Estimating Wind Power Potential And Its Variabilities Over Europe

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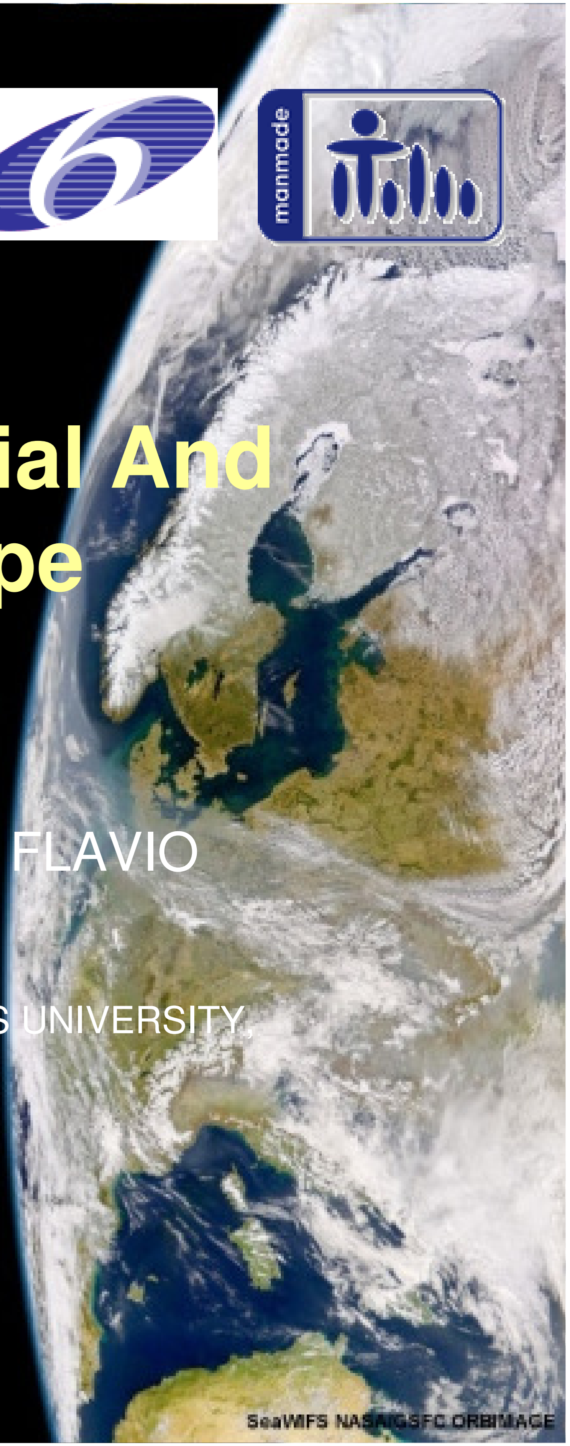

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1. Introduction – Global power consumption

Solar radiation: 1520 EWh (outside the atmosphere)

(174 PW average)

2005 data:

Global energy consumption:

140 PWh (16 TW average)

~0.01 % of the solar radiation !

Electricity out of this:

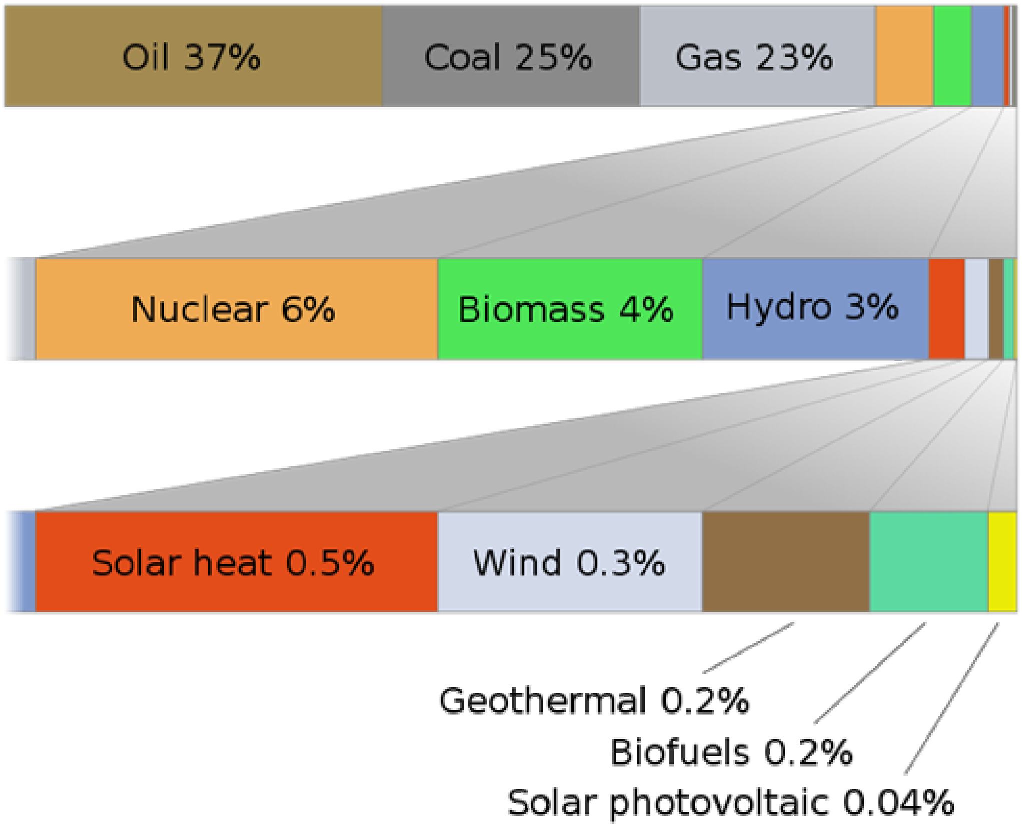
16.6 PWh (1.9 TW average)

E (exa) 10^{18}

P (peta) 10^{15}

T (tera) 10^{12}

Global energy usage



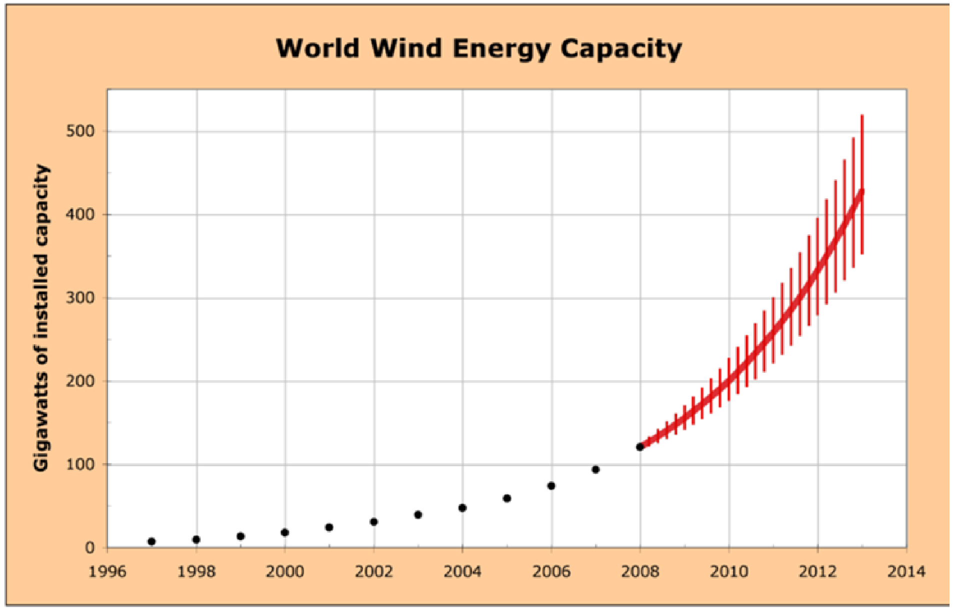
Source: Wikipedia, 2006 data

1. Introduction – Global wind power – **present state**

Global installed wind power nameplate capacity: 121.2 GW (2008)

Europe: 64.9 GW (2008)

1.5 % of electricity generated by wind farms (global, 2008)



Source: World Wind Energy Association
http://www.wwindea.org/

Installed windpower capacity (MW)[46][47][48][49][50][51]

#	Nation	2005	2006	2007	2008[1]
1	United States	9,149	11,603	16,818	25,237
2	Germany	18,415	20,622	22,247	23,933
3	Spain	10,028	11,615	15,145	16,543
4	China	1,260	2,604	6,050	12,121
5	India	4,430	6,270	8,000	9,655
6	Italy	1,718	2,123	2,726	3,736
7	France	757	1,567	2,454	3,404
8	United Kingdom	1,332	1,963	2,389	3,288
9	Denmark (& Faeroe Islands)	3,136	3,140	3,129	3,160
10	Portugal	1,022	1,716	2,150	2,862
11	Canada	683	1,459	1,856	2,369
12	Netherlands	1,219	1,560	1,747	2,225
13	Japan	1,061	1,394	1,538	1,880
14	Australia	708	817	824	1,494
15	Sweden	510	572	788	1,067
16	Ireland	496	745	805	1,245
17	Austria	819	965	982	995
⋮					
32	Hungary	18	61	65	127

Source: Wikipedia

1. Introduction – Global wind power – **potential**

Global wind power potential:

- >5x current energy usage
- >40x current electricity usage

Table 1. Annual wind energy potential, CO_2 emissions, and current electricity consumption for the top 10 CO_2-emitting countries

Country	CO_2 emission, million tonnes	Electricity consumption, TWh	Potential wind energy, TWh	
			Onshore	Offshore
U.S.	5,956.98	3,815.9	74,000	14,000
China	5,607.09	2,398.5	39,000	4,600
Russia	1,696.00	779.6	120,000	23,000
Japan	1,230.36	974.1	570	2,700
India	1,165.72	488.8	2,900	1,100
Germany	844.17	545.7	3,200	940
Canada	631.26	540.5	78,000	21,000
U.K.	577.17	348.6	4,400	6,200
S. Korea	499.63	352.2	130	990
Italy	466.64	307.5	250	160

CO_2 emission and electricity consumption are for 2005; data are from the Energy Information Administration (http://tonto.eia.doe.gov/country/index.cfm).

