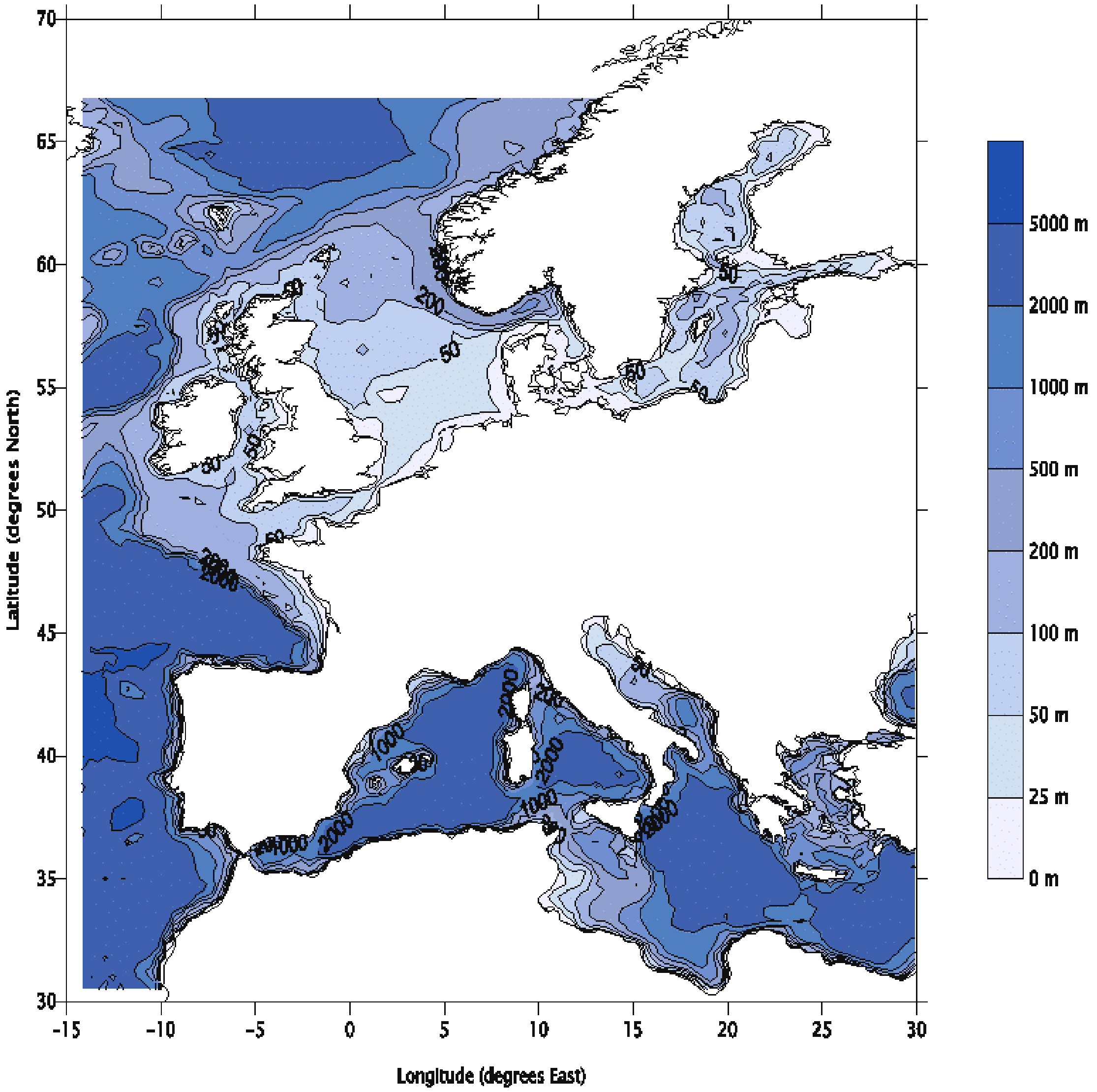
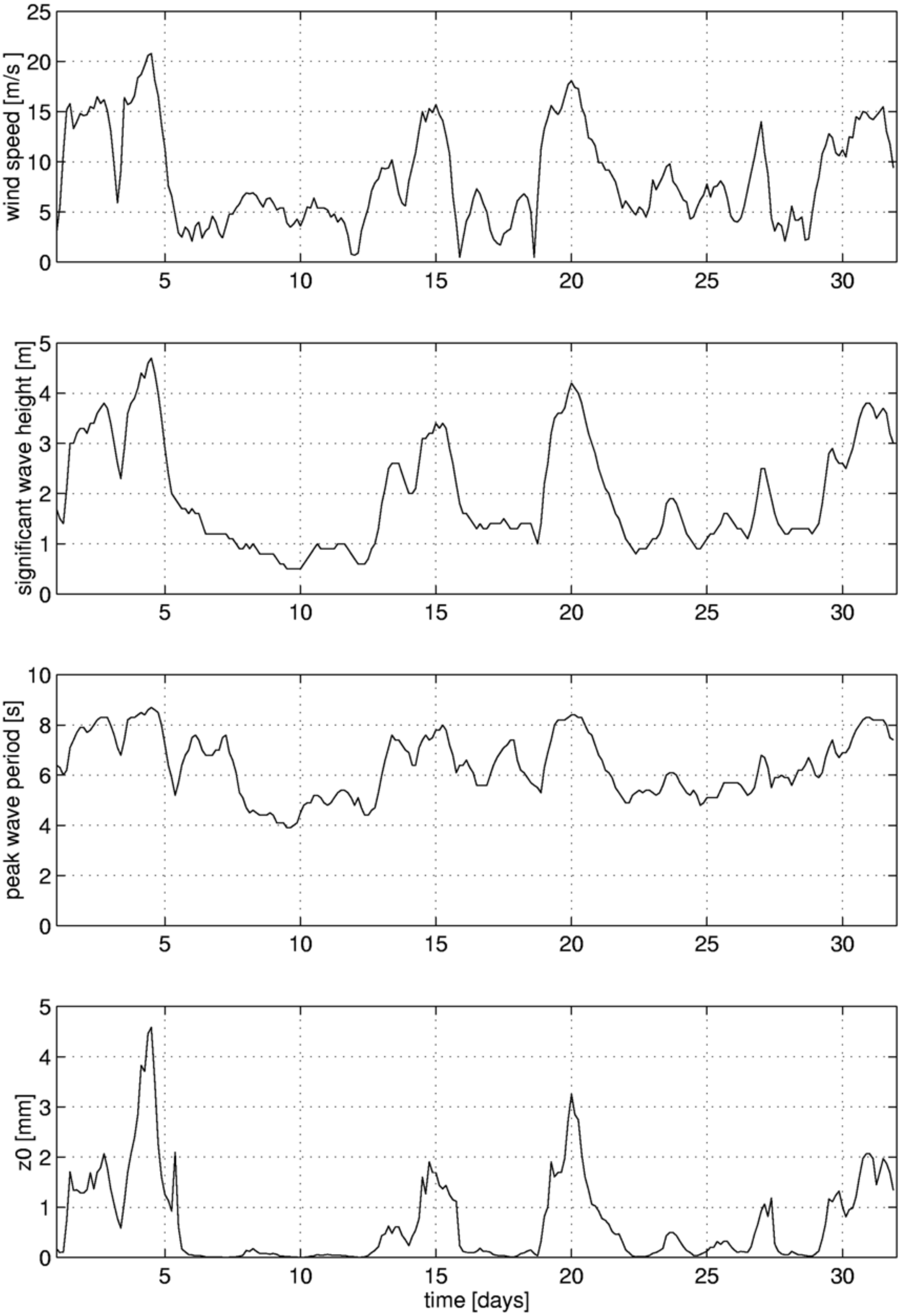


