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Assessing the vulnerability of wind energy to climate change and extreme events

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IAEA workshop: April 2010

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CES Nordic Project on Climate and Energy Systems

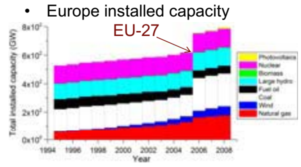
nordon Nordic Energy Research

INDIANA UNIVERSITY

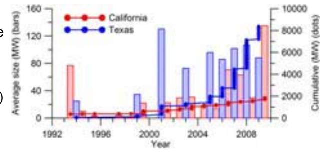
Wind energy industry: Overview

- Global installed capacity:
  - 2007: 94 GW
  - 2008: 121 GW
  - 2017: > 700 GW ?
  - > 80 countries have commercial installations
- USA:
  - End 2009: > 35 GW (>33,000 turbines)
- Europe:
  - 2009: 65 GW, > 2 GW offshore
- Bigger is better! US example:
  - Last quarter of 2009
    - 55 new plants (2319 turbines)
    - 37 had capacity > 40 MW

- Europe installed capacity

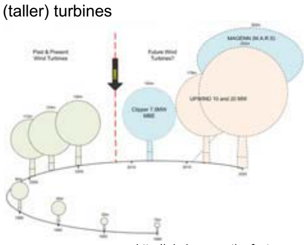


- Getting bigger.. USA example



Wind energy industry: Growth of turbines

- Global av. capacity of turbine:
  - 2008: Av. turbine installed = 1.886 MW
- Current commercially available:
  - 3.6-5 MW (all major manufacturers) Enercon – 6 MW!
- Bigger capacity means BIGGER (taller) turbines



http://wind-energy-the-facts.org

Climate change mitigation

- Energy sector 2/3 of global greenhouse gas emissions
- Wind turbines
  - Design lifetime ~ 20 yrs
  - 3-7 months of operation recover energy spent in full life-cycle
  - Avoid emissions: 391-828 g of CO_2/kWh
  - E.g. In Europe:
    - 65 GW installed capacity
    - Avoided 108×10^6 tons CO_2 during 2008 (24% of EU-27 obligation under Kyoto)
    - Avoided fuel costs > 6 million Euro (assuming $90/barrel of oil)

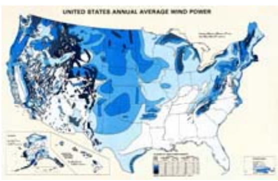
Purpose

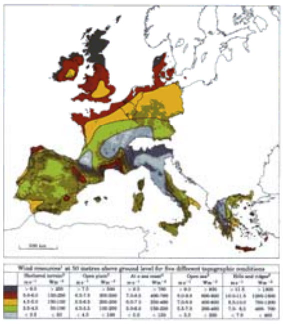
1. Develop and evaluate tools for making 'projections' of wind climate (and other) parameters relevant to the wind energy industry
2. Determine if:
   - Descriptors of wind climate (or parameters) pertinent to wind energy are likely to change under global climate change
3. Identify:
   - Major sources of uncertainty in answering 2).

A priori knowledge

- High current inter-annual variability of wind resource
  - Due to inherent climate variability – e.g. climate 'modes' such as ENSO
- Highly fractured historical records confounds efforts to quantify variability & trends
- Why might climate change matter?
  - E.g. n. Europe – high wind resource, largely controlled by synoptic-scale (transient) phenomena. Why might it change?
    - Δ Storm dynamics: Largely baroclinic (⇒ƒ(Variance of Temperature) which MAY decline as equator-pole gradient ↓). *Exception = polar lows.*
    - Δ Storm tracking: Possible links to changes in Temperature-gradient & wave features which MAY change as climate warms HOWEVER also ƒ(internal variability (teleconnections))

Wind resources: Will the spatial patterns change?