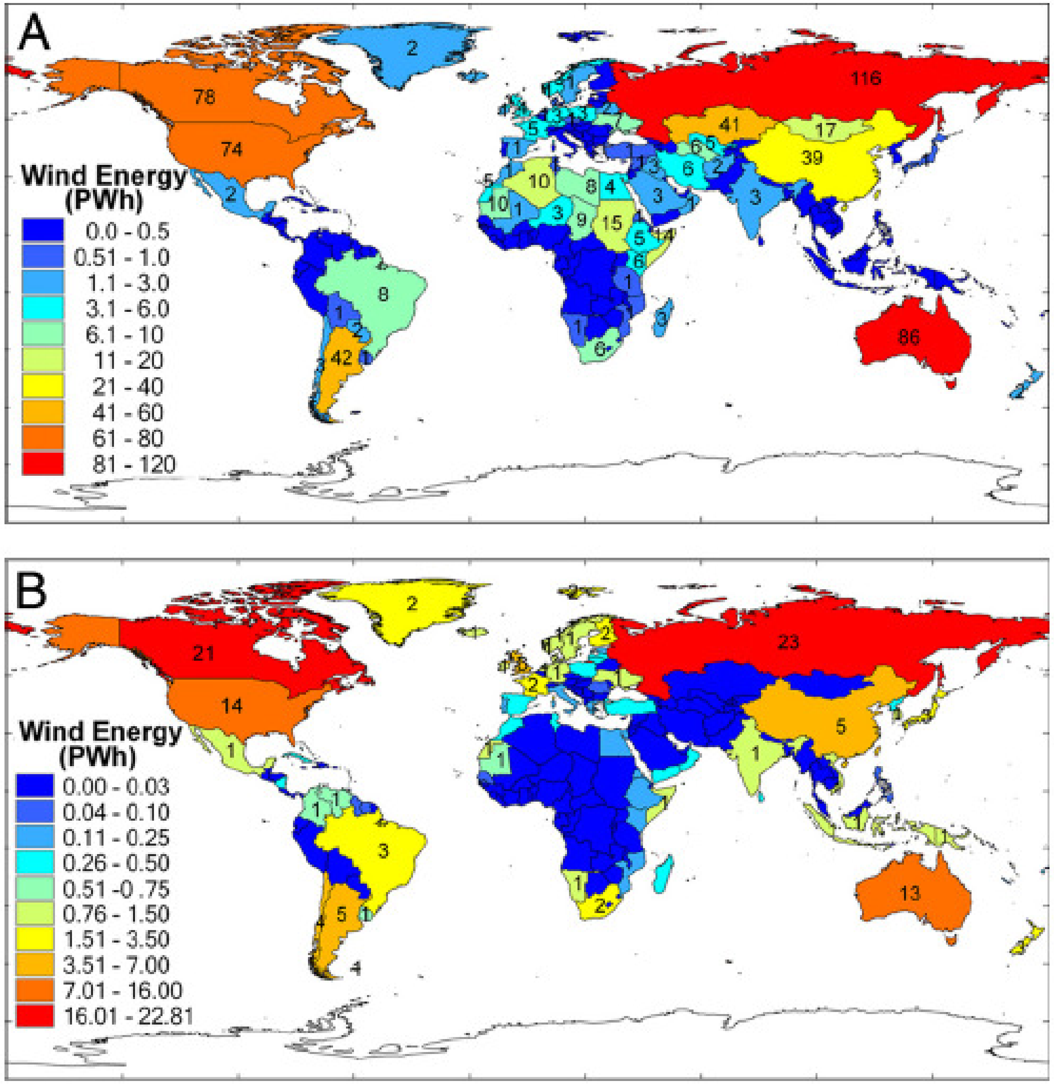


Fig. 2. Annual wind energy potential country by country, restricted to installations with capacity factors >20% with siting limited. (*A*) Onshore. (*B*) Offshore.

Source: Lu et al. www.pnas.org/cgi/doi/10.1073/pnas.0904101106

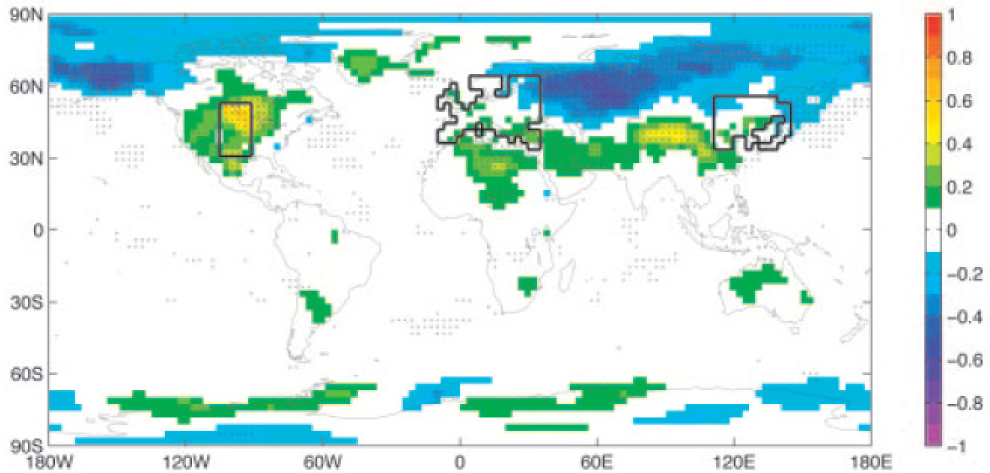
1. Introduction – Global wind power – **future challanges**

• environmental issues / public opposition

• climate change caused by wind farms vs. displaced CO_2 emission

Surface air temperature response for increased drag. Outlined areas: huge wind farms.

Possible effects: negligible compared to benefits



Source: Keith et al. www.pnas.org/cgi/doi/10.1073/pnas.0406930101

• major reorganisation of the grid needed to accept fluctuating wind energy

• storage techologies needed (e.g. separate grid for electric cars, H_2 storage, water storage)

Major problem: *intermittency* of the wind resource

2. The data

- Re-Analysis wind fields: ECMWF ERA-40 provided by Hungarian Met. Office

  Time span: 1 Sep 1958 – 31 Aug 2002 (44 years)

  Temporal resolution: 6 hours

  Spatial resolution: 1°x1°, 2501 gridpoints over Europe

  Fields: ***u*** and ***v*** at 10 m

  u and ***v*** at 1000 hPa

  geopotential at 1000 hPa

  Additionally ERA Interim 10 m ***u***, ***v*** data were used near Mosonszolnok, Hungary for the period 2000-2005.

- Turbine wind speed measurements at Mosonszolnok and Kulcs, Hungary

  provided by L. Varga and B. Stelczer

  Enercon E-40 turbines (600 kW), high frequency nacelle anemometer readings at 65 m above the ground

  Location: 47.816° N, 17.174°E (Mosonszolnok)

  47.057°N, 18.914°E (Kulcs)

  Time span: 1 Jan 2004 – 31 Dec 2006 (Mosonszolnok)

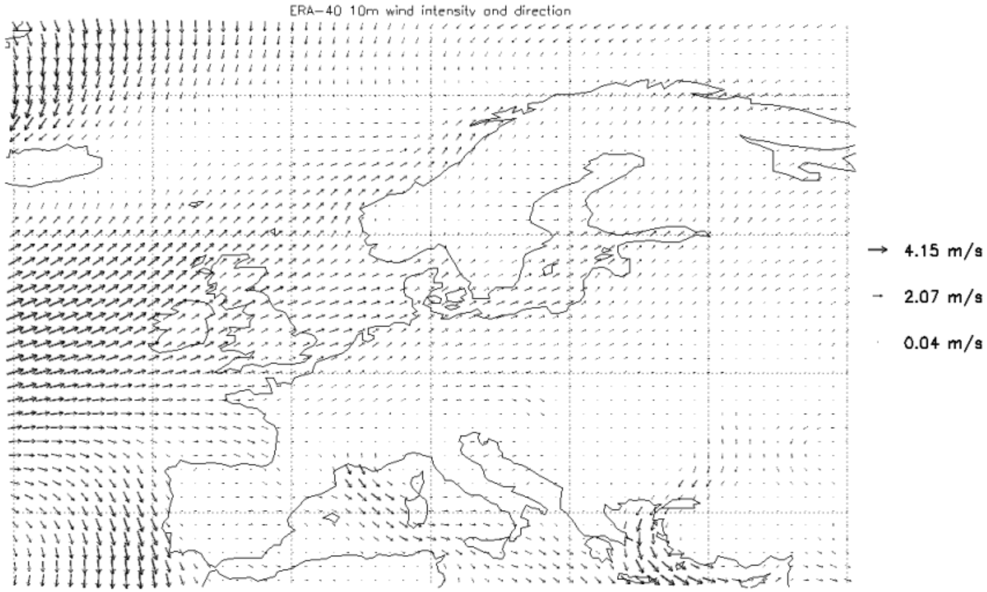
  1 Jan 2005 – (Kulcs)

