Extremes of near-surface wind speed over Europe and their future changes as estimated from an ensemble of RCM simulations

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Abstract

In this study, we analyse the uncertainty of the effect of enhanced greenhouse gas conditions on windiness projected by an ensemble of regional model simulations driven by the same global control and climate change simulations. These global conditions, representative for 1961-1990 and 2071-2100, were prepared by the Hadley Centre based on the IPCC SRES/A2 scenario. The basic data sets consist of simulated daily maximum and daily mean wind speed fields (over land) from the PRUDENCE data archive at the Danish Meteorological Institute. The main focus is on the results from the standard 50km-resolution runs of eight regional models.

The best parameter for determining possible future changes in extreme wind speeds and possible change in the number of storm events is maximum daily wind speed. It turned out during this study that the method for calculating maximum daily wind speed differs among the regional models. A comparison of simulated winds with observations for the control period shows that models without gust parameterisation are not able to realistically capture high wind speeds. The two models with gust parametrization estimate an increase of up to 20% of the number of storm peak (defined as gusts ≥ 8 Bft in this paper) events over Central Europe in the future.

In order to use a larger ensemble of models than just the two with gust parameterisation, we also look at the 99th percentile of daily mean wind speed. We divide Europe into eight sub-regions (e.g. British Isles, Iberian Peninsula, NE Europe) and investigate the inter-monthly variation of wind over these regions as well as differences between today's climate and a possible future climate. Results show differences and similarities between the sub-regions in magnitude, spread, and seasonal tendencies. The model ensemble indicates a possible increase in future mean daily wind speed during winter months, and a decrease during autumn in areas influenced by North Atlantic extra-tropical cyclones.

1. Introduction

Climate models can be applied to simulate the future climate associated with emission scenarios as provided by the Intergovernmental Panel on Climate Change (IPCC, 2001). Regional aspects of these climate scenarios can be simulated by regional climate models (RCMs). They provide a higher resolution in space as well as in time and can be used for more detailed studies not only on mean conditions but also on extremes and changes in extremes (Beniston et al., 2006). Estimates of future climate from RCM simulations are affected by several kinds of uncertainties including, e.g., the specification of emission scenarios, land use changes, boundary conditions from global climate models, and RCM model formulation. The spread in different climate realisations can be used to assess the uncertainty in climate change projections and to express future developments in terms of a probability of the occurrence of certain events. Such ensembles of realisations can be constructed by, e.g., using different simulations from the same RCM (e.g. Giorgi and Francisco, 2000) or by driving different models with the same boundary conditions (e.g. Crossley et al., 2000).

Both approaches were taken into account in the project „*P*rediction of *R*egional scenarios and *U*ncertainties for *D*efining *E*uropea*N* *C*limate change risks and *E*ffects“ (PRUDENCE, Christensen et al., 2006), funded by the European Commission. However, the main emphasis in our study is on driving several different RCMs with boundary conditions from the same global model.

This paper contributed to PRUDENCE with an investigation on the quantity “wind”. More precisely, this study focuses on extremes of near-surface wind speed over European land areas. Two parameters are examined in particular: maximum daily near-surface wind speed and the 99th percentile of mean daily wind speed.

To date, only a few studies on future changes of wind speed have been performed based on RCM simulations over Europe. The most recent one is by Pryor et al. (2005a) who investigated the potential impact of climate change on wind energy. The basis of their study are simulations performed with the Rossby Centre coupled Regional Climate Model (RCAO) using boundary conditions from the ECHAM4/OPYC3 global atmosphere ocean model and the HadAM3H global atmosphere model for two climate scenarios (SRES/A2 and B2). They found that the differences between the different RCAO present-day simulations and the NCAR/NCEP reanalysis data are of similar magnitude as the future changes. Räisänen et al. (2003) found that large differences due to different boundary conditions are also reflected in the maximum daily wind speed.

In their study on the relationship between cyclones and extreme wind, Leckebusch and Ulbrich (2004) found that the future change in track density of cyclones is supported by related changes in daily maximum wind speed patterns. Pryor et al. (2005b) used an empirical downscaling method to determine the wind speed for a number of measurement stations from relative vorticity in 500 hPa and the mean sea level gradient given by ECHAM/OPYC3 global simulations. They found a high degree of agreement between the empirically downscaled station wind speeds and those calculated by the regional climate model RCAO. However, in contrast to the results from empirical downscaling, future changes in the RCAO simulations show evidence for a small increase in annual energy source. For a more general overview of wind storms and its impacts we refer to the PSICC overview article by Beniston et al. (2006).

2. Models and Data

The data used in this study were produced in the international project PRUDENCE from simulations with eight different RCMs (Table 1). Each model provided data on a horizontal grid of approximately 50 km resolution from two 30-year simulations: a control run under present-day climate conditions for the time period 1961-1990 and a simulation under conditions projected for the period 2071-2100. Boundary conditions for these regional experiments were taken from climate simulations carried out with the Hadley Centre global atmosphere model HadAM3H (Pope et al., 2000), which was forced by the IPCC emission scenario SRES-A2 (Nakicenovic et al., 2000). Sea surface temperature and sea ice conditions were prescribed by observations (Rayner et al., 2000) during the control period while, for the scenario, the mean change simulated by HadCM3 (the Hadley Centre global coupled atmosphere ocean model) for 2071-2100 was added onto the control data set. HadAM3H output is given 6-hourly on a grid mesh of 1.875°x1.25° resolution. However, due to the large data amount, only every second grid point value was distributed among the partners performing RCM simulations; the effective grid resolution is therefore 3.75° x 2.5°.

The same parameters were extracted from each of the RCM simulations and stored in the joint archive at the Danish Meteorological Institute. More details on model simulations and experimental designs are given by Déqué et al. (2006) and Jacob et al. (2006) in this special issue.

In the following, we will not distinguish between the individual models except where it is essential. The main intention of PRUDENCE and the study presented here is not an inter-comparison of regional climate models. Instead, the major point of interest is the spread in the results from the eight different RCMs, which will be interpreted to assess the uncertainty of regional climate predictions of near-surface wind speed. Only the inter-model uncertainty is addressed. Uncertainties due to emission scenarios and boundary conditions have recently been explored by, e.g., Räisänen et al. (2003) and Déqué et al. (2006).