Figure 4.1 Bathymetry in European waters (as used in UKMO European Wave Model)

An example of some typical results are presented in Figure 4.2. These plots show simultaneous time series of wind speed (at a nominal height of 19.5m a.s.l.), wave height, wave period and z_0 for a North Sea location at 3-hourly intervals over a typical winter month. The results suggest that that for the bulk of the time, z_0 values are very small indicating the sea surface is aerodynamically very smooth.



However, there are relatively short periods, mostly corresponding to the high wind events, when the sea surface roughness increases significantly, in this case reaching a maximum value of $z_0 \approx 4.6$mm.

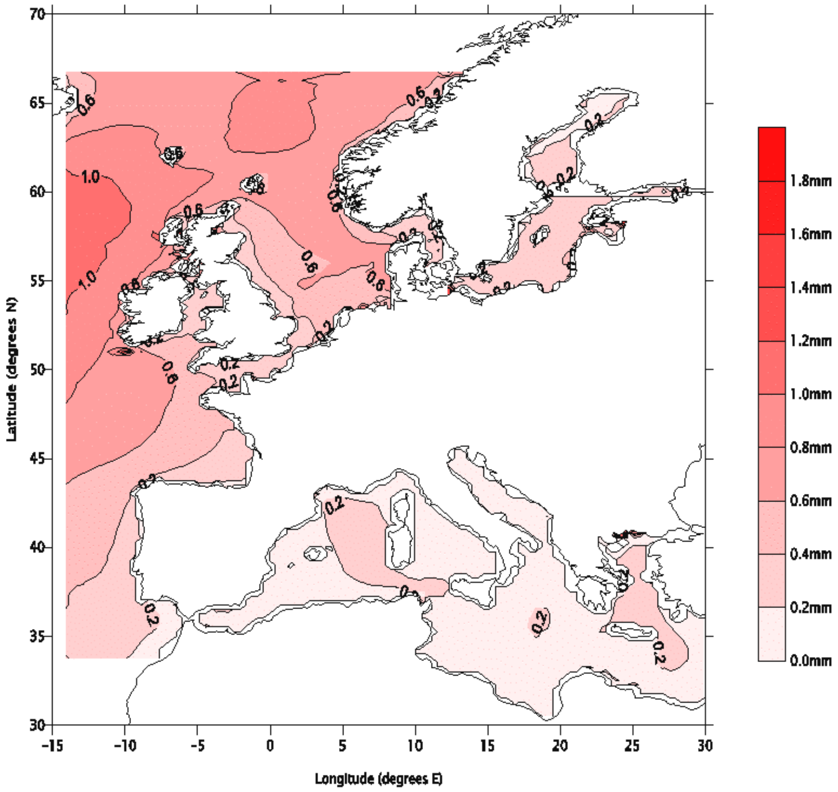
Figure 4.2 Plots showing simultaneous values of wind speed, wave height, wave period and z_0 at a North Sea location during a typical winter month

In order to get an indication of the distribution and overall variability of the sea surface roughness in European waters, the mean value of z_0, as well as its standard deviation, was calculated for each point in the UKMO grid over the period January 1987 to December 1996. The results are illustrated in Figures 4.3a and 4.3b. The overall pattern suggests that relatively high values of sea surface roughness (as well as variability) can be expected along the Atlantic Margin and into the North Sea, with relatively low (and less variable) values of sea surface roughness in the Baltic and Mediterranean Seas. There are also some indications that the values and variability of sea surface roughness are elevated in shallow waters, such as the Dogger Bank (off eastern England) and the shoal waters along the Dutch, German and Danish North Sea coasts. From this, it can be implied that the variability in sea surface roughness is likely to be more of an issue in these areas than elsewhere.