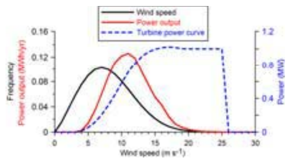


http://rredc.nrel.gov/wind/pubs/atlas/maps/chap2/2-01m.html

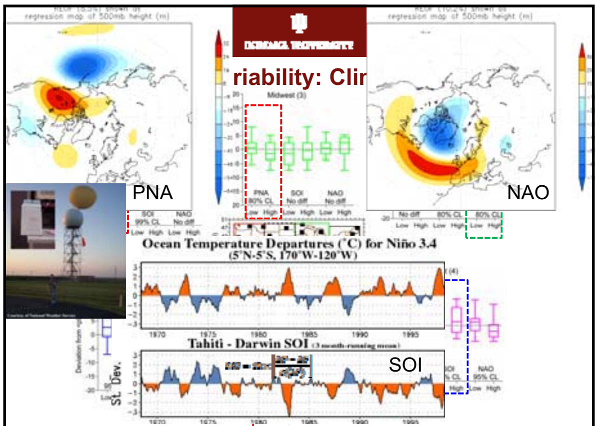
www.windatlas.dk/Europe/About.html

Wind resource

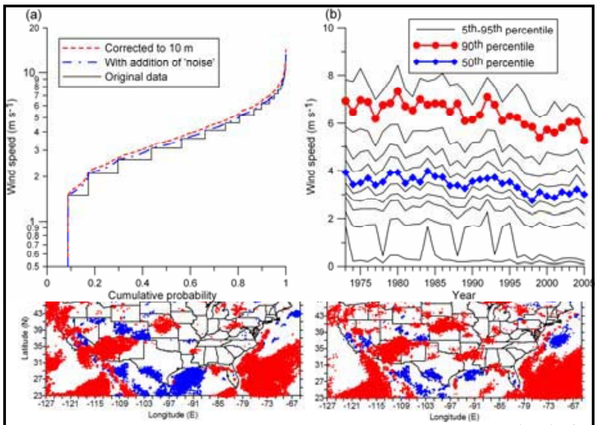
- Weibull distribution of wind speeds $P(U)=1-\exp\left[-\left(\frac{U}{A}\right)^k\right]$
  - A = Scale parameter (ms^{-1})
  - k = Shape parameter
- Energy density $E=\frac{1}{2}\rho A^3\Gamma\left(1+\frac{3}{k}\right)$
  - An example:
    - $U_{50th\ percentile} \approx 7\ ms^{-1}$
    - 11% of power
    - $U_{90th\ percentile} \approx 12.5\ ms^{-1}$
    - 75% of power



Pryor & Barthelmie (2010): Renewable and Sustainable Energy Reviews



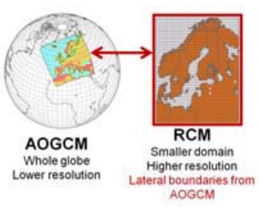
Pryor & Ledolter (2010): JGR (in press)

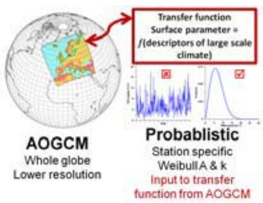


Pryor et al. (2009): JGR

Making projections: Approaches

- Dynamical downscaling: Apply Regional Climate Model (0.22 × 0.22°)
- Probabilistic downscaling: Apply transfer functions (station specific)

