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Are we facing increasing extreme winds in the future?

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Summary

Climate and Energy Systems (CES) is a research project with 55 Nordic and Baltic participants, public and private, creating and analysing climate and energy system scenarios in order to investigate climate change impact on renewable energy in the Nordic region. The goal of the project is to assess the development of the Nordic electricity system for the next 20-30 years by assessing risks, potentials and needs for adaption to climate change, focusing on hydropower, wind and bio-energy. The present work presents an assessment of climate change impact on extreme wind speeds through three different approaches.

Empirical downscaling of Weibull parameters was applied for eight GCMs at 43 stations in northern Europe. The majority of the 43 stations show 0-5% increases in the U_{50yr} in the periods 2046-65 and 2081-2100 compared to the period 1961 to 1990.
Two regional model simulations with different boundary conditions show a strong influence from the boundary conditions (the driving AOGCM) on the climate change impact to 50-year wind speed. In contrast to the importance of the nesting AOGCM, the choice of SRES emission scenario appears to have little influence on the U_{50yr}.
Based on ERA-40 850 hPa level data (1958-2001) an extreme wind atlas for Finland at 10 m height was calculated. Extreme winds U_{50yr} in the range 19-21 m/s was found. The 99-percentile geostrophic wind over Finland showed no significant change when comparing the period 1884-2006 to 2006-2100.

1. Introduction

Renewable energy sources will play a major role in the attempts to reduce human impact on the global climate. On the other hand the projected climate changes will influence our energy requirements as well as the conditions and possibilities for energy production from renewable sources. Furthermore, extreme weather events could impact the operation of the energy system as well as other infrastructure of our society.

On a global scale renewable energy contributes 18% to our electricity generation of which large hydro plants is 15% and so-called new renewables 3.4% (i.e small hydro < 10 MW, solar, wind and modern biomass). Figures are from 2006 [1]. Many renewable energy technologies exhibit two-digit annual growth rates e.g. grid-connected solar PV 60%, wind 25% and off-grid solar PV 20% (2002 to 2006 average [1]).

In the five Nordic countries renewable energy plays a very important role with some 58% contribution mainly due to a large contribution from large hydro plants. For generation of electricity renewable energy contribute by some 99% in Norway (hydro: 98% and wind 1%); 40-50% in Sweden (hydro) wind 1%; 30-40% in Finland (10%-20% from hydro and 20% based on peat and biomass) and in Denmark 20% of the electricity is generated from wind. Iceland is generating its large electricity consumption (per capita 37.700 kWh) entirely by renewable energy sources (i.e. hydro 70% and geothermal plants 30%). Figures are from 2007 [2].

The high contribution from renewable energy in the Nordic countries underlines the importance of analysing the future of renewable energy and the possible impact from climate change.

Within the framework of Nordic Energy Research (www.nordicenergy.net) the work started in 2003 with the Climate and Energy (CE) project 2003-06 (www.os.is/ce) studying the consequences of climate changes on the Nordic Energy sector up to the year 2100 in detail. Two emission scenarios (A2, B2) and two general circulation models (ECHAM4/OPYC3, HadAM3H) were studied for the period 2070-2100. The main results pointed in the direction of significantly larger run-off (potential) for hydro power due to melting glaciers and increased precipitation. One GCM (HadAM3H) suggested that the average wind power potential remained constant, while the other (ECAHM4) suggested a 10-15% increase. For production of biomass the projected climate changes according to both models appeared to be beneficial.

In 2007 the Climate and Energy Systems (CES) was initiated - a research project with more than 30 Nordic and Baltic participants, public and private, divided in nine working groups creating and analysing climate and energy system scenarios in order to support coming policy making and industry within the region. CES focus on risks, potentials and needs for adaption related to predictable future changes in climate and weather, focusing on hydropower, wind and bio-energy. One goal of the project is to assess the development of the Nordic electricity system for the next 20-30 years. The project aim at addressing how the conditions for production of renewable energy in the Nordic area might change due to global warming. The focus is on the potential production, extreme events and the future safety of the electricity generation system as well as uncertainties.

The objective of the present work is to quantify potential changes in extreme wind speeds across northern Europe under a variety of climate change scenarios. Three different approaches will be applied.