The main focus of this study is on the change of daily mean and maximum near-surface wind speed. When analysing storm events, we use the Beaufort scale (Bft) which is a measure often used to categorise observed wind strength. 8 Bft (gale) and 10 Bft (storm) correspond to wind speeds in the range of 17.2ms^{-1} - 20.7ms^{-1} and 24.5ms^{-1} - 28.4ms^{-1}, respectively. It turned out that maximum daily wind speed, $u_{\max}$, was not uniformly defined across the models. In the first of three different definitions, $u_{\max}$ was calculated from three-hourly, instantaneous 10-metre wind fields:

$$u_{\max} = \max(u_{00}^{10m}, u_{03}^{10m}, u_{06}^{10m}, \cdots, u_{21}^{10m}) \qquad (1)$$

The second type of determining $u_{\max}$ uses the maximum of the values from all time steps t_i within each day:

$$u_{\max} = \max(u_{t_1}^{10m}, u_{t_2}^{10m}, u_{t_3}^{10m}, \cdots, u_{t_n}^{10m}) \qquad (2)$$

where the time step interval, t_{i+1}- t_i ,varies from 3 to 36 minutes between the models.

For the third type, $u_{\max}$ is computed from the wind in the lowest model level for each time step. In addition, these values are multiplied by a gustiness factor f (Grachev et al., 1998) accounting for turbulence-induced near-surface gusts:

$$u_{\max} = \max(\, f(c_{t_1})u_{t_1}^{k},\, f(c_{t_2})u_{t_2}^{k},\, f(c_{t_3})u_{t_3}^{k}, \cdots\ f(c_{t_n})u_{t_n}^{k}) \qquad (3a)$$

where c is the transfer coefficient for momentum, k is the lowest model level and $f(c)$ is an empirical function of c defined as

$$f(c_{t_i}) = 1 + 7.2c_{t_i} \qquad (3b)$$

(Schrodin, 1995). f was derived for land areas; results over ocean must therefore be treated with caution.

Definitions 1 and 2 are based on 10-metre wind, which is a diagnostic variable calculated from the prognostic atmospheric wind field on model levels. For definition 3, the prognostic wind on the lowest model level is used. Differences between wind maxima computed using definitions 1 and 2 are negligible compared to the difference to wind maxima of type 3 (not shown here). In the following, we will therefore distinguish only between two groups of models: those calculating u_{max} with gust parameterisation (two models, CHRM and CLM) and those calculating u_{max} using definition 1 or 2 (six models).

In the following section, we also analyse mean daily wind speed which was calculated according to Equations 1 and 2 using "mean" as operator instead of "max". The mean wind does not include any gusts.

3. Analysis of RCM ensemble wind speeds

3.1 Daily maximum wind speed

Whether a gust parameterisation is applied to the near-surface wind or not makes a substantial difference in its strength and thus in the frequency of occurrence of strong wind events. Calculating the maximum daily wind speed by equations 1 or 2 (see top left panel of Figure 1) does not yield any days with strong winds (8 Bft and above) inland, and the number of storms of 10 Bft and above (bottom of Figure 1) also drops to zero in coastal regions. This is unrealistic since storms with 8 Bft and above can actually be observed (Schiesser et al., 1997). In contrast, if gust parameterisations are applied, the model simulations (Figure 1, right) produce a number of events over Central-Europe, between 800 and 1500 inland and twice as much in coastal regions in 30 years, averaging to about 30 events per year inland.

We found two studies on observed maximum wind speeds in the present literature covering the entire control simulation period 1961-90 of the RCM ensemble. Lefebvre (2001) published observations of gust peaks measured at two stations of the German Weather Service, both located at the German coast of the North Sea: Bremerhaven and List on the island of Sylt west of the Danish-German border. Brázdil and Dobrovolny (2001) compiled measurements from several stations in the Czech Republic. We compared data from both studies with those from the ensemble of model simulations produced in the PRUDENCE project (Figures 2 and 3).

Observations at Bremerhaven (Figure 2, left) give a minimum of 30, a maximum of 80 and a mean of 55 events per year with wind speeds ≥ 8 Bft, while the number of observed storm peaks at List is twice as high. Compared to the observations, the number of strong wind events for the two models with gust parameterisation are shifted towards higher values at Bremerhaven. The opposite is true at List where the two models simulated a frequency of storm peak events almost in the same order of magnitude as for Bremerhaven, and thus underestimate the observed storm peaks. The number of peak values from models without gust parameterisation are mostly less than 10. List on the island of Sylt is strongly influenced by the westerly winds from the North Sea whereas Bremerhaven lies in a bight at the mouth of the river Weser and is thus not exposed to North Sea winds as much. This is reflected in the large differences seen in the observations. The models, on the other side, treat both locations as land-only grid boxes since they don't support fractional land-sea masks. This results in an underestimation of wind speeds for List.

Comparisons with measurement stations in the Czech Republic are shown in Figure 3 where results from models without gust parameterisation are not shown since these models do not exhibit any events during the thirty years with values of at least 8 Bft (see Figure 1). The five measurement sites are Brno Airport (1), Cheb (2), Hradec Kralove (3), Mt. Milesovka (4), and Prague Airport (5). Compared to the observations, the peak gusts from the CHRM model are shifted towards lower values at all measurement stations. The same is true for the CLM results, although to a lesser extent . There are two exceptions: at Cheb, the number of storm peak events from the CLM simulations are slightly higher than measured, and at Hradec Kralove, the average number of events in the CLM simulations are comparable to those measured, though the distribution is broader in the observations.

Large differences occur at Mt. Milesovka. This station is located in the mountains where it is more exposed to extreme winds than the other stations. The observed number of gusts is about three times higher than at the other measurement sites. Mt. Milesovka belongs to the Erz Mountains, which is a steep mountain range at the border of the Czech Republic, only a few kilometres wide . The models do not capture these very local characteristics due to the smoother orography of the 50-km grid mesh.

In the right panel of Figure 3, the results from control and scenario simulations are plotted side by side for each station. It can be seen that the mean number of strong wind events in the future climate increases by about 2-5 events per year as compared to the control period. The widths of the distributions change only slightly. The statistical significance of these changes in model-simulated storm events due to wind gusts exceeds 90% in this region.