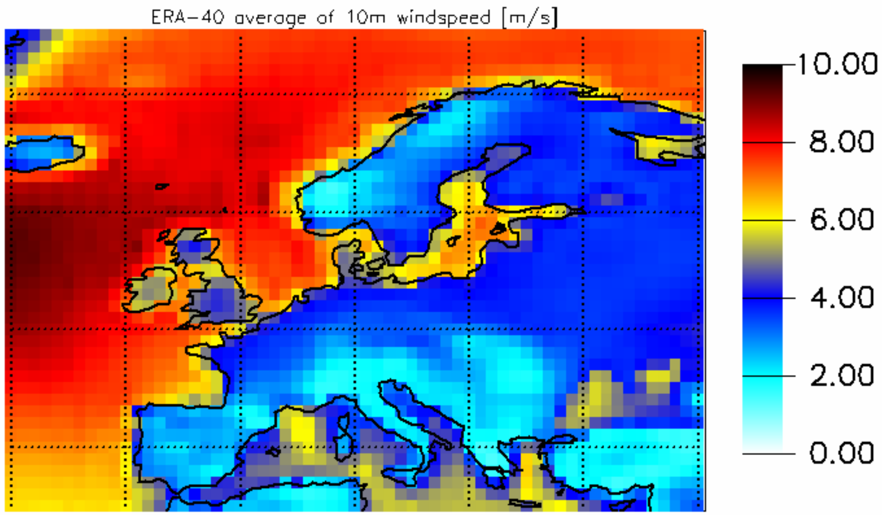
Photo: Sándor Zátonyi

3. Wind speed statistics – Basic statistics

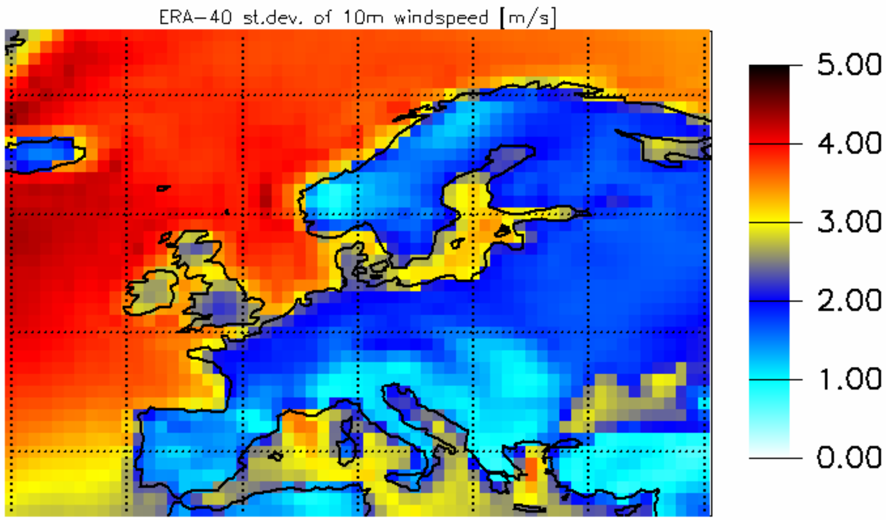
ERA-40 **10 m** wind speed

Average wind velocity





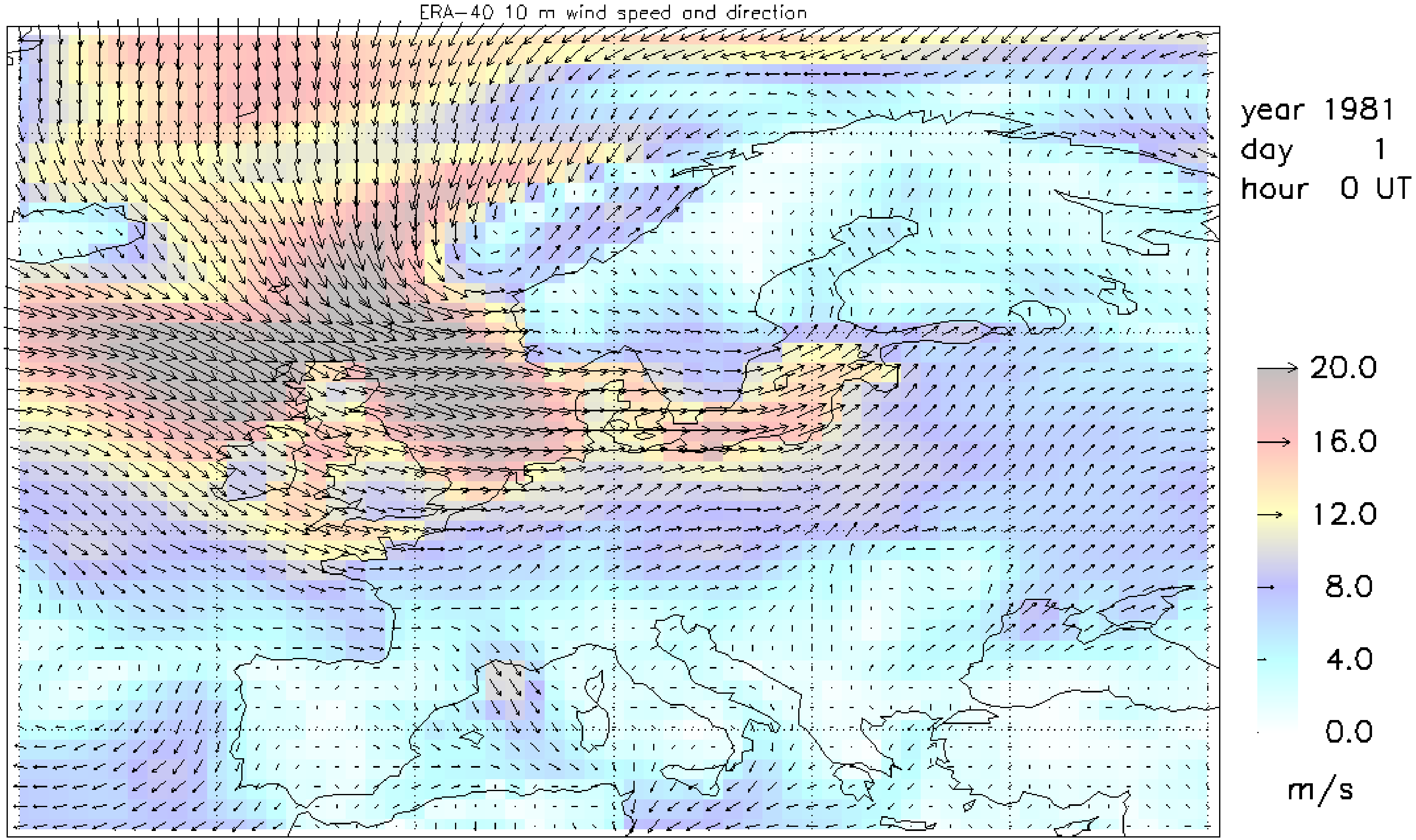
Average wind speed [m/s]



Standard deviation wind speed [m/s]

3. Wind speed statistics – Basic statistics

Animation showing ERA-40 wind filelds at 10 m above the surface



3. Wind speed statistics – Distributions

Wind speed as a random variable – what distribution does it follow?

Simplest concept: ***u***, ***v***: independent Gaussian distributions, 0 mean, common st. dev. → Rayleigh distribution - *unrealistic*

A possible generalization: u, v still Gaussian, but linearly correlated, nonzero mean, different st. dev. - *many parameters, not universal*

Another generalization: Weibull distribution … Generalized gamma distr.