2. Extreme winds: Gumbel distribution

For wind energy applications we conform to the common wind turbine design criteria and base our assessment of extreme winds on the 50-year return period wind speed (U_{50yr}) derived from the Gumbel distribution:

$$U_T = \frac{-1}{\alpha}\ln\left[\ln\left(\frac{T}{T-1}\right)\right]+\beta \qquad (1)$$

Where: U_T is the wind speed for a given return period (T), and α and β are the distribution parameters.
Two downscaling tools are applied to output from coupled Atmosphere-Ocean General Circulation Models (AOGCMs) to generate higher resolution realizations of surface winds from which we calculate the extreme wind speeds under future climate scenarios. The two approaches are empirical downscaling, where transfer functions are used to relate large scale climate variables to station specific wind speeds, and dynamical downscaling, where a regional climate model is nested with a global climate model and used to simulate grid-cell average wind speeds.

3. Empirical downscaling

Method

Empirical downscaling is used to develop site specific estimates of extreme wind speeds using output from eight coupled Atmosphere-Ocean General Circulation Models (AOGCMs); BCCR-BCM2.0, CGCM3.1, CNRM-CM3, ECHAM5/MPI-OM, GFDL-CM2.0, GISS-ModelE20/Russell, IPSL-CM4, and MRI-CGCM2.3.2 (Table 1). These span the range of AOGCMs available in terms of spatial resolution (coarsest ~ 4 × 5º, finest ~ 1.875 × 1.875º) and model formulations (spectral v. Cartesian). AOGCM output for two historical periods (1982-2000 and 1961-1990) are taken from climate simulations of the twentieth century. AOGCM output for 2046-2065 and 2081-2100 are from simulations conducted using the A2 emission scenario (SRES).

Table 1: Summary of the AOGCMs used herein for the empirical downscaling.

Model	Source institution
BCCR-BCM2.0	Bjerknes Centre for Climate Research, Norway
CCCMA-CGCM3.1	Canadian Centre for Climate Modelling and Analysis, Canada
CNRM_CM3	Météo-France/Centre National de Recherches Météorologiques, France
ECHAM5/MPI-OM	Max Planck Institute for Meteorology, Germany
GFDL-CM2.1	National Oceanic and Atmospheric Administration (NOAA)/Geophysical Fluid Dynamics Laboratory (GFDL), USA
GISS-ER	National Aeronautics and Space Administration (NASA)/Goddard Institute for Space Studies, USA
IPSL-CM4	Institut Pierre Simon Laplace, France
MRI-CGCM2.3.2	Meteorological research Institute, Japan

The wind speed observations used for the empirical downscaling are drawn from data sets collected by national weather services in the respective countries and as reported in two data sets provided by NCDC; International Surface Weather Observations (1982-1997) and Integrated Surface Hourly Observations (1995-2002) [3] (the site locations are shown in Figure 1). As in [8] the data are used as reported in the aforementioned data sets, though in the process of site selection, all data sets have been checked to determine that they accurately fit a two-parameter Weibull distribution using techniques described in [4]. Further all observations were corrected to a common measurement height of 10-m, using the power law with a coefficient of 1/7.

The empirical downscaling technique applied is described in detail in [6,7], but in brief this probabilistic downscaling approach relies of the assumption that a two-parameter Weibull distribution is a good representation of the probability distribution of near-surface wind speeds:

$$P(U) = 1 - \exp\left[-\left(\frac{U}{A}\right)^{k}\right] \tag{2}$$

Under this assumption, downscaling models of Weibull A and k at each site are developed based on data from the conditioning period which is used to compute 12 values (one for each calendar month) of the predictands (A and k) and each predictor (mean (overbar) and standard deviation (σ) of 500 hPa relative vorticity (ζ) and the mean daily sea-level reduced pressure gradients (PG)) as simulated by the AOGCMs. The linear regression equation for each site AOGCMs and each of the two Weibull parameters is thus determined from:

$$A_i = c_1 \cdot \overline{PG_j} + c_2 \cdot \overline{\zeta_j} + c_3 \cdot \sigma(\zeta_j) \tag{3}$$

$$k_i = c_4 \cdot \overline{PG_j} + c_5 \cdot \overline{\zeta_j} + c_6 \cdot \sigma(\zeta_j) \tag{4}$$

Where: i is the station, j is the value of the circulation parameters for the AOGCM grid-cell containing the station, and $c_{1,2,3,4,5,6}$ are the regression coefficients.