The change in total number of storm peak events over Europe from 1961-1990 to 2071-2100 for the two models with gust parameterisation is shown in Figure 4. Both models simulate an increase in the number of events over land areas in Western, Central and Eastern Europe. A decrease is modelled in the other parts of Europe, which are mostly over the ocean. However, the gust parameterisation is derived for land areas, thus results over the ocean are questionable and should not be considered in the interpretation of the results. CHRM seems to give a larger change in percent than CLM. As shown before in this section, absolute values in control and scenario simulations with CLM are generally higher than those with CHRM, whereas the absolute changes are similar in both models. This certainly affects the values in Figure 4, which are given in percent.

3.2 99th percentile of daily mean wind speed

Daily maximum wind speed is the appropriate parameter to assess future changes in near-surface wind speed extremes from the eight RCMs. However, as discussed earlier, the calculation of $u_{\max}$ is not the same in all RCMs. Unfortunately, this was only realised after the model simulations had finished, and a recalculation of the maximum daily wind speed from the output fields is not possible. To still obtain an assessment of future changes in extreme wind based on a consistent treatment of wind speed in all models (which was one of the purposes of PRUDENCE), we therefore analysed the 99th percentiles of daily mean wind speed. We cannot get the absolute values for change in maximum wind from daily mean wind speed. However we can assess whether the wind speed will increase or decrease in future and whether this shows up in the majority of the models considering statistical significance tests. This approach can be justified e.g. by Räisänen et al.

(2003) who found in their study with the Swedish regional climate model RCA that the changes in maximum wind speed tend to follow those of the mean wind speed.

In order to assess the statistical significance of the simulated future changes in wind speed, we applied Student's t test separately to the eight regional model outputs, for each month separately and based on the 90% significance level. Since we use daily data for 30-year periods, each sample consists of 900 values (30 years x 30 days) for each month both for the control and the scenario simulation. The results are summarized in Table 2 for each of the eight sub-domains shown in Figure 5. 60% of the cells in Table 2 are empty indicating cases where there is no clear tendency towards significant or non-significant results. The strongest agreement between the models is found in November, which is also the month with the largest number of significant results. June and August exhibit no clear tendency for any of the eight areas, except for the British Isles in August. In areas that are mostly affected by low pressure systems from the Atlantic (British Isles and Central-Europe), the RCMs give the most similar results (for seven and eight months, respectively).

Quantitative values of the 99th percentile of regionally averaged near-surface mean daily wind speed and its possible future changes for each region are shown in Figure 6. There are two box plot diagrams for each sub-domain: one shows the absolute values of the 99th percentile of wind speed for the present-day climate simulations, the other one shows the difference between the future scenario and the present-day simulations. The significance results from Table 2 are indicated in the appropriate column just above the horizontal axis. Each box plot contains the results from each of the eight models, i.e. a box plot includes 8 values.

The British Isles (sub-domain 1) is the region with the highest simulated wind speeds. The 99th percentile follows a broad distribution with short tails for the months October, January, February and March. The simulations show an increase in wind speed in the future scenario for winter months, whereas velocities decrease in late summer and early fall. This decrease is significantly different from zero at the 90% significance level in the majority of the models, but the increase is only significant in February. The spread in the results between the RCMs is not homogeneous throughout the year. In March, July, November and December, the RCMs produce similar results. The largest spread occurs in April, June and August.

Over the Iberian Peninsula (sub-domain 2), the results of the control runs show a large inter-model spread throughout the year. The difference between the model with the lowest values and the one with the highest values exceeds 5 ms^{-1} in most of the months. 50% of the models fall in a fairly constant range of 2 ms^{-1} throughout the year. The annual cycle (high wind speeds in winter, low wind speeds in summer) is not as pronounced as for sub-domains 1, 3, 4 and 5. Most models show a small increase of wind speed in spring and mid-summer (July) and a small decrease in autumn and winter. For July (increase) and November (decrease), the results from most RCMs are statistically significant.

The annual variation over France (sub-domain 3) in the control simulations is similar to that over the British Isles. However, the absolute values for the velocities are about 2 ms^{-1} lower and the distributions of the model results for each month are narrower. Statistically significant changes are found for January, February and November. For January, all models show a slight increase in wind speed, while for February and November, results of the RCMs scatter around zero. Thus, no definite statement can be made concerning an increase or a decrease.

Over Central Europe (sub-domain 4), the annual cycle of strong winds in the control simulations is similar to that of sub-domain 3. The longer tail in the distributions towards higher wind speed is even more dominant over Central Europe. The differences between the model with the lowest and that with the highest values reach up to 4 ms^{-1}. This is the region where results are statistically significant for most of the months, indicating a significant increase in wind speed in January/February and a significant decrease in March/April.

Over NE Europe (sub-domain 5), the control distributions of the 99th percentile of daily mean wind speed are similar for each month. In the scenario, all models show a clear increase in February and a decrease in March, April and September (except fore one outlier). However, only the decrease in September is statistically significant.

Large variations in present-day wind velocities are found among the different model results over the Alps (sub-domain 6). This is most likely due to the different treatment of mountain areas in the models. However, this does not necessarily influence the future changes which do not show larger variations between the models than in the other sub-domains. For February, August, October and November, all models show a decrease (except for one outlier in November), but changes are statistically significant only in November.

For the Mediterranean (sub-domain 7), the RCMs vary strongly with respect to high wind velocity in the control simulations. Over most of the year, the model results do not give a clear signal of an increase or a decrease in the future climate projections. Only in December and January do all models show a decrease, which is not significant from the statistical point of view.

Over Eastern Europe (sub-domain 8), most of the RCMs show an increase of wind speed for the scenario run in winter and in July. Only the result for January is statistically significant.

4. Conclusions

The main objective of this study was to assess the possible future change in extreme near-surface wind speeds over European land areas from an ensemble of eight regional climate model simulations. This study shows that an ensemble of models is essential in assessing the future change in extreme wind speeds: only in a few regions and for a few months did all models even agree on the sign of the change.