The annual variation in sea surface roughness was investigated by calculating the mean value and standard deviation of z_0 during each quarter of the year over the period 1987 to 1996. The results are presented in Figures 4.4 and 4.5.

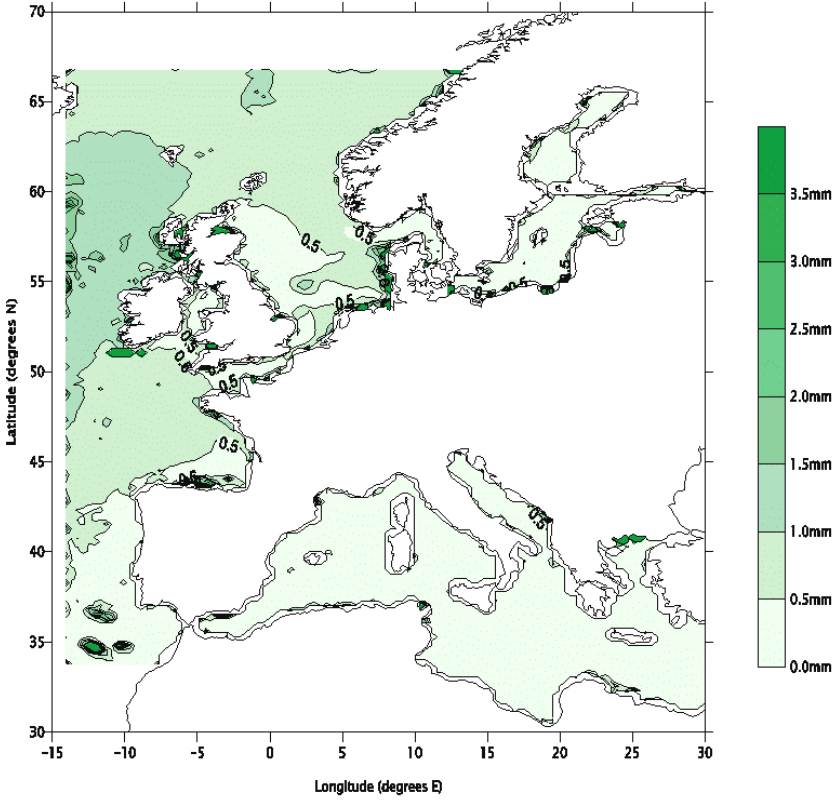
The final component of this task was to assess the impact of variable sea surface roughness on the POWER offshore wind resource predictions. In POWER, offshore wind resource predictions have been performed using the WAsP model. The version of WAsP applied uses a very simple approach to roughness modelling, assuming a constant sea surface roughness of z_0=0.2mm for all sea areas, wind conditions and sea states. Recent modelling studies at Risø and NEG Micon A/S [*Frank et al.*, 2000] [*Lange et al.*, 2000] indicate that these roughness models result in relatively small differences in predicted wind speeds (less than 0.5%). In addition, Barthelmie [2002] has investigated the effect of varying roughness by predicting a range of wind speeds at 50m height, based on 10m wind speeds and using logarithmic wind speed profiles and a range of different roughness between z_0=0.02mm and z_0=30mm (for more details see Chapter 5, Section 5.2.3). Her results indicate a maximum of only 2.8% difference in log-predicted wind speed at 50m from a 25ms^{-1} wind speed at 10m height. This implies that the z_0 values predicted here would result in only small differences in predicted mean wind speeds compared to the existing WAsP predictions. Furthermore, [*Frank et al.*, 2000] suggests that thermal stratification/stability issues have a much greater impact on offshore wind resources than changes in sea surface roughness. Finally, the tidal range at a site may also impact on the wind speed predictions, particularly as in some areas large expanses of rough foreshore may be exposed at low water. It should be remembered that some parts of the POWER project area are subject to large tidal ranges and so this could be a significant effect. Although a preliminary attempt at quantifying the impact of varying water levels on turbine hub level wind speeds has been made, more work is needed on this issue. This is beyond the scope of this project.

Therefore, although it is clear that variable sea surface roughness will modify wind speed predictions slightly, the impact of other contributory factors are expected to dominate. In view of all these findings (and the amount of additional time and effort it would entail for very little improvement in accuracy), it was decided that it is *not* appropriate to apply correction factors to the WAsP model estimates to take account of variations in sea surface roughness.