The regression models are developed independently for each of the Weibull parameters from each station using output from each AOGCM. The resulting models are subsequently applied to estimates of $\overline{PG}$, $\bar{\zeta}$, and $\sigma(\zeta)$ from AOGCM output for any time period to derive Weibull A and k parameters for each station. This approach is advantageous in the current context because it avoids a focus on mean conditions, underestimation of variance, and difficulties associated with reproducing the time structure of wind speeds. Once the downscaled Weibull A and k for each time period, AOGCM and station are known they are used to compute U_{50yr} using eq. (1) and the following approximations of the Gumbel parameters:

$$\alpha = \frac{k}{A}\left(\left(\ln(n)\right)^{1-\frac{1}{k}}\right) \tag{5}$$

$$\beta = A\left(\ln(n)\right)^{1/k} \tag{6}$$

Where n is the number of independent observations

Results

For the 8 AOGCMs presented and the 43 stations, the range of downscaled U_{50yr} for 1961-1990 lie within ±4% of the ensemble mean U_{50yr} and 95% lie within ±2%. This implies the downscaling results for extreme winds from the Weibull A and k parameters are relatively consistent for the historical period. Equally, as shown in Figure 1, the average U_{50yr} described from the Weibull parameters for 1982-2000 shows good agreement with estimates derived from the REMO gridded climate model output for 1979-2003 [2], particularly when one recalls:

- Difficulties in comparing spatial averages with point measurements. The REMO output has a spatial resolution of 50 × 50 km. A major component in dictating observational wind speeds is the exposure of the stations and local land-cover. This is manifest at the macro-level by the obvious land-sea differences in wind speeds from the REMO model, but naturally there are fine-scale variations in the wind field that are manifest in the station data but absent in the gridded model output.
- Different time periods covered (REMO 1979-2003 v. observations 1982-2000).

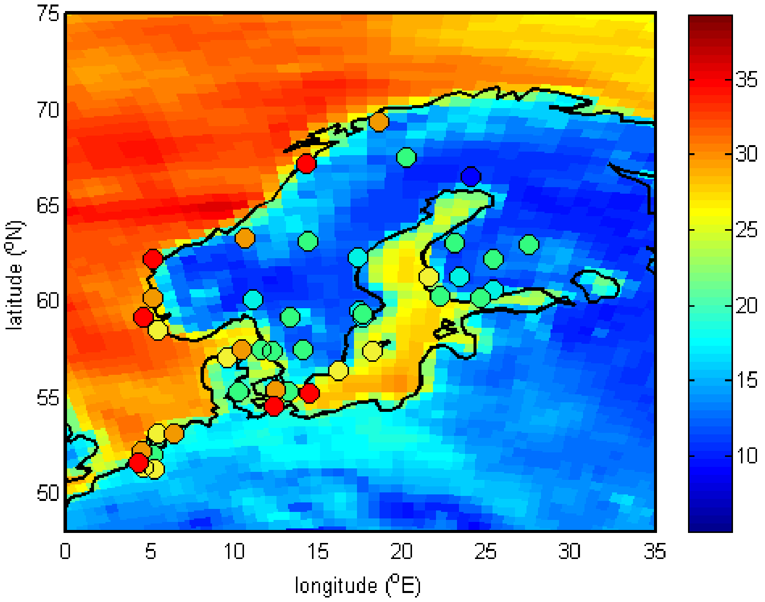

Figure 1: 50-year return period wind speeds from the REMO data set (50 × 50 km resolution) and computed from the Weibull parameters from the observational data. Note the colour bar shown on the right is derived from the REMO data, the observational data have been mapped onto that colour scale.