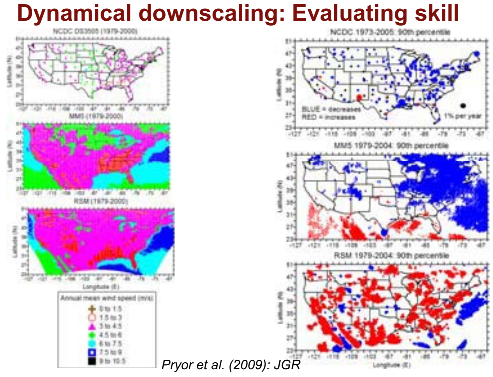




Pryor et al. (2005): Climate Dynamics

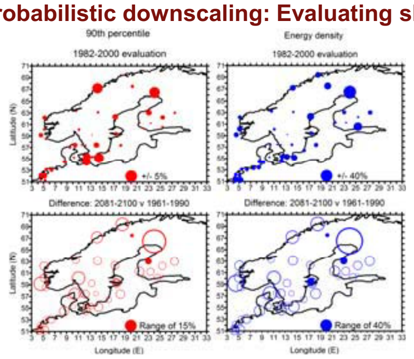
Pryor et al. (2005): JGR, Pryor et al (2006): GRL, Pryor & Schoof (2010): Meteorologische Zeitschrift

Dynamical downscaling: Evaluating skill



Pryor et al. (2009): JGR

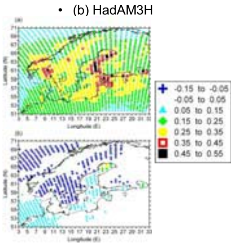
Probabilistic downscaling: Evaluating skill



Pryor et al. (2006): GRL

Sensitivity analyses

- Dynamical downscaling: Δ Energy density
  •RCAO (2071-2100 v 1961-1990). Lateral boundary (A2):
  - (a) ECHAM4/OPYC3
  - (b) HadAM3H



- Probabilistic approach: Δ p90

Parameter	# AOGCM	SRES	Outcome
Driving AOGCM	10	A2	±25% (45 of 46 stations)
GHG forcing (SRES)	ECHAM5	A2, A1B, B1, Commit	±15%
Perturbed initial conditions	ECHAM5	2 of C20th	±15%
Stochastic w/in AOGCM	5	A2 (1 station, CPH)	95% of realizations w/in ±10%

Pryor et al. (2005): Climate Dynamics, Pryor & Schoof (2010): Meteorologische Zeitschrift

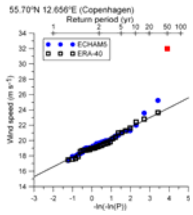
Extreme conditions & loads

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

- Design standards (IEC 61400-1) – onshore turbines
  - Extreme wind speed:
    - 50yr RP 10-minute sustained wind speed
  - Extreme operating gust
    - 3-second gust
  - Extreme wind shear
  - Extreme direction change
  - Extreme coherent gust
  - Extreme coherent gust & change of direction

IEC 61400-1 conservative in Mid-latitudes..
Caveat: Thunderstorms!

- Find α and β by:
  •Graphical method (Gumbel plot)
  •Method of moments
  •Weibull A & k
- IEC 61400-1 $U_T = 5\bar{U}_{ann}$

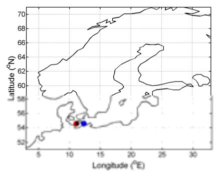


Pryor & Barthelmie (2010): Renewable and Sustainable Energy Reviews

Extreme wind speeds: Evaluating skill

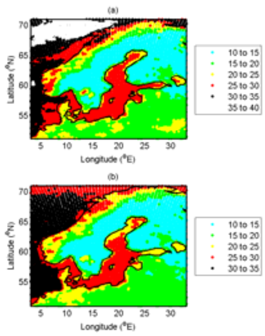
- Evaluation v. independent data in historical period

1961-1990	Lat (N)	Lng (E)	U_{50} (ms^{-1})	95% C.I. (1.96σ)
Westermarkels-dorf 1 (hr av)	54.55	11.1	26.62	3.69
HIRHAM5/ECHAM5 (hr av)	54.53	11.28	24.34	1.80
HIRHAM5/ERA-40 (hr av)	54.53	11.28	28.31	3.81
Probabilistic/ ECHAM5 (hr av)	54.57	12.33	26.40	1.63



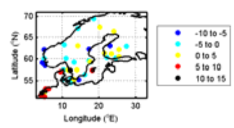
U_{50yr}: Importance of lateral boundary conditions