Mean value of sea surface (aerodynamic) roughness - 1987 to 1996

(a)



Standard deviation in sea surface (aerodynamic) roughness - 1987 to 1996

(b)

Figure 4.4 Distributions of mean value of sea surface roughness, z_0, and its standard deviation – 1987 to 1996

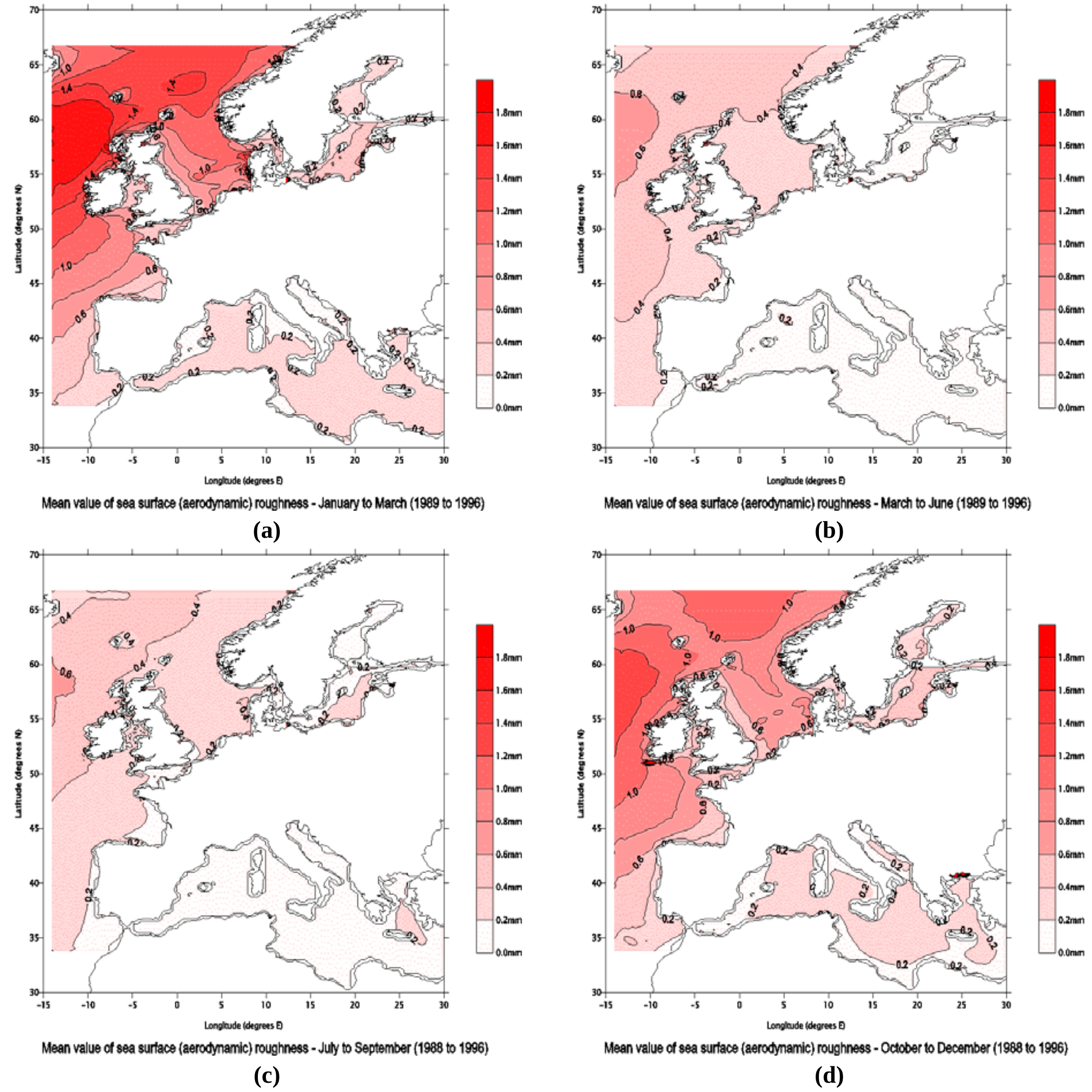
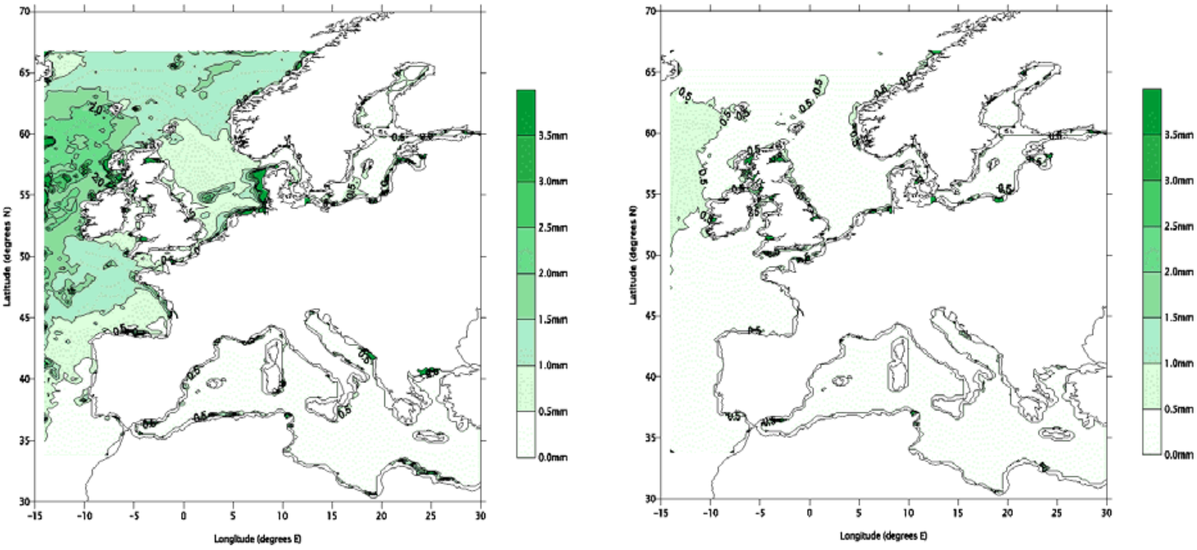