U_{50yr} for each observational station were computed from the downscaled Weibull A and k parameters for the 8 AOGCMs for three time periods; 1961-1990, 2046-2065 and 2081-2100. The ensemble mean U_{50yr} for 1961-1990 and the ensemble average change between 1961-1990 v 2081-2100 are shown in Table 2 and Figure 2. In the ensemble average there are a large number of stations that exhibit no change in U_{50yr} (26 of 43 stations for 2046-2065, and 14 of 43 for 2081-2100 exhibit change of less than 1% relative to 1961-1990), this is also true for the majority of individually downscaled AOGCMs. However, of the stations that exhibit a $|d(U_{50yr})|$ >1% between 1961-1990 and the future period, the majority exhibit increases. Seventeen of 43 stations (i.e. 40%) exhibit an ensemble average increase in U_{50yr} of 1-5% in 2046-2065 relative to 1961-1990. Twenty-seven of 43 stations (i.e. 63%) exhibit an ensemble average increase in U_{50yr} of 1-10% in 2081-2100 relative to 1961-1990. This bias towards increased extreme wind speeds is also exhibited in results from the majority of individually downscaled AOGCMs. However, for the majority of stations considered, results from at least one downscaled AOGCM exhibit declining U_{50yr}.

A further key caveat that should be noted is that application of the Weibull method to compute U_{50yr} is subject to some uncertainty related to the accuracy of the Weibull fit. The 95% confidence intervals computed using Monte Carlo simulation for the 1961-1990 period to represent the uncertainty in the Weibull fit are -12% to +10%. Downscaling results from only two AOGCMs show results for any single station in which the difference in U_{50yr} in the historical period (1961-1990) and future time periods (2046-2065 or 2081-2100) exceeds the 95% confidence intervals computed for 1961-1990. This implies that the current uncertainty bounds on U_{50yr} for the historical period exceed the climate change signal.

Table 2: Ensemble average d(U_{50yr}) from the empirically downscaled Weibull A and k expressed in terms of the number of stations from which U_{50yr} estimates show a change of the specified magnitude (in %) between the future period and 1961-1990 (if positive the future period exhibits a higher U_{50yr} than the historical period).

% change	2046-65 v 1961-90	2081-2100 v 1961-90
-10 to -5	0	0
-5 to 0	6	7
0 to 5	37	33
5 to 10	0	3

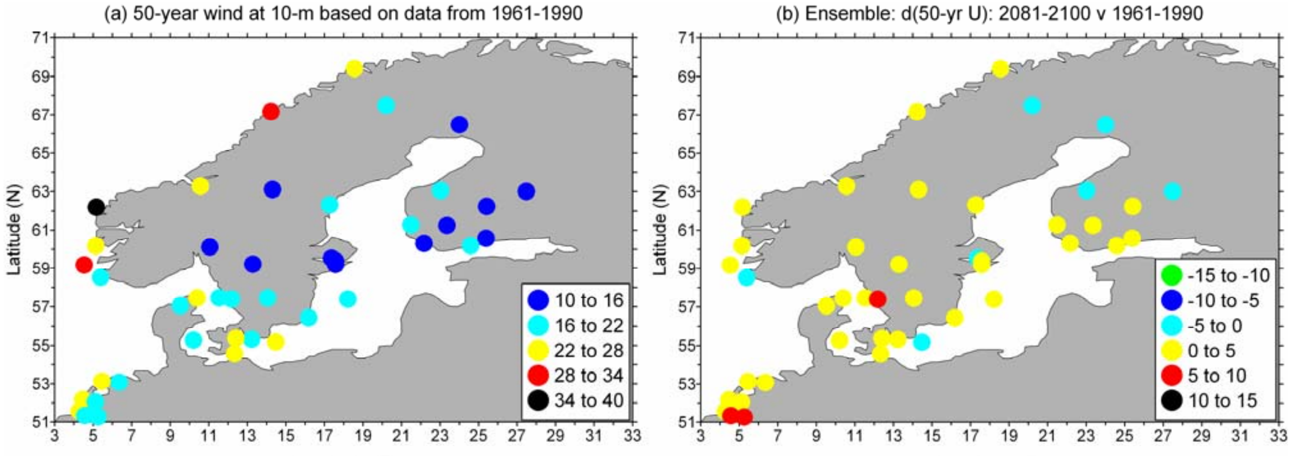

Figure 2: (a) U_{50yr} at 10-m empirically downscaled for 1961-1990 (ms^{-1}), (b) the ensemble average change (%) in U_{50yr} computed from the 8 AOGCMs for 2081-2100 relative to 1961-1990 (if positive the future period exhibits a higher U_{50yr} than 1961-1990).