It turned out that a detailed assessment of uncertainties in the provided maximum daily wind speed as well as in the derived number of storm peak events for both present-day climate and future scenarios was not feasible since only two models with a diagnostic gust parameterisation were able to produce high enough wind speeds. The other six models were hardly able to simulate any wind velocities above 8 Bft, i.e. storms, over land areas during the two 30-year periods. This is not due to any physical or numerical shortcomings in these models in comparison to the other two models, but simply due to the absence of a diagnostic parameterisation for gusts. As a consequence for future studies on maximum wind speeds, it is essential to introduce parameterisations allowing the determination of more realistic near-surface winds. One possibility is the use of a gust parameterisation, either derived empirically as presently applied in the CHRM and CLM models, or based on a more physical approach as described by Brasseur (2001) and Goyette et al. (2003).

Even though it is not possible to determine storm events from maximum daily wind speeds for all models, an assessment of the possible future change in daily mean wind is feasible. We analysed the extreme values of daily mean wind speed, nameley the 99th percentile, in eight different European sub-regions and tested the changes between the scenario and control periods for their statistical significance.

Regions that are strongly influenced by the North Atlantic extra-tropical cyclones show more significant results than other regions. However, the months where significant results occur vary between the regions. Overall, we found a future increase of wind speed in winter and a decrease in autumn. Most changes fall into a range of about 1% to 5%, which seems to be small, but one has to take into account that the degree of wind-induced damage increases exponentially with increasing velocity (Dorland et al., 1999) and that wind power is the cube of wind speed. Other studies, e.g. on change of pressure anomaly (Zwiers and Kharin, 1998) and cyclone track density (Leckebusch and Ulbrich, 2004), also deduce an increase in wind speeds over regions influenced by North Atlantic cyclones. Simulations for areas influenced by the Mediterranean show a different behaviour. Here we can see an increase for the most of spring and a decrease or ambiguous tendency during the rest of the year. Over the Mediterranean and the Alps, the spread between the models even in the present-day climate simulations is much larger than in the other sub-domains.

The results of this study already have an impact on the design of the RCM simulations in the EU project ENSEMBLES. Model groups are encouraged to include or switch on a gustiness parameterisation in their models. Follow-up studies on the basis of ENSEMBLES data sets will thus include a larger ensemble of models with gust parameterisations. Boundary forcings from additional GCMs and RCM simulations using finer grid mesh sizes will be available.

Therefore, it will be possible to study the dependency of the results on driving fields and resolution. It has been shown by Räisänen et al. (2003) that different boundary conditions have a strong impact on RCM-simulated wind speed and extremes of wind speed. The impact of different gust parameterisations in RCM long-term simulations is also a point that should be addressed in future investigations.

It should also be noted that, besides the dynamical downscaling using RCMs, other methods for downscaling wind speed are available as well. For example, Pryor et al. (2005b) describe a statistical downscaling method based on relative vorticity and mean sea level pressure from a global climate model. They found a high agreement between the results from their method and those from the Rossby Centre regional climate model. De Rooy and Kok (2004) propose a combination of statistical and dynamical downscaling. They found that statistical downscaling gives good results for locations where observations are available and where local peculiarities can therefore be included. However, their results also show that physical, or dynamical, downscaling is necessary where observations are sparse.

The major outcome from this study for impact studies is that the RCM simulations analysed support results from other studies that found an increase in extreme wind speeds over Western and Central Europe. However, it could also be shown that the changes are not statistically significant for each month of the year.

Based on the same data set as used in this study, Woth et al. (2005) and Woth (2005) evaluated wind and pressure data with respect to future storm surge statistics along the North Sea coast and found changing storm surge characteristics such as an increase in the amplitude, the frequency and the average duration of storm surge heights, locally outside the range of natural variations. For this kind of studies, it is essential to have access to an ensemble of long-term and high-resolution simulations as provided for the first time in the PRUDENCE project. For additional information, we also refer to the overview on extremes by Beniston et al. (2006) in this special issue.

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References

Beniston, M., D. Stephenson, D., O.B.Christensen, C. Ferro, C. Frei, S. Goyette, K. Halsnaes, T. Holt, K. Jyllhä, B. Koffi, J. Palutikof, R. Schöll, T. Semmler, and K. Woth, : 2006, Future Extreme Events in European Climate: An Exploration of Regional Climate Projections, . Clim. Change, (submitted, this issue).

Brasseur, O.: 2001, Development and Application of a Physical Approach to Estimating Wind Gusts, *Mon. Weather Rev.*, **129**, 5-25.

Brázdil, R. and P. Dobrovolny: 2001, History of strong winds in the Czech lands: causes, fluctuations, impacts, *Geographica Polonica*, **74**, 11-27.

Castro, M., C. Fernández, M.A. Gaertner: 1993, Description of a mesoscale atmospheric numerical model, In Díaz JI, Lions JL (eds), Mathematics, Climate and Environment. Rech. Math. Appl. Ser. Mason, pp 230-253.

Christensen, J.H., O.B. Christensen, P. Lopez, E. van Meijgaard, and M. Botzet: 1996, The HIRHAM4 Regional Atmospheric Model, *Scientific Report 96-4*, DMI, Copenhagen, 51 pp.

Christensen, J.H., T.R. Carter, and M. Rummukainen: 2006, Evaluating the performance and utility of regional climate models: the PRUDENCE project. Clim. Change, (submitted, this issue).

Crossley, J.F., J. Polcher, P.M. Cox, N. Gedney, and S. Planton: 2000, Uncertainties linked to land-surface processes in climate change simulations, *Climate Dynamics*, **16**, 949-961.

Déqué, M, D.P. Rowell, D. Lüthi, F. Giorgi, J.H. Christensen, B. Rockel, D. Jacob, E. Kjellström, M. de Castro, and B. van den Hurk: 2006, An intercomparison of regional climate simulations for Europe: assessing uncertainties in model projections, Clim. Change, (submitted, this issue).

De Rooy, W.C., and K. Kok: 2004, A combined physical-statistical approach for the downscaling of model wind speeds, *Weather Forecast*, **19**, 485-495.

Dorland, C., R.S.J. Tol, and J. Palutikof: 1999, Vulnerability of the Netherlands and Northwest Europe to storm damage under climate change, *Climate Change*, **43**, 415-535.

Döscher, R., U. Willén, C. Jones, A. Rutgersson, H.E.M. Meier, U. Hansson, and L.P. Graham: 2002, The development of the coupled regional ocean-atmosphere model RCAO. *Boreal Env. Res.* **7**, 183-192.