Further attempts: Lognormal distribution

(i) Conceptually simple: Rayleigh

$$f(x;\lambda) = \frac{2}{\lambda}\left(\frac{x}{\lambda}\right) e^{-(x/\lambda)^2}$$

(ii) Textbook generalization: Weibull

$$f(x;k,\lambda) = \frac{k}{\lambda}\left(\frac{x}{\lambda}\right)^{k-1} e^{-(x/\lambda)^k}$$

(iii) Better fits: generalized gamma

$$f(x;k,\lambda,\varepsilon) = \frac{k}{\lambda\Gamma(\varepsilon)}\left(\frac{x}{\lambda}\right)^{\varepsilon k-1} e^{-(x/\lambda)^k}$$

3. Wind speed statistics – Distributions

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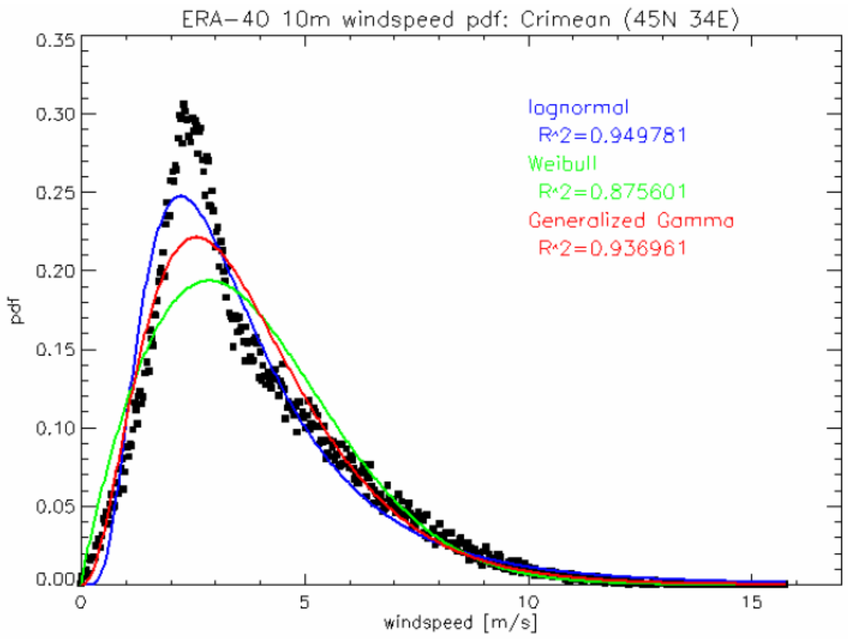
Further attempts: Lognormal distribution



$$f(x;\lambda)=\frac{2}{\lambda}\left(\frac{x}{\lambda}\right)e^{-(x/\lambda)^2}$$

$$f(x;k,\lambda)=\frac{k}{\lambda}\left(\frac{x}{\lambda}\right)^{k-1}e^{-(x/\lambda)^k}$$

$$f(x;k,\lambda,\varepsilon)=\frac{k}{\lambda\Gamma(\varepsilon)}\left(\frac{x}{\lambda}\right)^{\varepsilon k-1}e^{-(x/\lambda)^k}$$

3. Wind speed statistics – Distributions

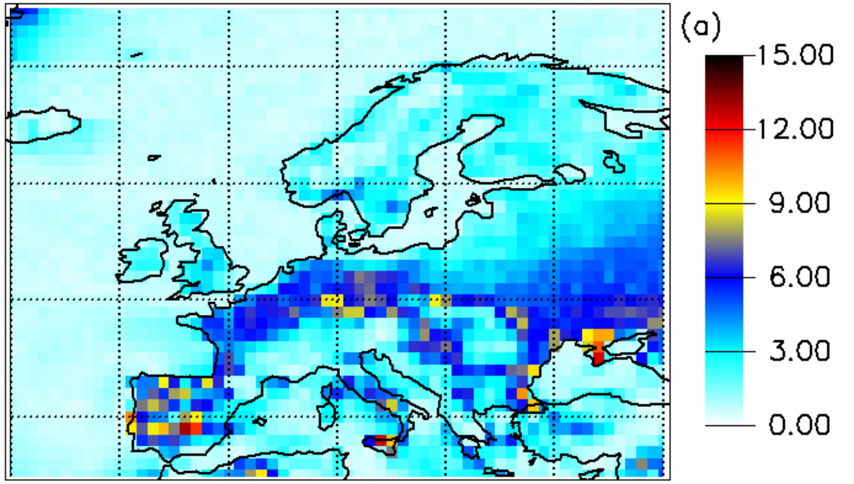
Goodness of fit of different distributions:

100 $(1-R^2)$

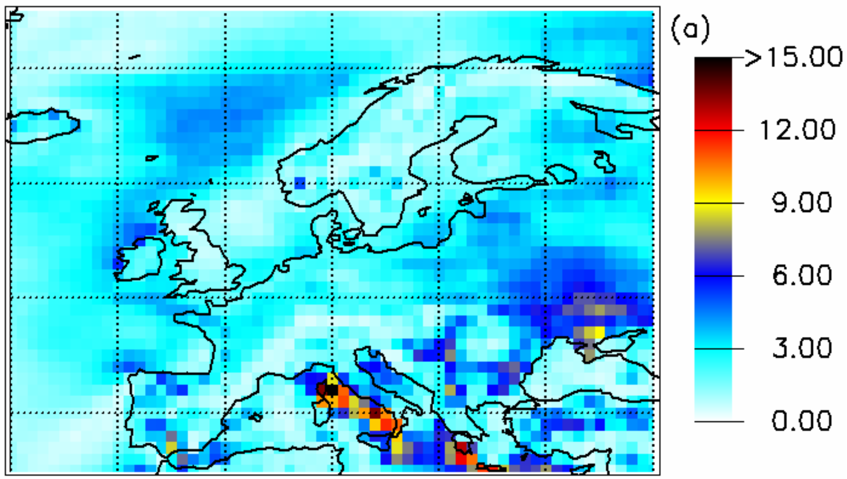
unexplained percentage variance

Best:

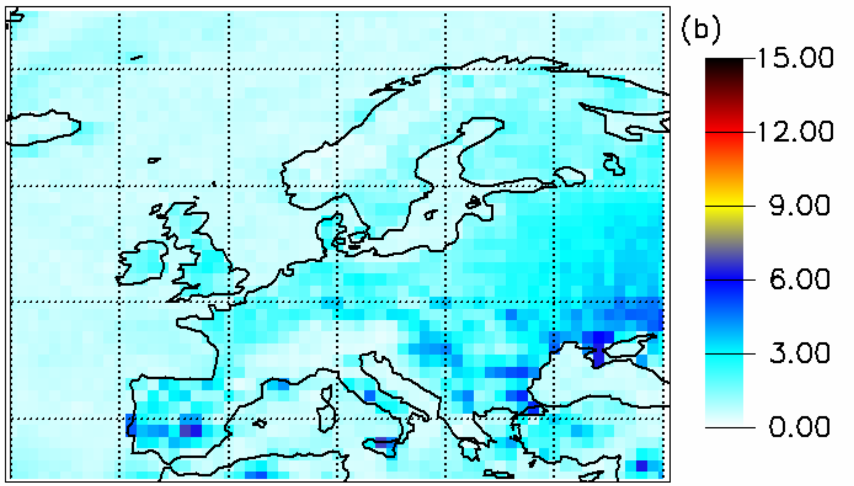
Generalized gamma distribution



Weibull distribution



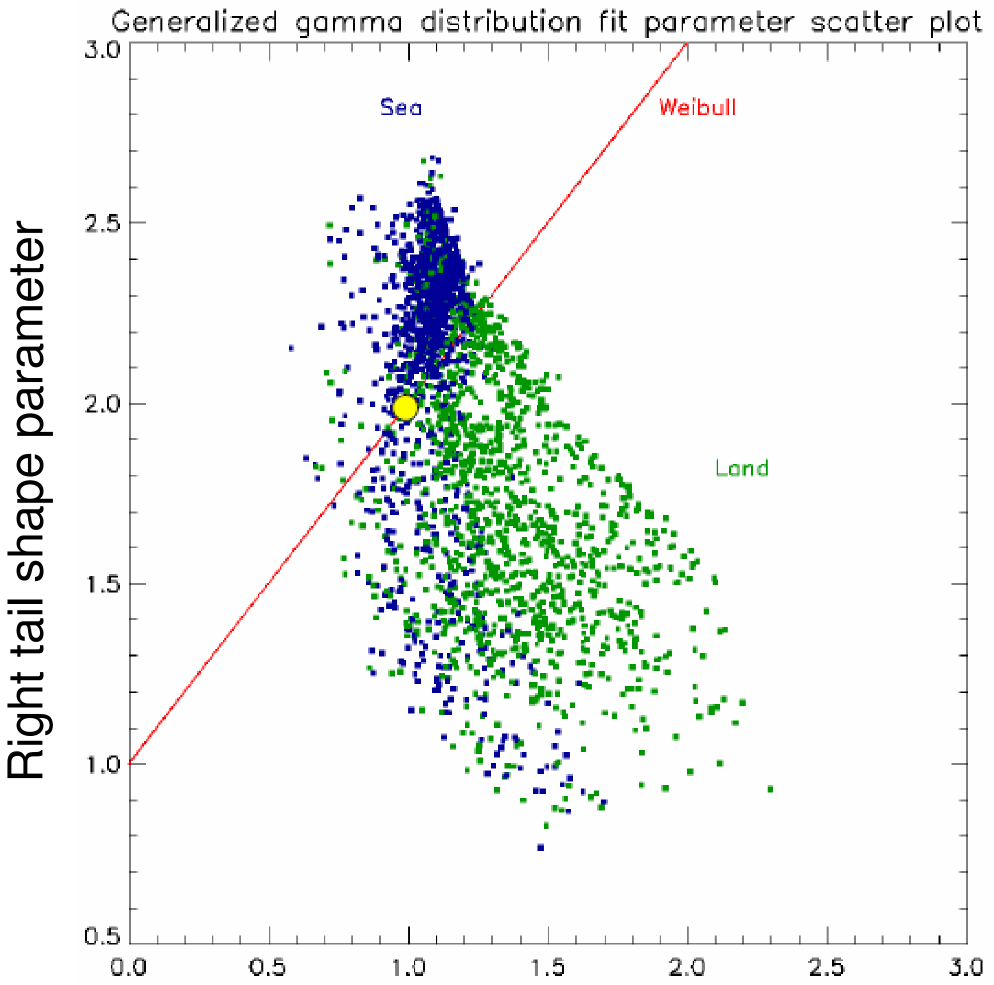
Joint Gaussian distribution



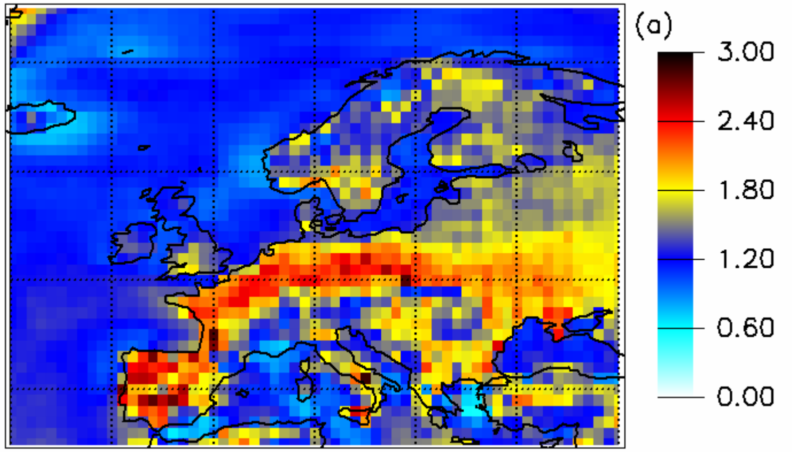
Generalized gamma distribution

3. Wind speed statistics – Distributions

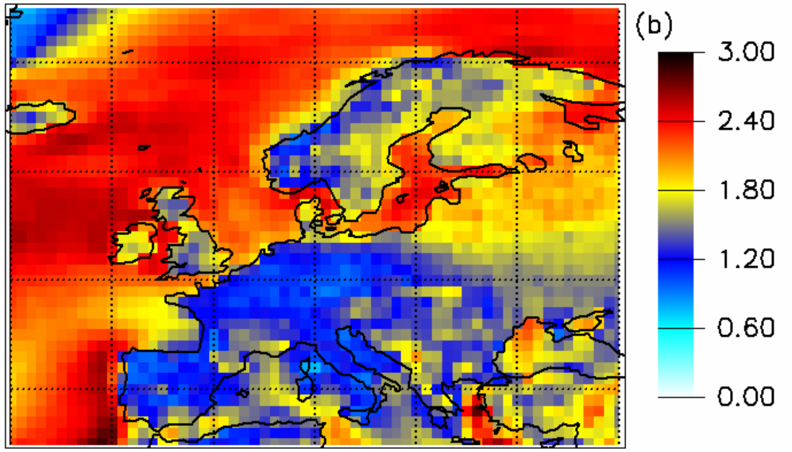
The Generalized gamma (GG) fit



Left tail shape parameter



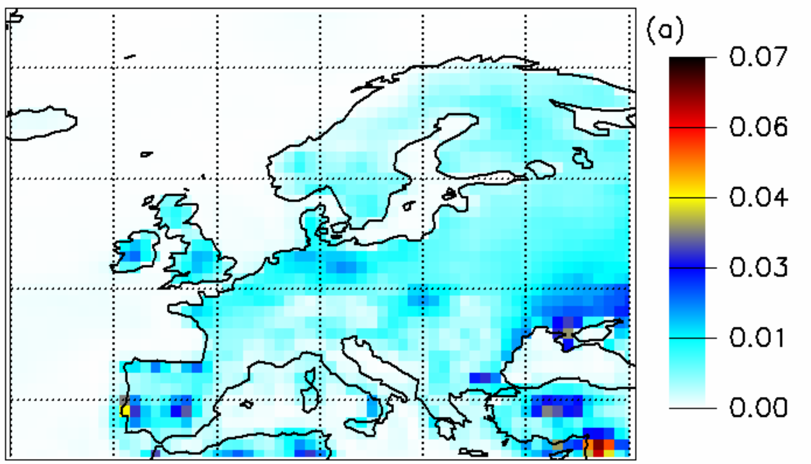
Left tail shape parameter



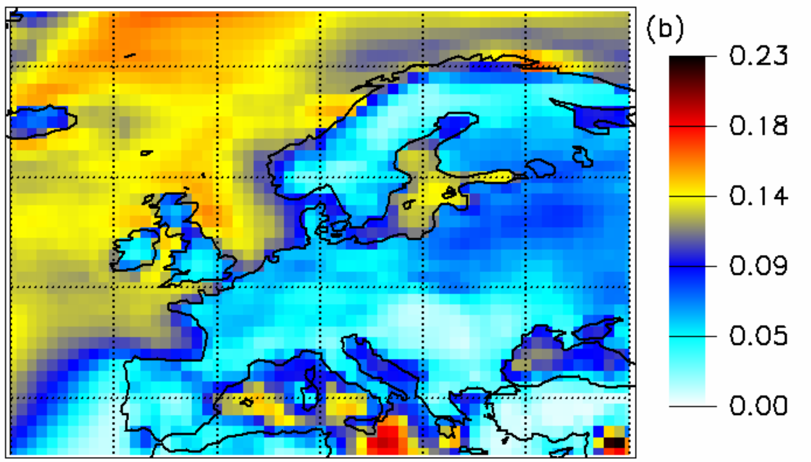
Right tail shape parameter

3. Wind speed statistics – Daily and annual varability

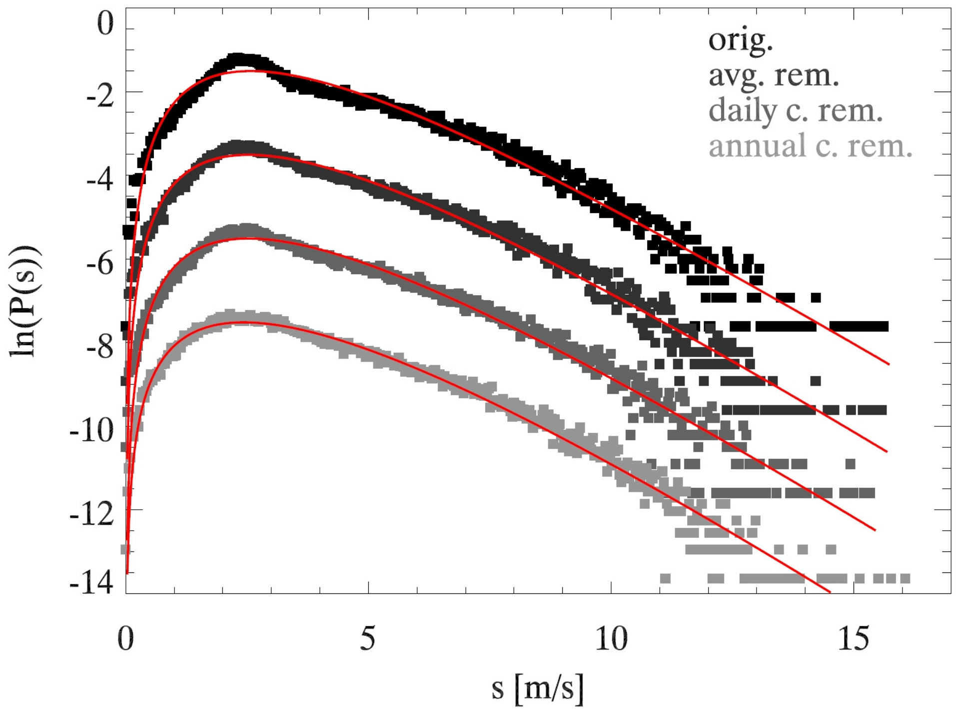
FFT power spectra: total power = 1



Daily power



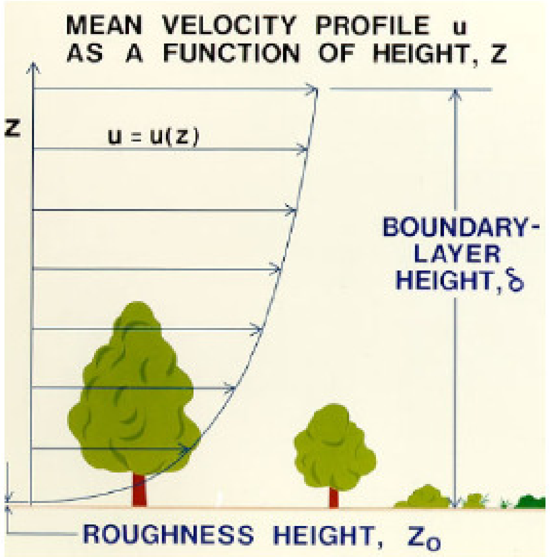
Yearly power



Wind speed pdf at the Crimean peninsula

By removing daily and yearly cycles (***u*** and ***v***) from wind speed records, the GG fit substantially improves.