Figure 4.4 Quarterly distributions of mean value of sea surface roughness, z_0, – 1988 to 1996

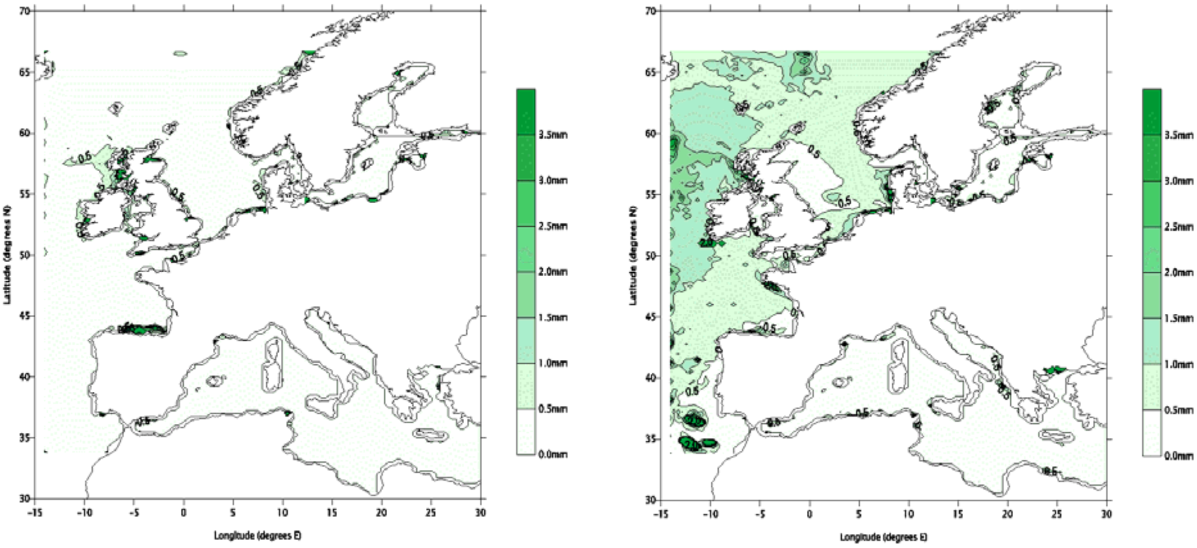


Standard deviation in sea surface (aerodynamic) roughness - January to March (1989 to 1996)

(a)

Standard deviation in sea surface (aerodynamic) roughness - March to June (1989 to 1996)

(b)



Standard deviation in sea surface (aerodynamic) roughness - July to September (1988 to 1996)

(c)

Standard deviation in sea surface (aerodynamic) roughness - October to December (1988 to 1996)

(d)

Figure 4.5 **Quarterly distributions of standard deviation of sea surface roughness, z_0, – 1988 to 1996**

4.6 WAsP results

A small selection of the results from the WAsP runs performed are presented here to give an overview of the findings of this section of the project. Full results are presented in the POWERtool (see Chapter 12), although it should be noted that some WAsP output parameters were included since the project team did not consider certain operations within WAsP to be statistically valid for small input data sample sizes involved.

Figure 4.6 presents a map showing the distribution of mean wind speeds for the period 1985-1997 at 50m above mean sea level throughout the POWER project area. The results indicate that the highest wind speeds are found in along the Atlantic margin, the North Sea and Baltic regions with mean annual wind speeds at 50m above sea level in excess of 8.0ms-1 throughout these areas. The highest wind speeds are experienced north and west of Scotland, where mean annual wind speeds greater than 10.5 ms^{-1} are expected. An interesting feature is evident in the North Sea, where a finger of relatively high wind speeds extends into the basin from the north. By contrast, the most of Mediterranean basin is less windy, with extensive regions experiencing mean annual wind speeds of less than $6ms^{-1}$. However, good wind speeds are to be found in parts of the Aegean.

Although there are some slight discrepancies present, overall these results broadly compare with earlier offshore wind resource estimates [Moore, 1982] and [Risø National Laboratory, 1989].