Giorgi, F., and R. Francisco: 2000, Uncertainties in regional climate change prediction: a regional analysis of ensemble simulations with the HADCM2 coupled AOGCM, *Climate Dynamics*, **16**, 169-182.

Goyette, S., O. Brasseur, M. Beniston: 2003, Application of a new wind gust parameterization: Multiscale case studies performed with the Canadian regional climate model, J. Geophys. Res., VOL. 108, NO. D13, 4374, doi:10.1029/202JD002646.

Grachev, A.A., C.W. fairall, S.E. Larson:1998, On the determination of the neutral drag coefficient in the convective boundary layer, *Boundary-Layer Meteorology*, **86**, 257-278.

IPCC: 2001, Climate Change. The scientific bases, *Cambridge Univ. Pr*ess, 881 pp.

Jacob, D.: 2001, A note to the simulation of the annual and inter-annual variability of the water budget over the Baltic Sea drainage basin, *Meteorology and Atmospheric Physics*, **77,** 61-73.

Jacob, D., L. Bärring, O.B. Christensen, J. H. Christensen, M. de Castro, M. Déqué, F. Giorgi, S. Hagemann, M. Hirschi, R. Jones, E. Kjeström, G. lenderink, B. Rockel, E.S. Sánchez, C. Schär, S.I. Seneviratne, S. Somot, A. van Ulden, B. van den Hurk: 2006, An intercomparison of regional climate models for Europe: design of the experiments and model performance, Clim. Change, (submitted, this issue).

Jones, R.G., J.M. Murphy, and M. Noguer: 1995, Simulation of climate change over Europe using a nested regional-climate model I: Assessment of control climate, including sensitivity to location of lateral boundaries, *Q. J. R. Meteorol. Soc.*, **121,** 1413-1449.

Leckebusch, G.C., and U. Ulbrich: 2004, On the relationship between cyclones and extreme wind storm events over Europe under climate change, Global and Planetary Change, 44, 181-193.

Lenderink. G., B. van den Hurk, E. van Meijgaard, A. van Ulden and H. Cuijpers: 2003, Simulation of present-day climate in RACMO2: first results and model development. KMNI, Technical Report TR-252, http://www.knmi.nl/samenw/regioklim/science.html, pp 24.

Lefebvre, Ch.: 2001, Häufigkeit von Stürmen im Nordatlantik, Deutscher Wetterdienst, http://www.dwd.de/de/FundE/Klima/KLIS/prod/spezial/sturm/haeufigkeit_stuerme.pdf, pp 6.

Lüthi, D., A. Cress, C. Frei, and C. Schär: 1996, Interannual variability and regional climate simulations. *Theor. Appl. Clim.*, **53,** 185-209.

Majewski, D.: 1991, The Europa Modell of the Deutscher Wetterdienst. *Proc. ECMWF Seminar on Numerical Methods in Atmospheric Models*, 1991 Reading UK, VOL II., 147-191.

Nakicenovic, N., J. Alcamo, G. Davis, B. de Vries, J, Fenhann, S. Gaffin, K., Gregory, A. Grübler, et al., 2000. Emission scenarios. A Special Report of Working Group III of the Intergovernmental Panel on Climate Change. Cambridge University Press, 599 pp.

Pope, V.D., Gallani, M.L., Rowntree, P.R., and Stratton, R.A.: 2000, 'The impact of new physical parametrizations in the Hadley Centre climate model: HadAM3', *Clim Dyn* **16**, 123-146.

Pryor, S.C., R.J. Barthelmie, and E. Kjellström: 2005a, Potential climate change impact on wind energy resources in northern Europe: analyses using a regional climate model, Climate Dynamics, DOI: 10.1007/s00382-005-0072-x

Pryor, S.C., J.T. Schoof, and R,J. Barthelmie: 2005b, Empirical downscaling of wind speed probability distributions, *J. Geophys. Res*., **Vol. 110**, D19109, DOI: 10.1029/2005.JD005899

Räisänen, J., U. Hansson, A. Ullerstig, R. Döscher, L.P. Graham, C. Jones, M. Meier, P. Samuelsson, and U. Willén: 2003, SMHI Reports Meteorology and Climatology, No. 101, pp 61.

Rayner, N.A., DE. Parker, E.B. Horton, C.K. Folland, L.V. Alexander, and P. Frich; 2000, Sea-Ice and Sea Surface Temperature Data Set, 1871-1999, *Hadley Centre Technical Note 17,* Hadley Centre for Climate Prediction and Research, Met Office, U.K.

Schiesser H.H., Pfister C., Bader J., 1997: Winter Storms in Switzerland North of the Alps 1864/1865-1993/1994. Theoretical and Applied Climatology, 58, 1-9 (1997).

Schrodin, R. ed.: 1995, Dokumentation des EM/DM Systems, Deutscher Wetterdienst, Offenbach a. Main.

Steppeler, J., G. Doms, U. Schättler, H. W. Bitzer, A. Gassmann, U. Damrath, and G. Gregoric: 2003, Meso-gamma scale forecasts using the nonhydrostatic model LM, *Meteorol. Atm. Phys*, **82**, 75-96.

~~Van den Hurk, B., M. Hirschi, Ch. Schär, G. Lenderink, E. van Meijgaard, A. van Ulden, B. Rockel, S. Hagemann, P. Graham, E. Kjellström, R. Jones: 2004, Soil control on runoff response to climate change in regional climate model simulations; KNMI Preprint report 2004/10, 25pp, (Available from KNMI, PO Box 201, De Bilt, The Netherlands)~~

Woth, K., 2005: North sea storm surge statistics based on projections in a warmer climate: How important are the driving GCM and the chosen emission scenario? Geophysical Res. Letters, **32**, L22708, doi:10.1029/2005GL023762

Woth, K., Weisse, R., von Storch, H., 2005. Climate change and North Sea storm surge extremes: An ensemble study of storm surge extremes expected in a changed climate projected by four different Regional Climate Models. Ocean Dyn. DOI: 10.1007/s10236-005-0024-3

Zwiers, F.W. and V.V. Kharin: 1998, Changes in the extremes of the climate simulated by CCC GCM2 under CO_2 doubling, *J. Climate*, **11**, 2200-2222.