3. Wind speed statistics – Height dependence



Wind speed changes with height

Analytical methods → u(z) ~ $\ln(z/z_0)$

Profile depends on atmospheric stability

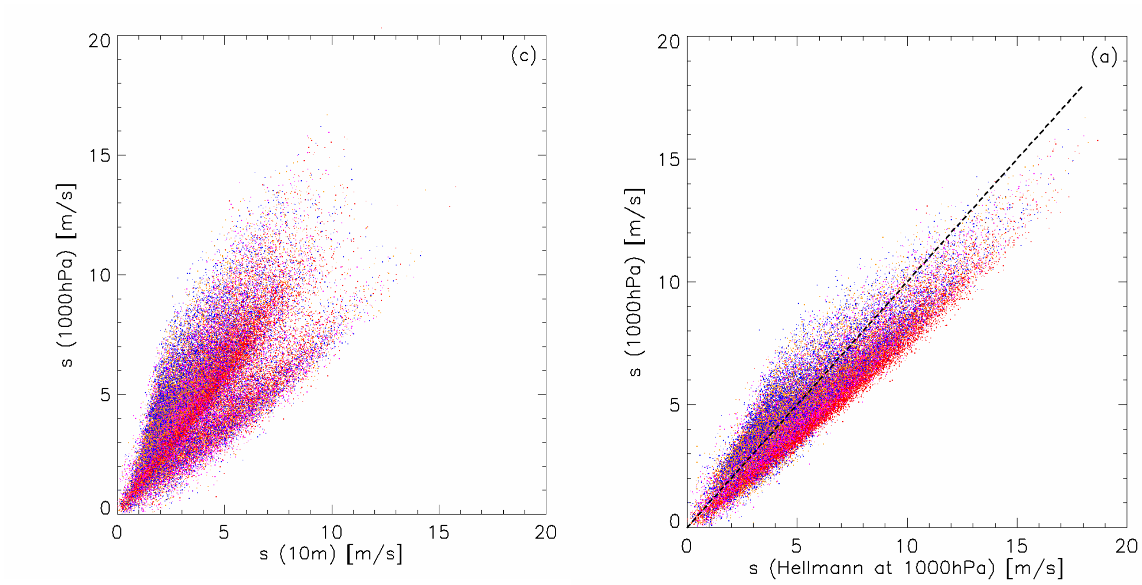
In practice: power law approximation: $$\frac{s_2}{s_1} = \left(\frac{h_2}{h_1}\right)^{\alpha}$$

α – Hellmann exponent

Using wind data at 10 m and 1000 hPa and the geopotential height of the 1000 hPa level, α can be determined *at some locations*.

But not everywhere.

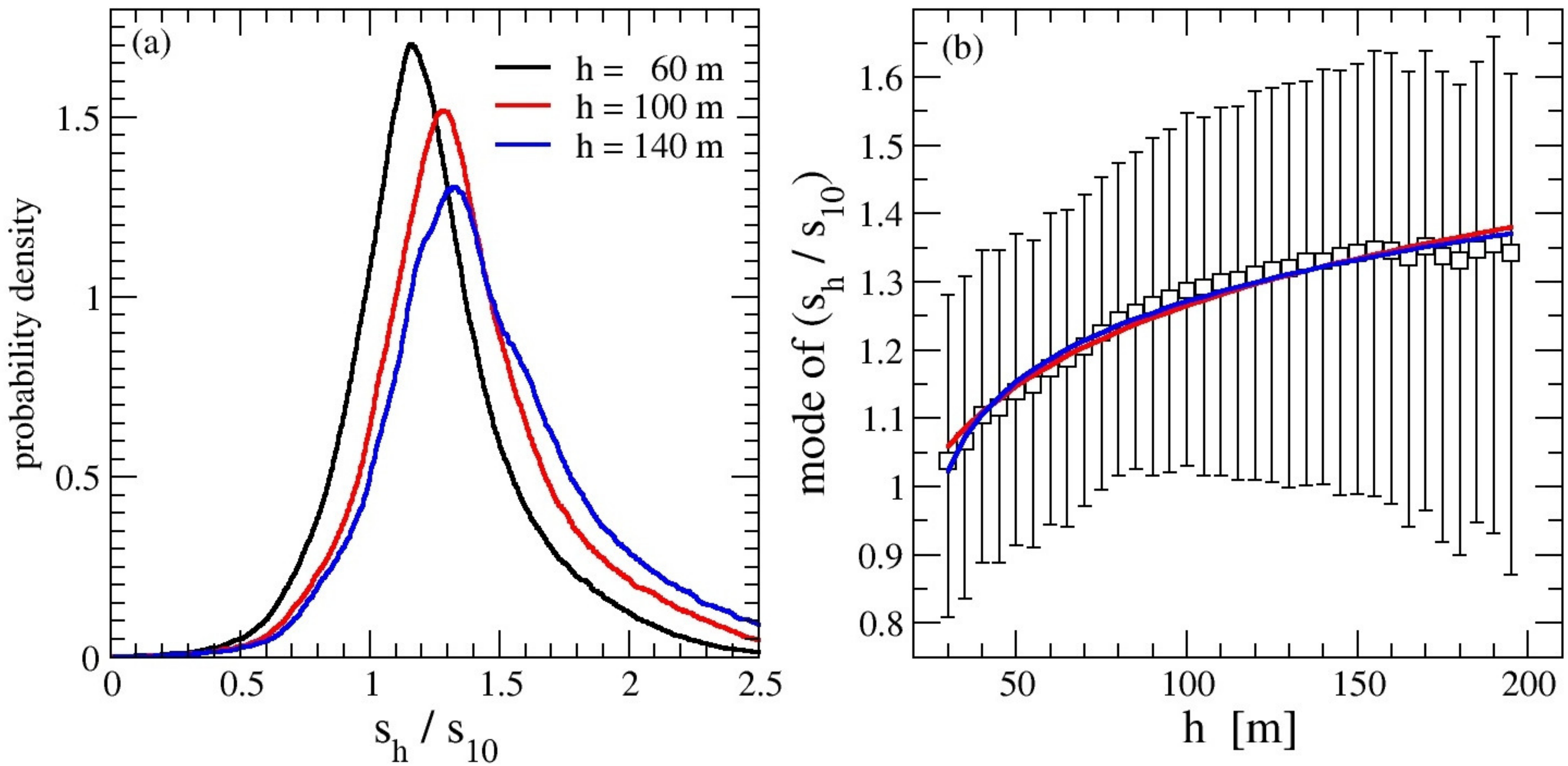
→ we used an average empirical profile.



Example of using the power law profile on ERA-40 data (in northern Germany).

3. Wind speed statistics – Height dependence

Average empirical profile - based on 10 m and 1000 hPa wind fields, where available



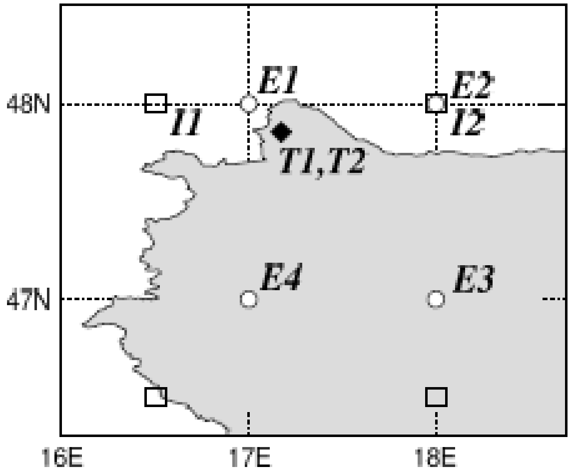
Used for wind power calculations (later): $s_{100m} = 1.28\ s_{10m}$

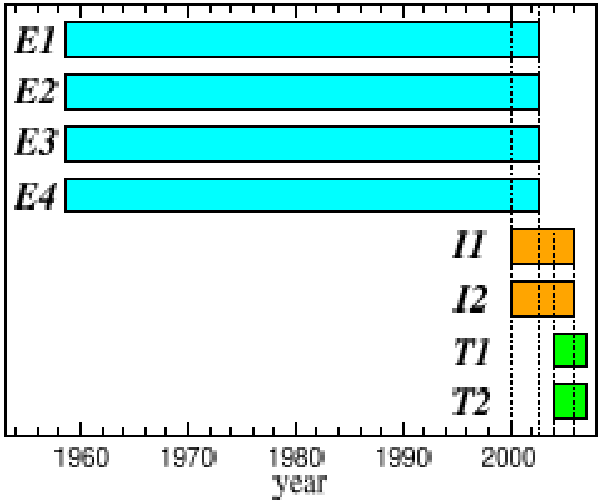
transforms surface wind speed to turbine height

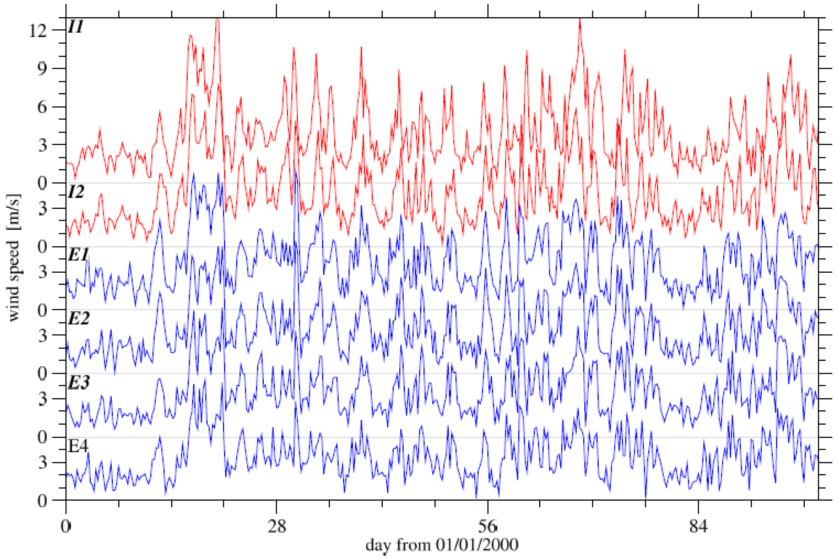
3. Wind speed statistics – Reanalysis - tower data comparison

Turbines at Mosonszolnok, Hungary operate only since 1 Jan 2004.