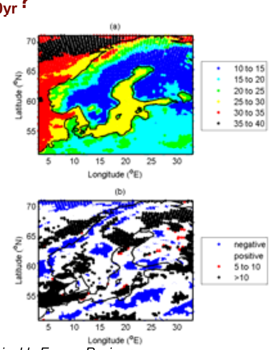
- For 1961-1990 HIRHAM5 (0.22 ×0.22°) nested in:
  - (a) ECHAM5
  - (b) ERA-40
- Generally high correlation (r = 0.95, mean ratio = 1.04) BUT:
  - ECHAM5 nested runs: Positive bias in Norwegian Sea
  - ECHAM5 nested runs: Negative bias west of Denmark



ΔU_{50yr}?

- (a) U_{50yr} HIRHAM5 (m s^{-1}) nested in ECHAM5 (1961-1990)
- (b) ΔU_{50yr} (2081-2100 v 1961-1990)
  - Sign for changes not significant
  - Magnitude for changes that are significant
  - LOWER = 20%
  - HIGHER = 58%
  - SIGNIFICANTLY HIGHER = 22%





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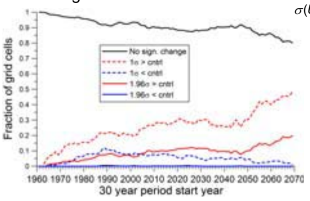
ΔU_{50yr}?: Dynamical downscaling

- Method – HIRHAM5 in ECHAM5
  - Evaluate σ on U_{50yr} for 1961-1990 in each grid cell
  - Compute U_{50yr} for each moving 30-year period (1961-1990, 1962-1991…. 2071-2100) in each grid cell
  - Determine if U_{50yr} (period) lies outside uncertainty bounds (σ) for 1961-1990
- Generally future lies within range of past BUT tendency towards increasing values



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

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

γ = Euler's constant (0.577216)

Internal (inherent) variability is large

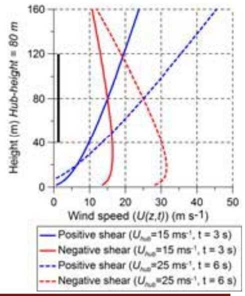
Extreme wind shear

- IEC 61400-1:

$$U(z,t)=\begin{cases} U_{hub}\left(\frac{z}{z_{hub}}\right)^{\alpha} \pm \left(\frac{z-z_{hub}}{D}\right)\left(2.5+0.2\beta\sigma_1\left(\frac{D}{\Lambda_1}\right)^{\frac{1}{4}}\right)\left(1-\cos\left(\frac{2\pi t}{T}\right)\right) & \text{for } 0\le t\le T \\ U_{hub}\left(\frac{z}{z_{hub}}\right)^{\alpha} & \text{otherwise}\end{cases}$$

- Meteorology state-of-art:

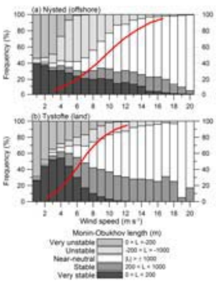
$$U_z = \frac{u_*}{\kappa}\left[\ln\frac{z}{z_0} - \Psi_m\left(\frac{z}{L}\right)\left(1-\frac{z}{2z_i}\right)\right]$$

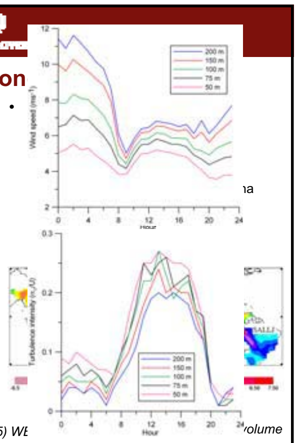


IEC 61400-1 conservative unless z_i < 200 m (L = 10 m)
Caveat: LLJ

Probability of stron

- Stable conditions – much more freq. offshore:
-





ia

Pryor & Barthelmie (2002): WE, Motta et al. (2005) WE ... 'olume

Extreme gust

- IEC 61400-1 (addition) $U_{gust} = Min\left\{1.35(U_{1yr}-U_{hub});\ 3.3\left(\frac{\sigma_1}{1+0.1\left(\frac{D}{\lambda}\right)}\right)\right\}$
- Meteorology GF (multiplier) – 10 m