Table legends

Table 1 Regional climate model simulations used in this paper.

Table 2 Significance of RCM-simulated changes in the 99th percentile of daily mean near-surface wind speed for eight European sub-domains. “S” means at least 6 out of 8 models show statistically significant changes. “I“ means at least 6 out of 8 models show changes that are not statistically significant.

Figure captions

Figure 1 Total number of events with maximum wind speed ≥ 8 Bft (top row) and ≥ 10 Bft (bottom row) for a model without gust parameterisation (left column, HIRHAM) and a model with gust parameterisation (right column, CLM).

Figure 2 Number of wind gusts per year with a strength of ≥ 8 Bft at Bremerhaven (left) and List/Sylt (right) for the time period 1961-1990. For the model/institute assignments, refer to Table 1. DMI and SMHI provide also model results on a 25-km grid resolution and SMHI an additional run with driving data from the MPI global model ECHAM4, which is denoted in the figures.

Figure 3 Number of wind gusts per year with a strength of ≥ 8 Bft at five stations in the Czech republic [Brno Airport, Cheb, Hradec Kralove, Mt. Milesovka, and Prague Airport]. A comparison of model results with measurements for the time period 1961-1990 is shown on the left. A comparison between the two models (CHRM and CLM) for 1961-1990 and 2071-2100 shows the future changes on the right. Data from measurements are denoted at the bottom of the figures by "M" (non-filled boxes). The results from CHRM and CLM simulations are denoted by "a" (filled boxes) and "b" (hatched boxes), respectively. "c" stands for control run (1961-1990) and "s" for the scenario (2071-2100). The circles denote outliers (i.e. the distance from lower 25% or the upper 75% quartile is larger than 1.5 times the interquartile distance).

Figure 4 Change in total number of storm peaks (gusts larger 8 Bft, in %) from 1961-1990 to 2071-2100, as simulated by the RCMs CHRM (left) and CLM (right).

Figure 5 The 8 sub-domains used in this study.

Figure 6 Distribution of 99th percentile of daily mean wind speeds from eight RCMs, averaged over the land area of the eight European sub-domains defined in Figure 5. Absolute values for present-day control simulations (CTRL) and changes between future scenario and control run (SRES/A2-CTRL). Open circles denote outliers (i.e. the distance from lower 25% or the upper 75% quartile is larger than 1.5 times the interquartile distance). The "S" and "I" at the bottom of each figure correspond to the same symbols in Table 2.

Tables

Institute	Model	Reference	u_{max} type
DMI	HIRHAM	Christensen et al., 1996	2
ETHZ	CHRM	Lüthi et al., 1996 Majewski, 1991	3
GKSS	CLM	Steppeler et al., 2003	3
HC	HadRM3	Jones et al. 1995	2
KNMI	RACMO	Lenderink et al., 2003	2
MPI-HH	REMO	Jacob, 2001 Majewski, 1991	2
SMHI	RCAO	Döscher et al. 2002	2
UCM	PROMES	Castro et al. 1993	1

Table 1

Area \ Month	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
1 British Isles		S		I	I			S	S	I	I	
2 Iberian Pen.	I	I		I			S				S	I
3 France	S	S									S	
4 Central-Eu.	S	S	S	S	I		I		S	I		
5 NE-Europe									S		I	I
6 Alps							I				S	I
7 Mediterran.			I		I					I	S	
8 East-Europe	S	I	I	I								I