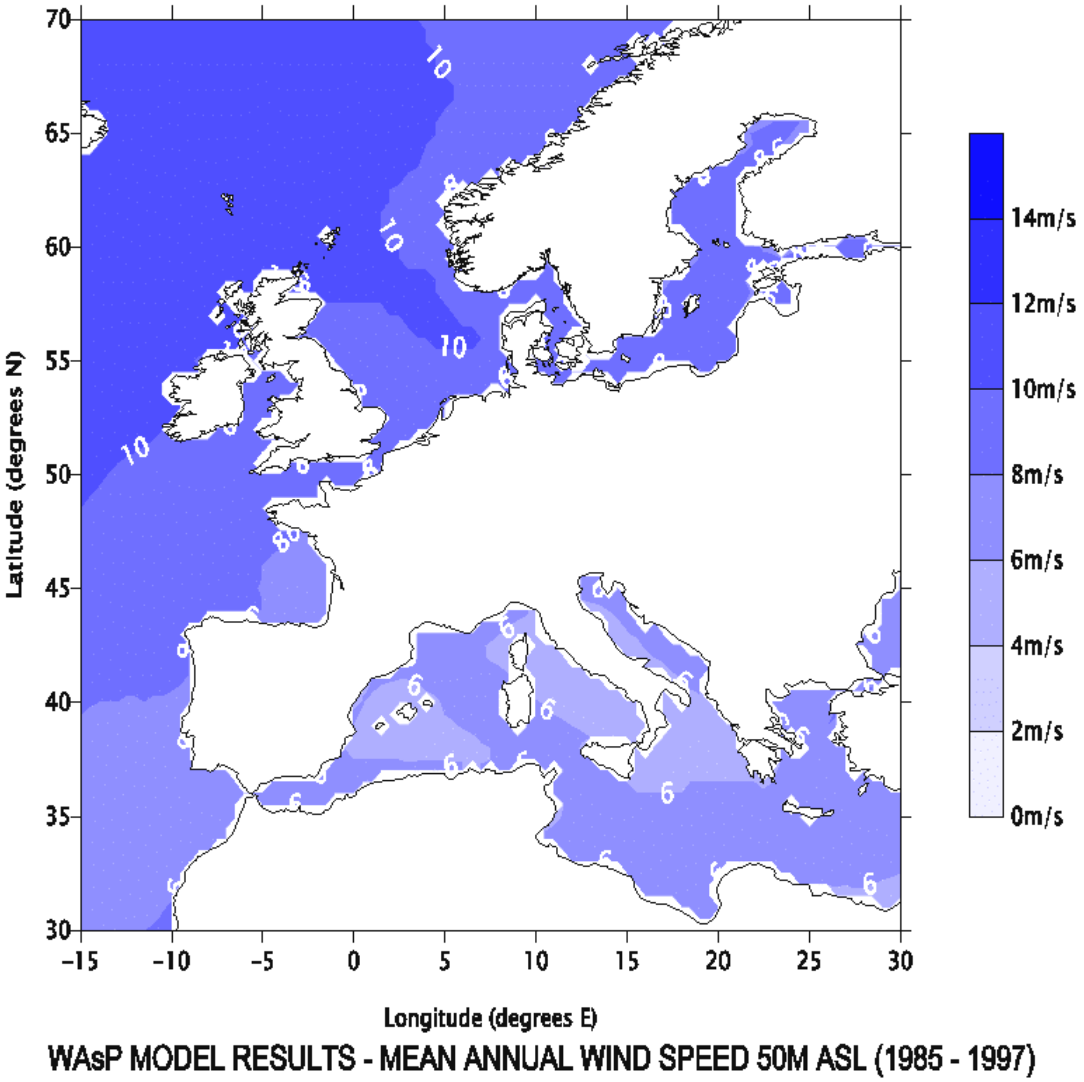


Figure 4.6 Plot showing the distribution of mean annual wind speeds at 50m a.s.l. throughout EU waters

Figures 4.7 to 4.18 illustrate WAsP results showing mean monthly wind speeds at 50m above sea level through the year. The result demonstrate the degree of variability in the offshore wind resource through the year, with significant variations of up to ±25% in mean monthly wind speeds compared to the mean annual values in some areas.

In northern Europe, the windiest month is predicted to be January, with mean wind speeds of over $14ms^{-1}$ shown west of Scotland and wind speeds in excess of $12ms^{-1}$ predicted throughout the North Sea basin. The WAsP results indicate that the least windy month in northern Europe is likely to be July with mean monthly wind speeds of no more than $8ms^{-1}$ predicted in all but a few areas. On this basis, offshore wind farms are likely to generate the largest amounts of power during the windy winter months, but their power output will probably drop in the relatively calm summer months. Happily, this pattern mirrors closely the demand for power by end users in northern Europe.

By contrast, the mean monthly wind distribution patterns in southern Europe are more complex. The WAsP results show parts of the eastern Mediterranean and the Aegean indicate experience relatively high wind speeds in excess of $8ms^{-1}$ in mid-summer.

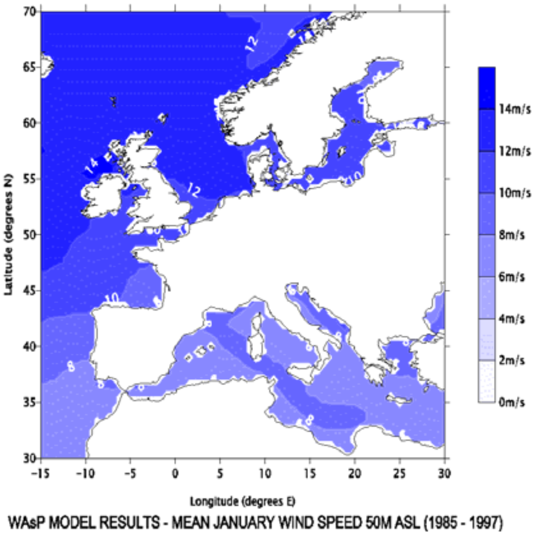


Figure 4.7 Mean January wind speeds at 50m a.s.l.