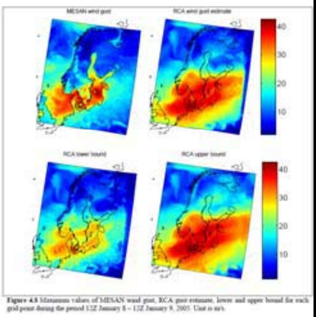
Averaging period	UK structural design (Cook 1986)	Tropical cyclones (Krayer & Marshall 1992)	Mixed climate (Yu & Chowdhury 2009)	
z_0 (m)	0.03	0.03	2×10^{-4} to 1×10^{-3}	0.03 to 0.06
10 minute	1.1	1.1	1.1	1.2
3 second (gust)	1.5	1.7	1.4	1.7

- 10-minute mean U_{hub} = 15 m s^{-1}, z_{hub} = 70 m, a rotor diameter (*D*) of 80 m, for a Turbine class I with a U_{ref} of 50 m s^{-1} and I_{ref} = 0.16
  - IEC 61400-1: U_{gust} = 7.5 m s^{-1}
  - Met: U_{gust} = 6.3 m s^{-1}

IEC 61400 conservative
Caveat: thunderstorm/strong hurricanes

Gust parameterizations within RCM

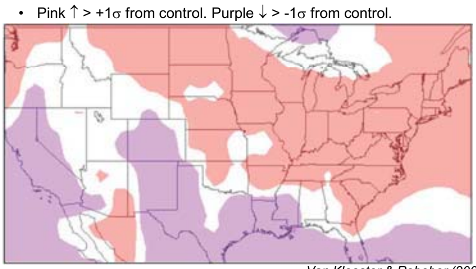
- E.g. RCA3
  - ƒ(max(U^2+V^2) within 'boundary layer')
  - Some skill relative to independent observations
- Likely limited applicability to synoptic scale phenomena



SMHI report by Maria Nordstrom, courtesy of Erik Kjellström, SMHI

Extreme gusts

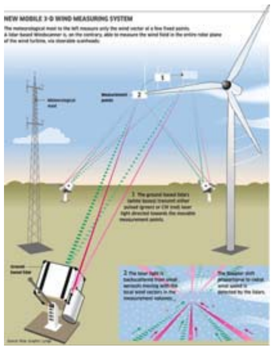
- Simulation very challenging if ƒ(deep convection)
- E.g. % change in severe convective potential (PCM downscaled with ANN)
  - Pink ↑ > +1σ from control. Purple ↓ > -1σ from control.



Van Klooster & Robeber (2009): J Climate

Extreme wind events

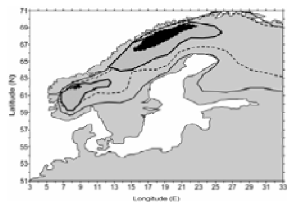
- Technical fixes – being developed:
  - Extreme event recognition (EER) & dynamic wind turbine & wind farm management
  - If 7 MW machines deployed COULD couple with lidar for inflow:
    - Nacele mounted OR
    - Wind scanner



www.risoe.dtu.dk

Other parameters: Icing

- Technical fix: Add blade heating
- Number of annual icing hours
  - RCAO nested in ECHAM4
    - Icing IF lowest model level (90-130 m agl): T < 0ºC RH > 95% (persist as long as T < 0ºC)
  - Solid lines: 400 and 1200 icing hours per year in 1961-2000
  - Dashed lines: 400 and 1200 icing hours per year 2061-2100 (A2 SRES)