Table 2

Figures

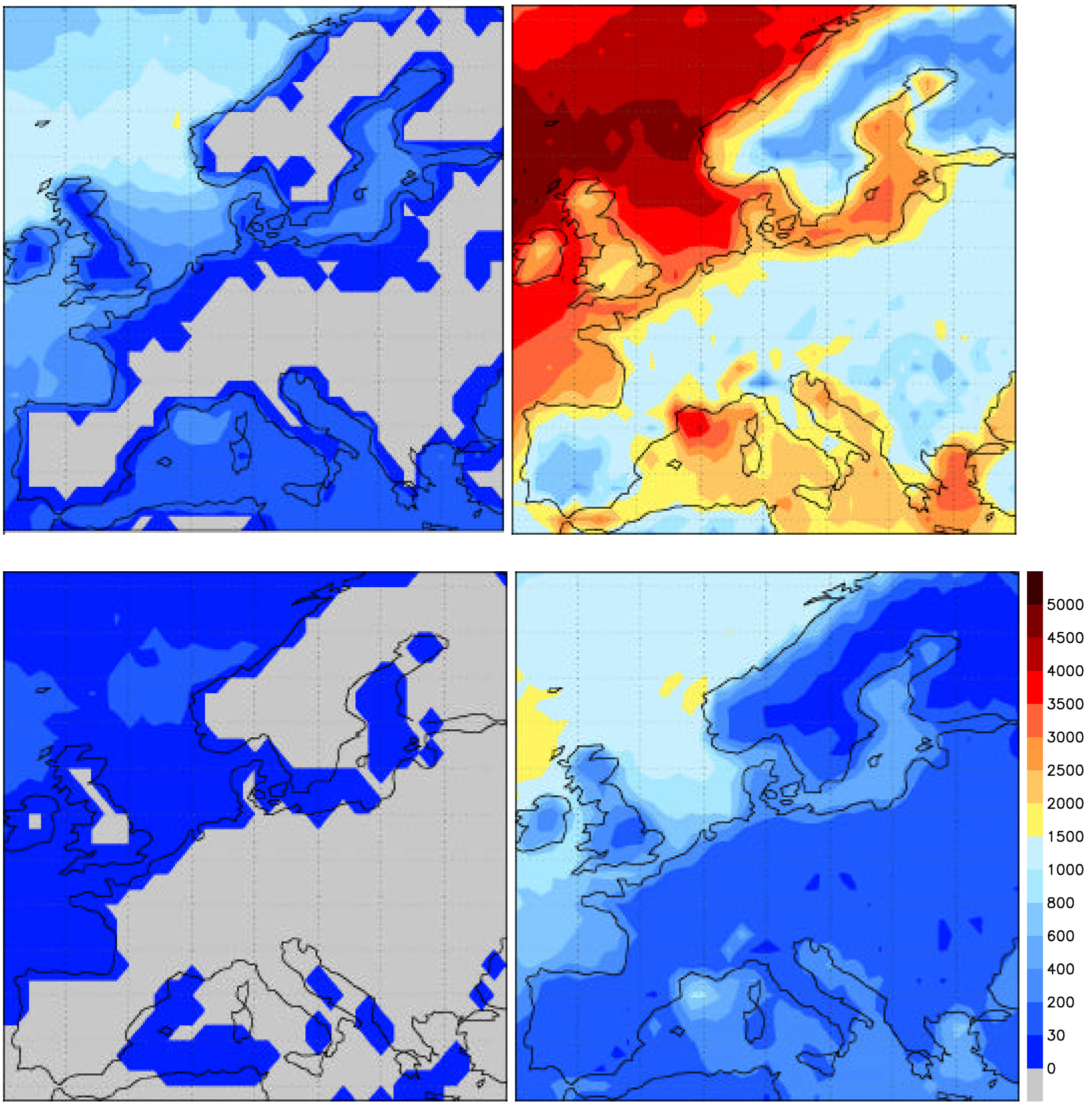


Figure 1

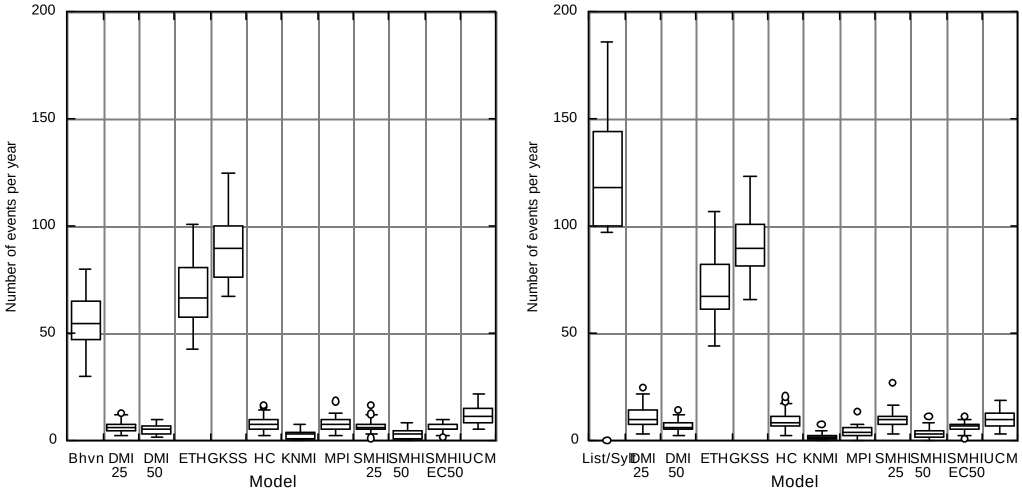
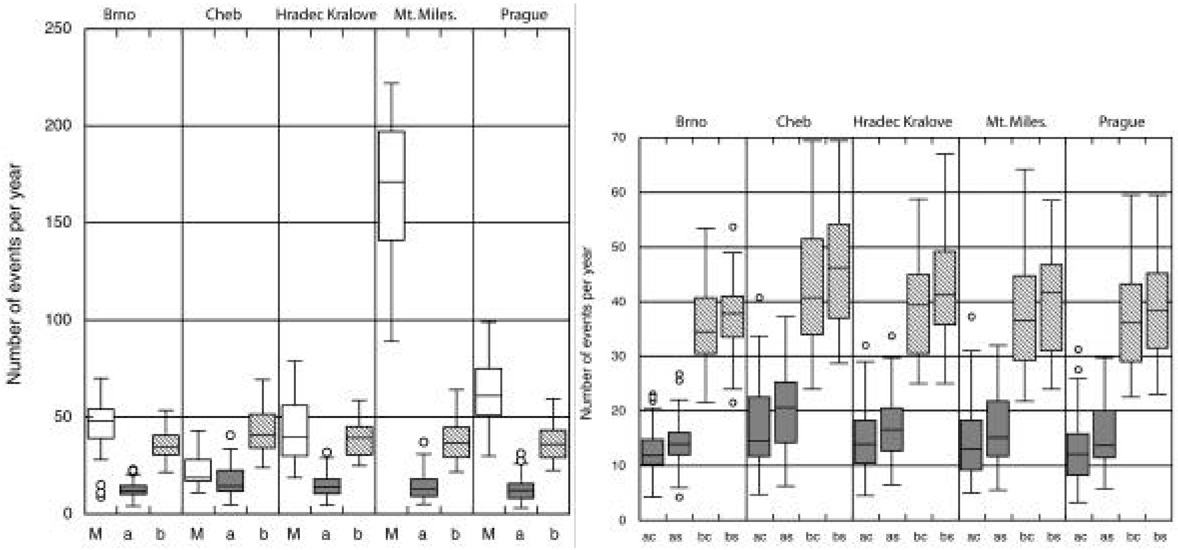


Figure 2



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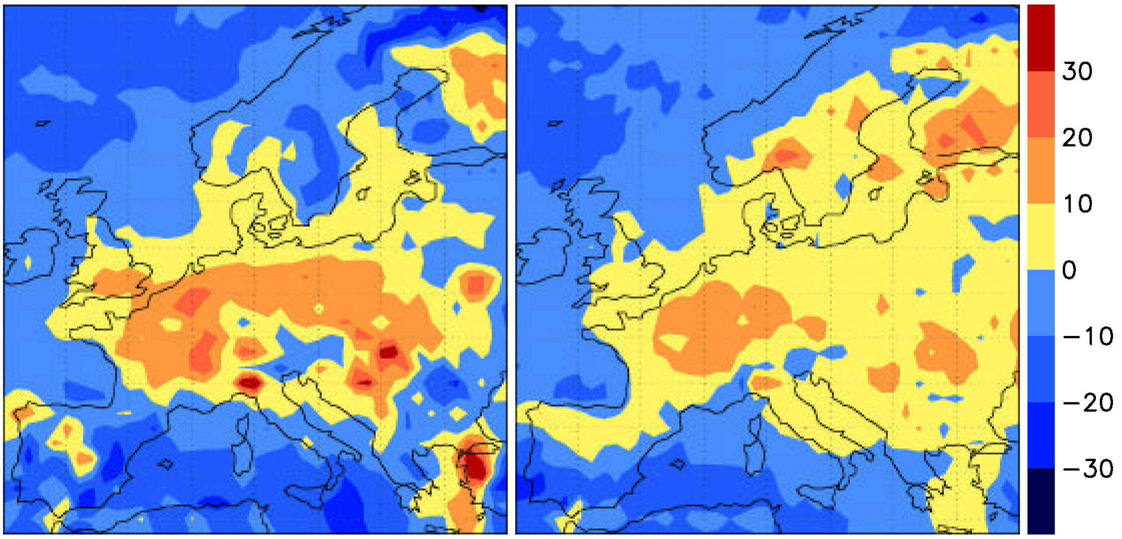