4. Dynamically downscaled extreme wind speeds

Method

The Regional Climate Model simulations presented here were undertaken at SMHI using the Rossby Centre coupled RCM (RCAO) [9] using lateral boundary conditions from two General Circulation Models (one coupled AOGCM - ECHAM4/OPYC3 and one atmosphere-only GCM - HadAM3H) and two emission scenarios (SRES A2 and B2). Previous analyses of these wind simulations demonstrated [5]:

- The RCAO scenarios exhibit reasonable and realistic features as documented in reanalysis data products during the control period (1961-1990).
- The scenarios indicate evidence for a small increase in the annual wind energy resource over northern Europe between the control run and climate change projection period and for more substantial increases in energy density during the winter season in simulations using boundary conditions from ECHAM4/OPYC3. However, the simulations conducted using lateral boundary conditions from HadAM3H exhibited little or no change in the wind energy density in the future time period.

Simulated time series of annual maximum wind speeds in each model grid cell (0.44 × 0.44°) for each simulation are used to compute U_{50yr} using the method of moments to determine the parameters of the Gumbel distribution (α and β):

$$\alpha = \frac{\ln 2}{2b_1 - \overline{U^{\max}}} \tag{7}$$

$$\beta = \overline{U^{\max}} - \frac{\gamma}{\alpha} \tag{8}$$

$$b_1 = \frac{1}{n}\sum_{i=1}^{n}\frac{i-1}{n-1}U_i^{\max} \tag{9}$$

The uncertainty on U_T is given by:

$$\sigma(U_T) = \frac{\pi}{\alpha}\sqrt{\frac{1+1.14k_T + 1.10k_T^2}{6n}} \tag{10}$$

Where n is the sample size, the frequency factor (k_T) is:

$$k_T = -\frac{\sqrt{6}}{\pi}\left(\ln\left[\ln\left(\frac{T}{T-1}\right)\right]-\gamma\right) \tag{11}$$

Where γ = Euler's constant (0.577216)

Assuming a Gaussian distribution of U_T, then 95% of all realizations will lie with $\pm 1.96\sigma$ of the mean, and thus σ can be used to provide 95% confidence intervals on the estimates of extreme winds with any return period.

Results

RCAO simulations for the end of the C21st conducted using boundary conditions from HadAM3H imply little change in U_{50yr} (Table 3). Estimated U_{50yr} for the future period (and both SRES) generally lie within the 95% confidence intervals derived from the control period simulations (approximately 4-15% of U_{50yr} in 1961-1990). This is also the case for simulations conducted using lateral boundary conditions from ECHAM4/OPYC3, although in those simulations U_{50yr} for the future period under either SRES show increases particularly in the southwest of the study domain (Figure 3). This influence from the lateral boundary conditions (i.e. driving AOGCM) was also evident in our prior analysis [5] of the model simulations in the context of possible changes in the wind energy density, and is in accord with the results from the empirical downscaling of the eight-AOGCMs reported above. In contrast to the importance of the nesting AOGCM, the choice of SRES appears to have little influence on the $d(U_{50yr})$ in either set of runs (Table 3).

Table 3: Fraction of grid cells (in %) that exhibit a significant increase (i.e. above the 95% confidence intervals derived for the historical period), decrease or no change for the 4 future simulations (2071-2100) relative to 1961-1990.

	Declines	No change	Increases
ECHAM4: A2	0.1	73.2	26.7
ECHAM4: B2	0.1	72.9	27.0
HadAM3: A2	6.0	90.1	3.9
HadAM3: B2	1.8	95.8	2.4