Direct ERA-40 – turbine comparison is not possible → we used ERA Interim data







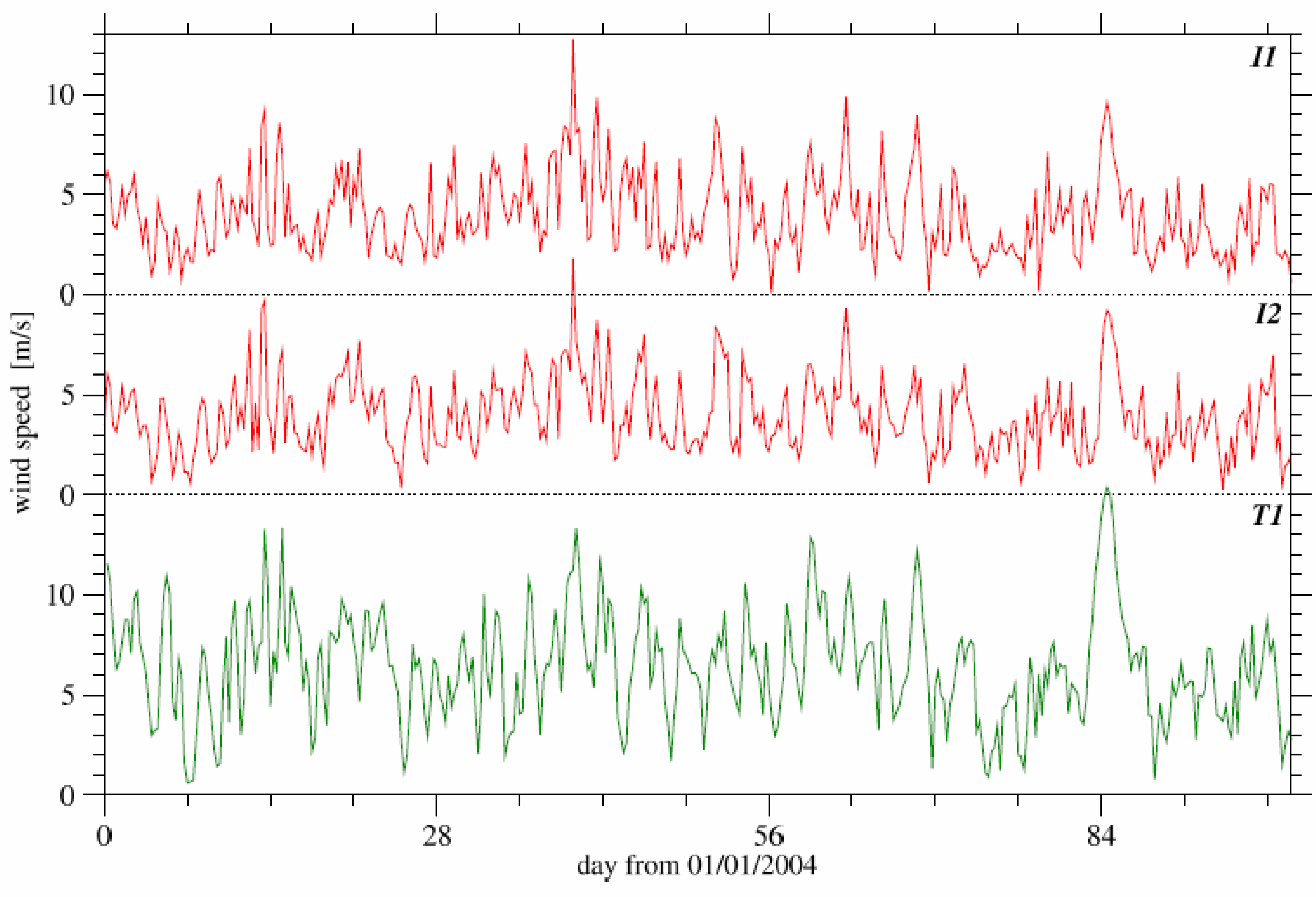
← ERA-40 – ERA Interim wind speed records

Location: Little Hungarian Plain

E1-4	ERA-40 gridpoints
I1-2	ERA Interim gridpoints
T1-2	Turbine locations

3. Wind speed statistics – Reanalysis - tower data comparison

ERA Interim (10 m) – tower data (65 m) wind speed records



3. Wind speed statistics – Reanalysis - tower data comparison

ERA reanalysis – tower wind speed correlation matrix $Corr(s_i, s_j) = \frac{\langle (s_i(t) - \overline{s_i})(s_j(t) - \overline{s_j}) \rangle_t}{\sigma_i \sigma_j}$

	$E1$	$E2$	$E3$	$E4$	$I1$	$I2$	$T1$	$T2$
$E1$	1	0.929	0.824	0.873	0.797	0.772	–	–
$E2$	(74.6)	1	0.902	0.841	0.765	0.847	–	–
$E3$	(134.3)	(111.2)	1	0.913	0.716	0.820	–	–
$E4$	(111.2)	(134.3)	(76.1)	1	0.742	0.757	–	–
$I1$	(37.3)	(111.9)	(158.5)	(117.4)	1	0.880	0.768	0.743
$I2$	(74.6)	(0)	(111.2)	(134.3)	(111.9)	1	0.753	0.734
$T1$	–	–	–	–	(53.7)	(63.3)	1	0.971
$T2$	–	–	–	–	(53.7)	(63.3)	(0.4)	1

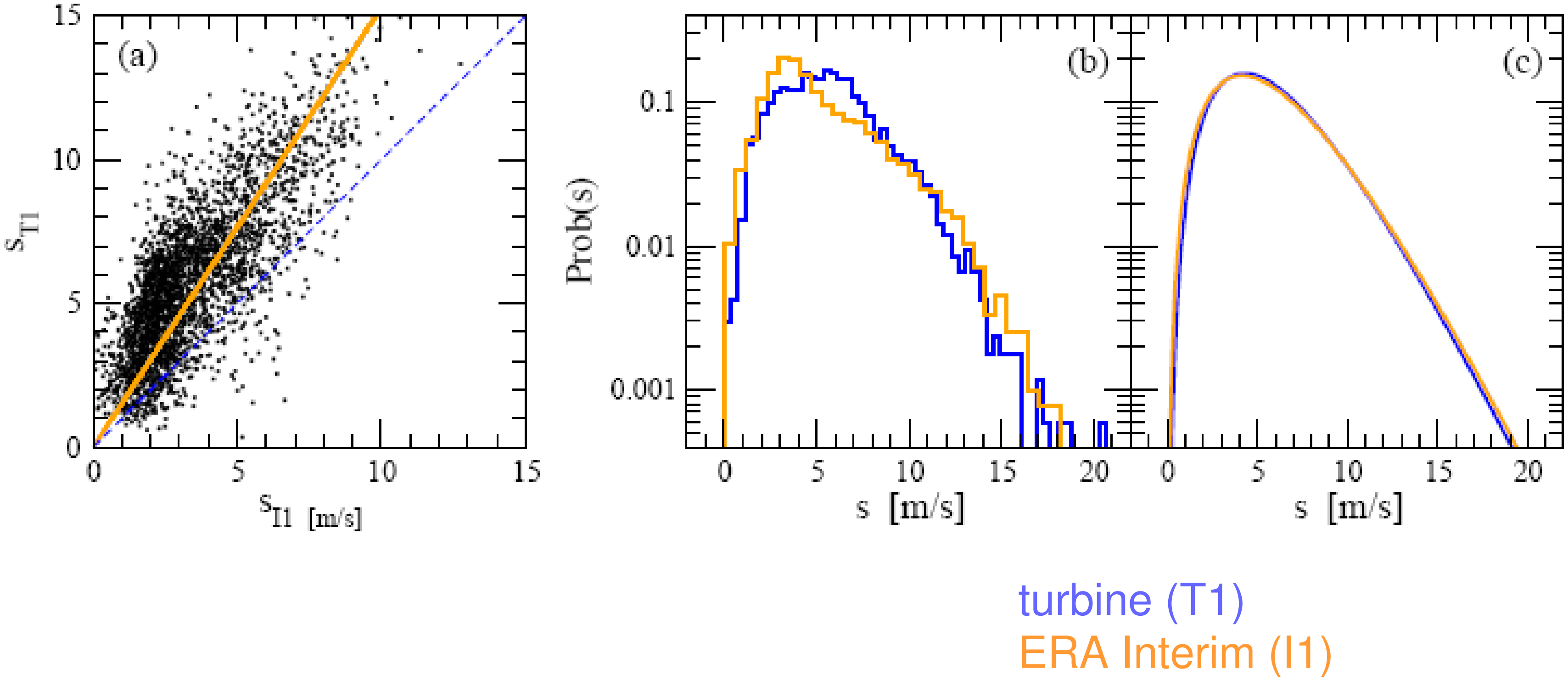
Relatively good agreement, gross features are reproduced.