Pryor & Barthelmie (2010): Renewable and Sustainable Energy Reviews

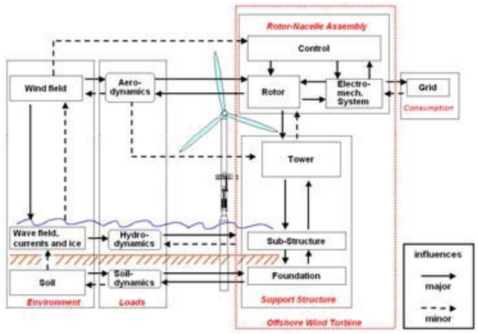
Other parameters: Lightning

- Technical fix: Add low electrical impedance parts to bypass critical turbine components
- Will lightning frequency inc.?
  - Might IF deep convection inc.
  - Very high uncertainty

Caveat: thunderstorm/strong hurricanes

http://longdown.com/downloads/documents/IMIA-EngineeringInsofOffshoreWindTurbines.pdf

Offshore….. Inc. wave & sea ice loading



Wave loading.. Thought exercise

- Airy waves

$$u_w = \frac{HgT}{2\lambda}\frac{\cosh[2\pi(z+d)/\lambda]}{\cosh(2\pi d/\lambda)}\cos\theta \qquad a = \frac{HgT}{2\lambda}\frac{\sinh[2\pi(z+d)/\lambda]}{\cosh(2\pi d/\lambda)}\sin\theta$$

- Fatigue loading

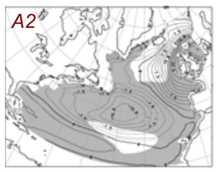
$$F = \frac{\rho_w}{2} D_f C_D\,|u_w|\,u_w + 0.25\rho_w \pi D_f^2 C_M a$$

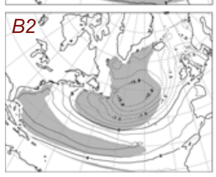
- ⇒ Bigger amplitude, faster moving wave generate maximum force
- Wind-wave coupled loading = key

Wave climates

Δ Significant wave height in winter 2080's – 1990's

- Strong BUT non-linear f(wind climate)
- Uncertain!
- Europe
  - INC by end of C21st:
    - N. Atlantic: 20-year RP wave, > double in freq. (Wang et al. 2004) * High SRES dependence
    - Baltic Sea: Mean significant wave height ↑ up to 0.5 m (Meier 2006)
    - North Sea: Mean significant wave height ↑ 5-8% (Grabemann & Weisse 2008)
  - DEC by end of C21st:
    - Mediterranean (Lionello et al. 2008)

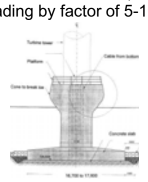




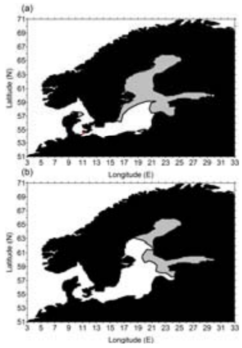
Wang et al.(2004): J Climate… CGCM2 AOGCM

Sea ice

- Technical fix: Ice cones (reduce sea loading by factor of 5-10)



- Area covered by sea ice for more than 25 days per year on average (hatched area & +)
- RCAO nested in HadAM3
  - •(a) 1960-1990
  - •(b) 2070-2100 (A2 SRES)



Summary

- Climate projections of parameters relevant to wind energy industry
  - Tools being developed & applied exhibit some skill!
- Wind resource
  - High inherent variability. MUST be accounted for in climate change projections
  - At least over n. Europe:
    - Δ wind energy resource may be more consequential that changes in extreme conditions. Δ wind energy resource: Major source of uncertainty: AOGCM
    - Ranked sources of uncertainty: different AOGCM > different runs with single AOGCM (perturbed initial conditions) > SRES > stochastic influences w/in AOGCM
- Extreme events
  - IEC 61400 design guidelines generally conservative (exception – tropical regimes? & combined extremes leading to excess loads)
  - BUT incomplete scientific understanding of phenomena responsible for extreme loads particularly in climates away from N. Europe