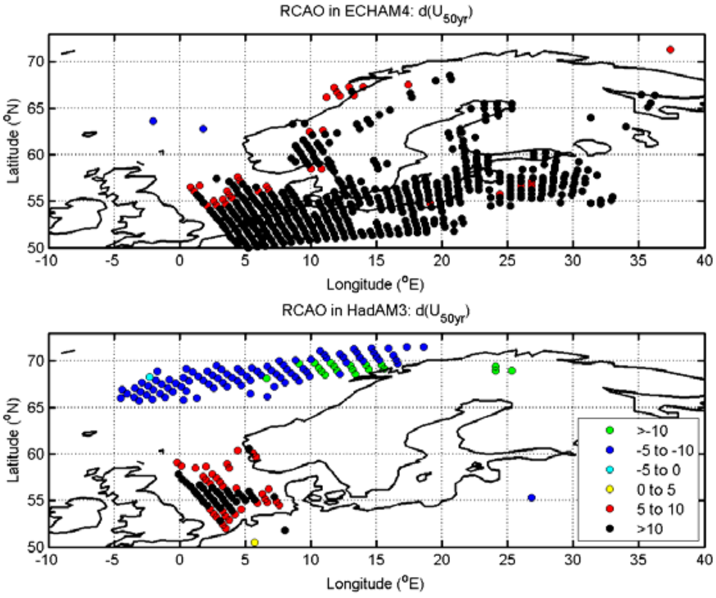

Figure 3: Magnitude (in %) of statistically significant differences in U_{50yr} computed by grid cell for 2071-2100 v 1961-1990 for simulations nested within (above) ECHAM4/OPYC3 and (below) HadAM3 for the A2 SRES.

5. Extreme wind in Finland

The 50-year wind speed, U_{50yr}, has been estimated over Finland using ERA-40 re-analysis data from ECMWF. The calculations were carried out based on methods described in [11] and [12]. Previously the Finnish standards used a U_{50yr} of 23 m/s and in other sources 21 m/s. The new Finnish standards use 21 m/s for most of Finland, except Åland in SW Finland and Utsjoki in Lapland, where 22 m/s is used. For off-shore sites 23 m/s is recommended.

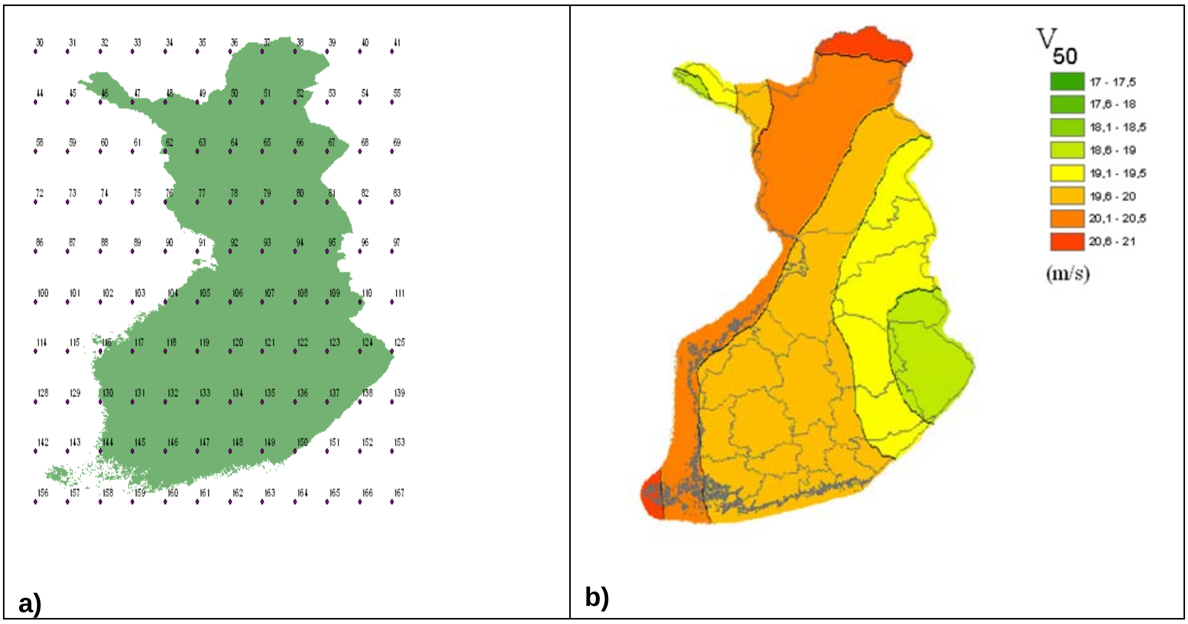

Figure 4 a) ERA-40 grid points over Finland. The resolution of ERA-40 is 1.125 °. b) Calculated U_{50yr} using period 1958–2001 ERA-40 850 hPA level wind speed. The Gumbel distribution was used to approximate the data of the 850 hPa level and the geostrophic drag law to obtain the surface wind. Using data for Denmark the calculated 50-year wind speed was compared to surface measurements and it was found that the measurements was 10–12 % higher than the calculated U_{50yr} from NCEP/NCAR reanalysis data [12]. In this study an empirical coefficient of 1.1 was applied. The zoning in b) NW Lapland is due to the orographic roughness effects.