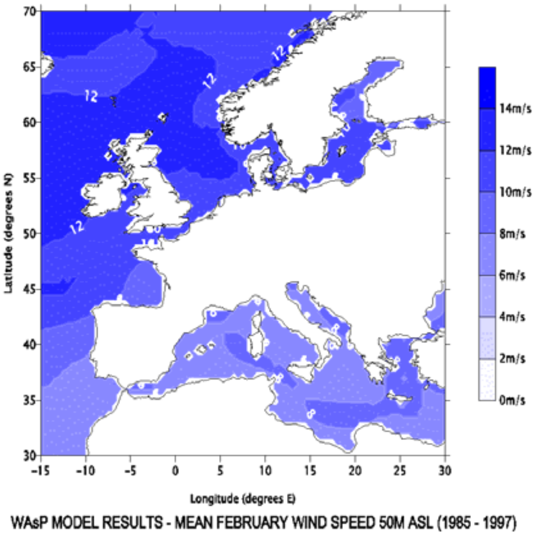


Figure 4.8 Mean February wind speeds at 50m

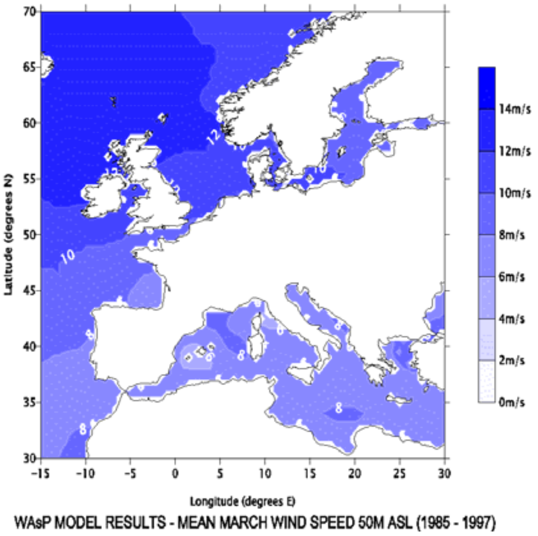


Figure 4.9 Mean March wind speeds at 50m a.s.l.

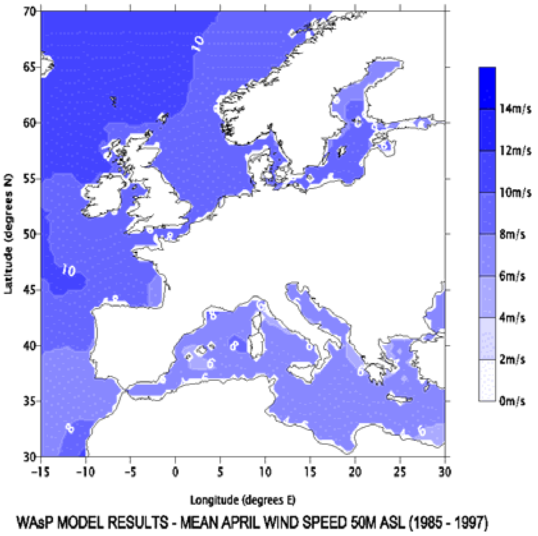


Figure 4.10 Mean April wind speeds at 50m a.s.l.

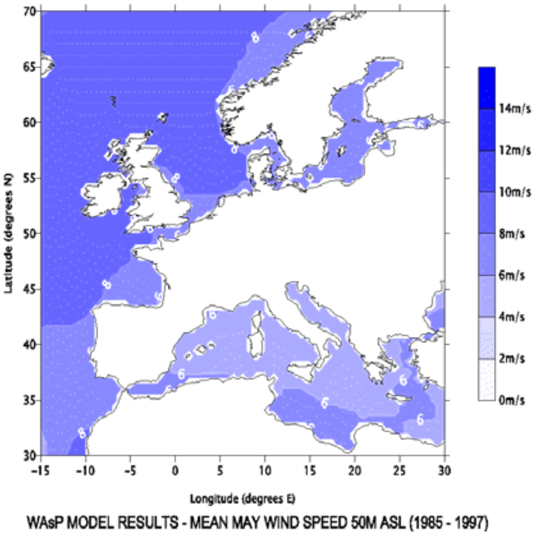


Figure 4.11 Mean May wind speeds at 50m a.s.l.

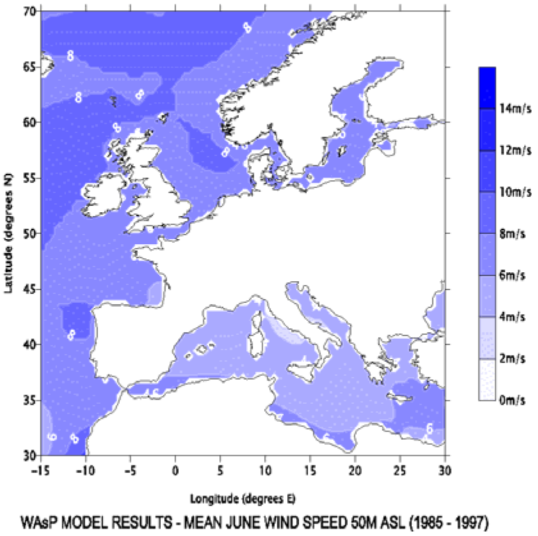


Figure 4.12 Mean June wind speeds at 50m a.s.l.

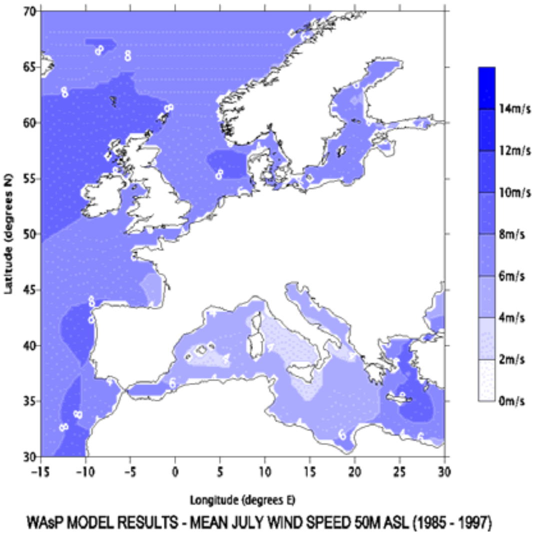


Figure 4.13 Mean July wind speeds at 50m a.s.l.