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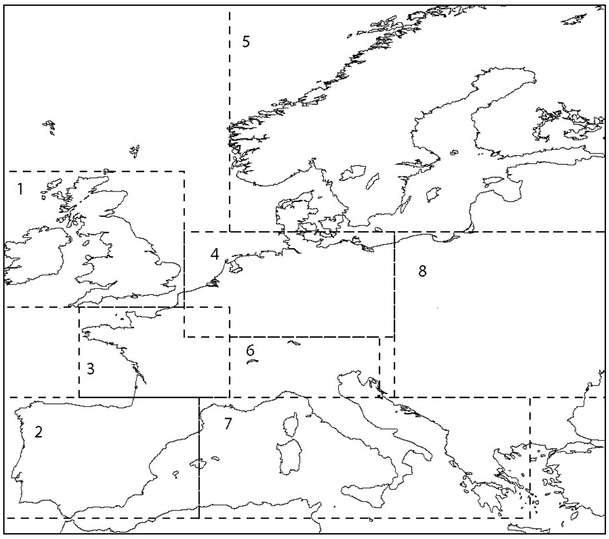

Figure 5

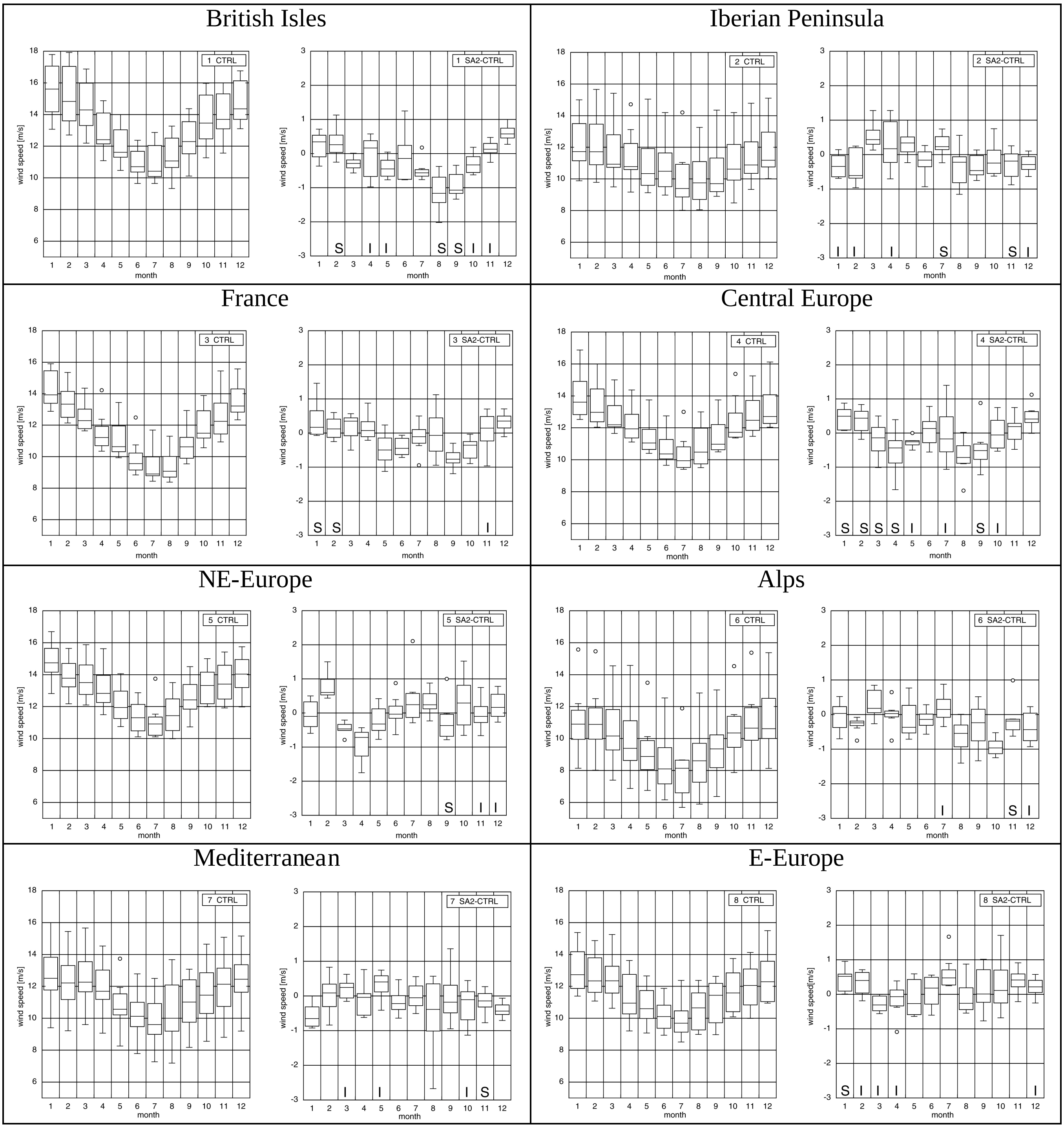
British Isles
Iberian Peninsula
France
Central Europe
NE-Europe
Alps
Mediterranean
E-Europe
1 CTRL
1 SA2-CTRL
2 CTRL
2 SA2-CTRL
3 CTRL
3 SA2-CTRL
4 CTRL
4 SA2-CTRL
5 CTRL
5 SA2-CTRL
6 CTRL
6 SA2-CTRL
7 CTRL
7 SA2-CTRL
8 CTRL
8 SA2-CTRL
wind speed [m/s]
month
S
I

Figure 6