Figure 5: The triangles used in the calculations of geostrophic wind speed. Triangle 1 used pressure observations, reduced to sea surface level, from Helsinki, Mariehamn and Vaasa.

The calculated reference wind was compared with extreme wind estimated from observed wind climate in Finland.

Approach

The surroundings of 8 weather stations where digitized for WAsP Engineering. The input wind for selected wind directions at each site was ERA-40 850 hPa level maximum winds at the nearest grid point as an approximation to the maximum geostrophic wind speed. The calculated U_{50yr} was compared to surface measurements. In five cases (Helsinki Vantaa WMO 02974, Joensuu Airport WMO 02929, Sodankylä observatory WMO 02836, Rauma Kuuskajaskari WMO 02961 and Helsinki Isosaari WMO 02988) the calculated U_{50yr} from ERA-40 data was higher values than the 50 years wind speed calculated from observations, however within the confidence limits. In one case (Vasa Airport WMO 02911) ERA-40 extreme wind speed was significantly higher than observations and outside of the confidence limits. The sensitivity of the results to roughness was investigated and found to be significant and a better roughness description in the model may lead to better agreement at this site. At two inland sites (Utsjoki Kevo WMO 02805, Maaninka WMO 02788) the measured maximum wind speed in certain sectors was clearly higher than at other inland weather stations. Even at these two sites the model results compared well with observations in the windy sectors. The model with ERA-40 gave a sector-wise maximum wind speed of 22 m/s at Maaninka in the windy sector, which compares well with the observed value 22.3 m/s. At Utsjoki the estimate for 50 years wind speed of 24 m/s is lower than the value 26.3 m/s calculated from observations, however this site is located in a ravine and complex to model.

The analyse of temporal variation of the geostrophic wind based on observations and regional climate model simulations (Figure 6) shows no clear signal of increase of the extreme wind (99-percentile geostrophic wind). In the analyses output of the five regional climate models were used. The models were from the Irish National Meteorological Service (C41), Meteo-France (CNRM), Max Planck Institute (MPI), the Norwegian Meteorological Institute (METNO) and from the Royal Netherlands Meteorological Institute (KNMI) and available from the EU FP6 project Ensembles. The results in Figure 6 appears to depict a typical year-to-year or decade to decade variation of climate. Similar results are obtained in [14].