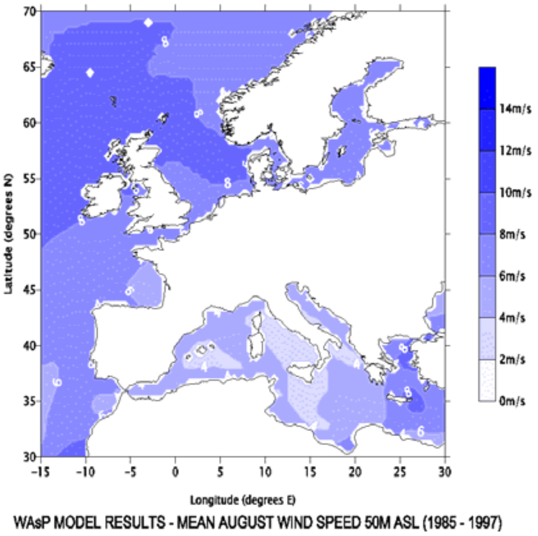


Figure 4.14 Mean August wind speeds at 50m a.s.l.

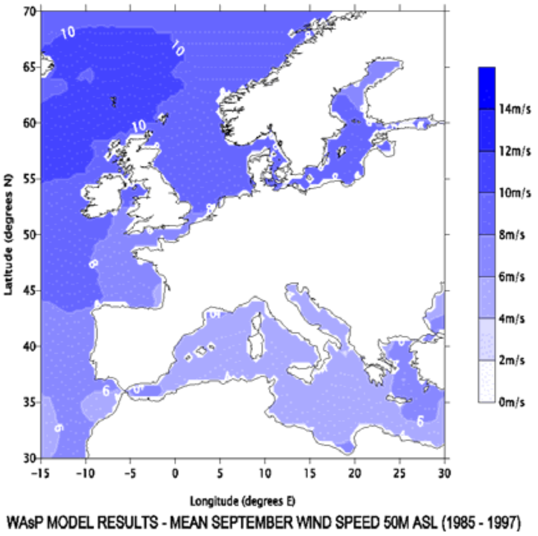


Figure 4.15 Mean September wind speeds at 50m a.s.l.

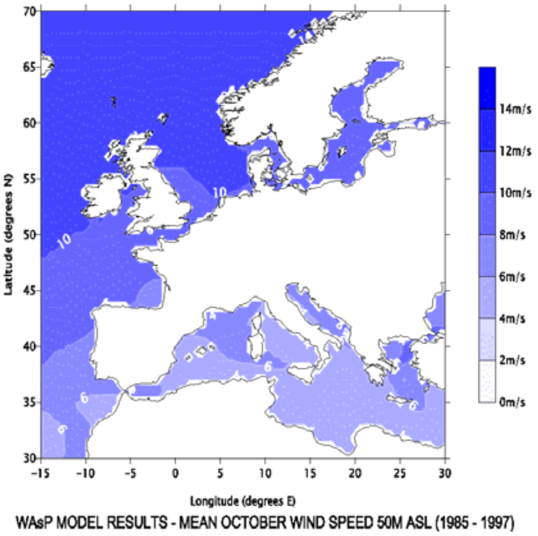


Figure 4.16 Mean October wind speeds at 50m a.s.l

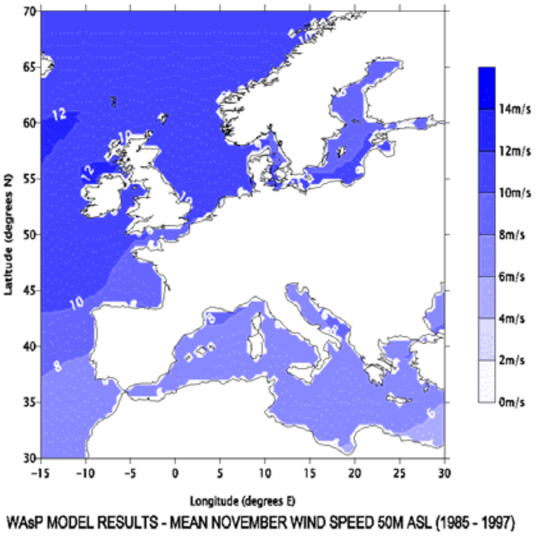


Figure 4.17 Mean November wind speeds at 50m a.s.l.

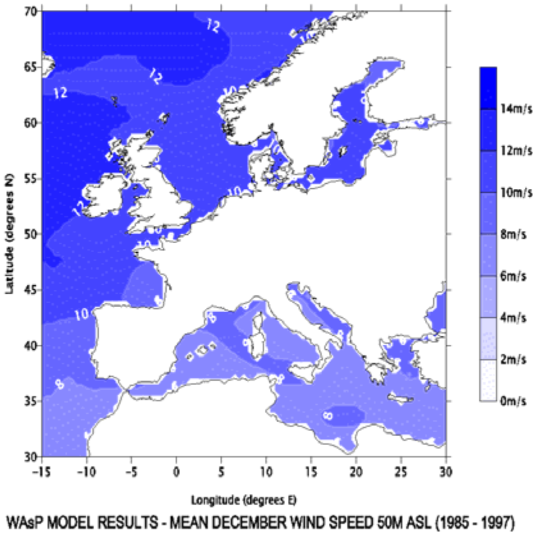


Figure 4.18 Mean December wind speeds at 50m a.s.l.

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