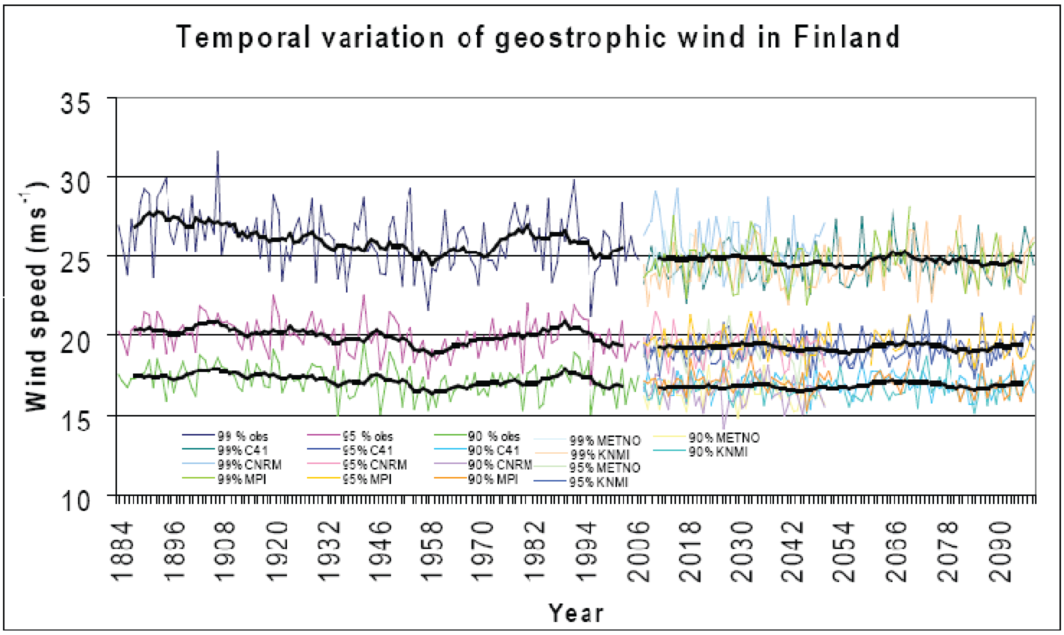

Figure 6: 99-percentile (upper curve), 95-percentile (middle) and 90-percentile (lower) of the wind in the triangle 1 for geostrophic wind speed. The calculations used observed surface pressure values until 2006 at selected Finnish weather stations (Figure 5). From 2006 onwards the calculations are based on five regional climate models (see http://www.ensembles-eu.org/).

6. Discussion

A critical component of climate change adaptation and mitigation efforts is focused on improved quantification of how changes in global climate have been manifest regionally and how future changes may be manifest at the regional/local scale. One of the major concerns is focused on the possibility of increasing intensity or frequency of extreme events. However, accurately representing extremes is a major challenge to the climate modelling community. Herein, we provide a first assessment of possible changes in extreme wind speeds in the context of wind energy.

The 50 year return period wind speed across northern Europe computed using both dynamically and empirically downscaled wind speeds exhibits some weak evidence for an increase during the middle and end of the C21st relative to 1961-1990. For example, two-thirds of all stations considered exhibit an ensemble average increase in U_{50yr} of 1-10% in 2081-2100 relative to 1961-1990. Results from both dynamical downscaling and empirical downscaling exhibit the largest magnitude (and most statistically significant) changes in the southwest of the study domain (over northern Germany and the Benelux countries), possibly extending into the southern Baltic. As a caveat to these findings it is important to recall that uncertainty calculations presented herein illustrate the challenge of estimating climate change impacts on geophysical extremes. The 95% confidence limits derived for both the empirical and dynamical downscaling exceed ±12% of U_{50yr} during the historical period (1961-1990). The Regional Climate Model simulations show a high degree of sensitivity to the AOGCM used to provide the boundary conditions as does the empirical downscaling. The dynamical downscaling exhibit lesser sensitivity to the emission scenario used. This finding may provide a key insight for future research, and emphasizes the critical importance of including multiple model combinations in downscaling analyses for wind climates.

7. Conclusions

Empirical downscaling of Weibull parameters was applied for eight GCMs at 43 stations in northern Europe. The majority of the 43 stations show 0-5% increases in the U_{50yr} in the periods 2046-65 and 2081-2100 compared to 1961 to 1990.
Comparing two regional model simulations with different AOGCM boundary conditions show a strong influence from the boundary conditions (i.e. the driving AOGCM) on the climate change impact to extreme wind. In contrast to the importance of the nesting AOGCM, the choice of SRES emission scenario appears to have little influence on the U_{50yr}

Based on ERA-40 850 hPa level data (1958-2001) an extreme wind atlas for Finland at 10 m height was calculated. Extreme winds U_{50yr} in the range 19-21 m/s was found. There is a reasonable agreement with the U_{50yr} found by empirical downscaling of eight AOGCMs for Finland.

8. Acknowledgements

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CES Project homepage *www.os.is/ces*

Abbreviations

AOGCM	Atmosphere-ocean General Circulation Model
ECHAM4	General circulation model from Max Planck Institute, Hamburg
ECMWF	European Centre for Medium-Range Weather Forecasts
GCM	General Circulation Model
HadAM3H	General circulation model from Hadley Centre, UK
IPCC	Intergovernmental Panel on Climate Change
NCAR	National Centre of Atmospheric Research
NCDC	National Climatic Data Center, USA
NCEP	National Center of Environmental Prediction
NEFP	Nordic Energy Research Program
NNR	NCEP / NCAR Re-analysis data
RCAO	Rossby Centre regional coupled Atmosphere-Ocean model
RCM	Rossby Center Regional Climate model
REMO	Regional climate model from Max Planck Institute
SMHI	Swedish Meteorological and Hydrological Institute
SRES	IPCC Special Report on Emission Scenarios
U_{50}	10 min average, extreme wind occurring once in 50 years