But: relatively simple (flat) orography might help (coherent wind fields)

3. Wind speed statistics – Reanalysis - tower data comparison

ERA Interim – turbine data: linear regression

Relatively good agreement of pdfs is reached by rescaling with 1.51 (from regression). This is close to matching the averages.

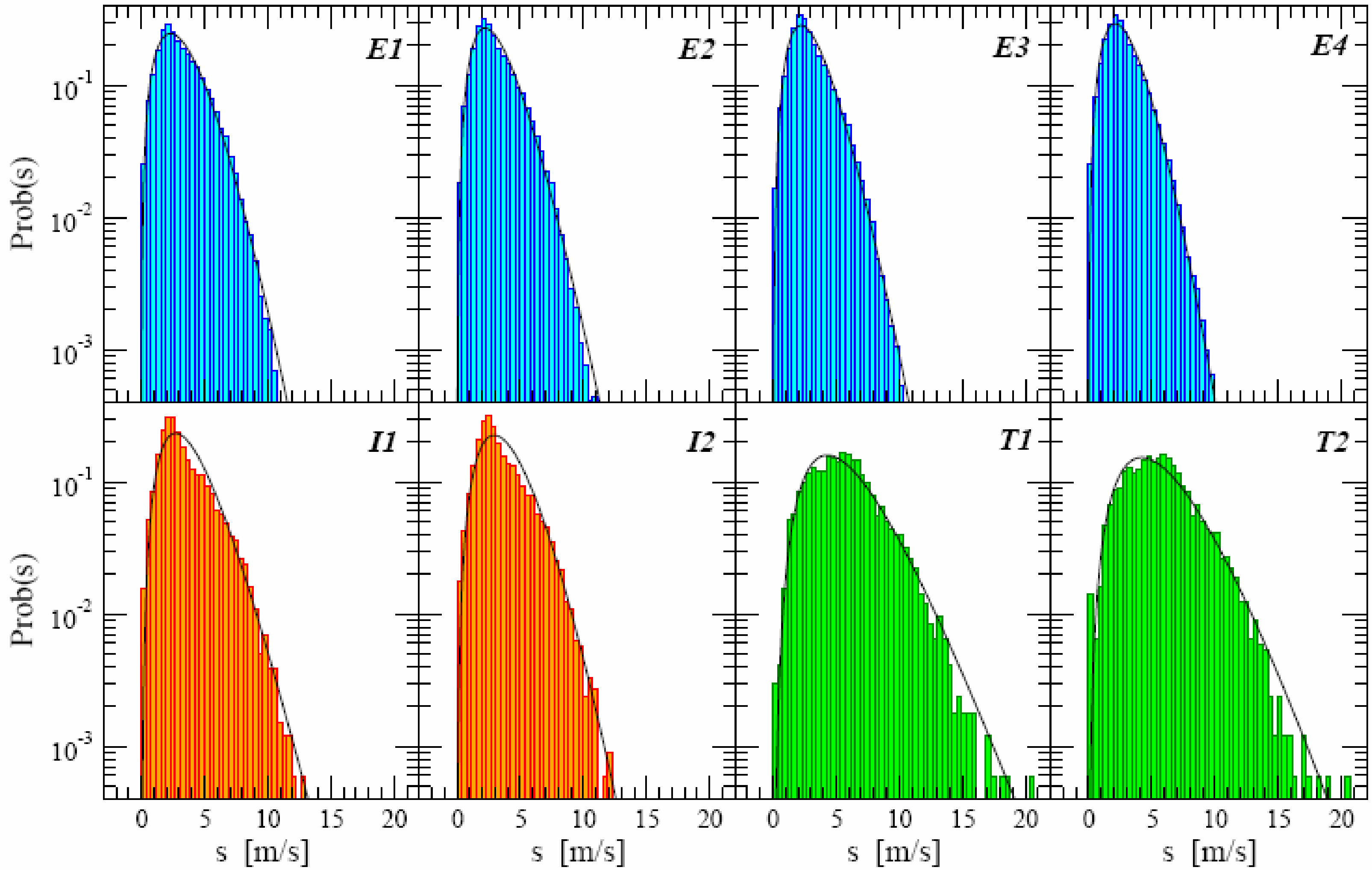


Note: the average empirical wind profile suggests rescaling with 1.19

A map of the scaling factor would be needed – E.ON data (?)

3. Wind speed statistics – Reanalysis - tower data comparison

Empirical probability density functions of wind speed



4. Wind power networks – All-European wind power integration

Motivation:

Wind is a volatile resource → intermittent power

Integration over large areas →
decreased fluctuations
„Wind always blows somewhere."

What are the possibilities / limitations
for Europe arising from the wind resource?

4. Wind power networks – Wind power estimation

Step 1:

Surface level (10 m) wind speed → hub height wind speed (100 m)

Using *empirical wind profile*: $s_{100m} = 1.28 \cdot s_{10m}$

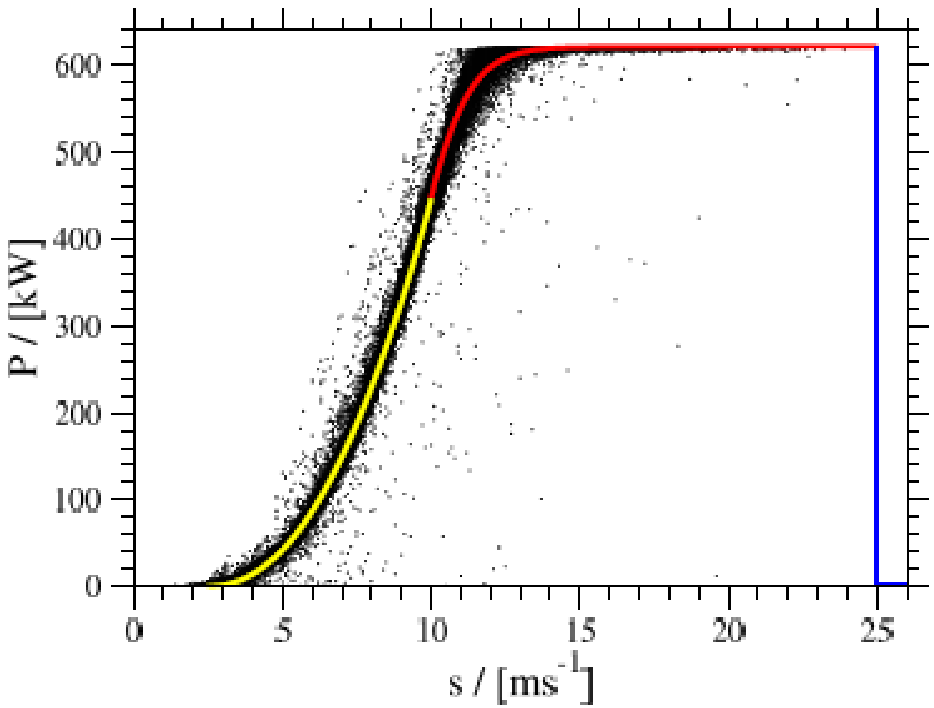
Step 2:

hub height wind speed (100 m) → wind power

using empirical power curve

(Enercon E-40, 600 kW, Mosonszolnok, Hungary)

power: capacity factor (similiar power curves)



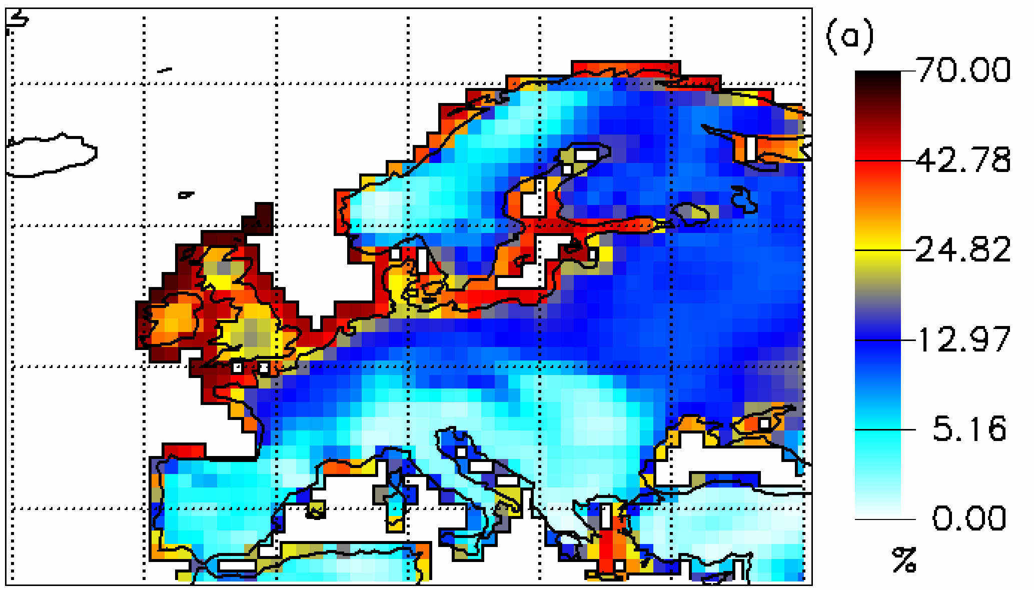
Cut-in: 1.2 m/s

Plateau: 103.3 %

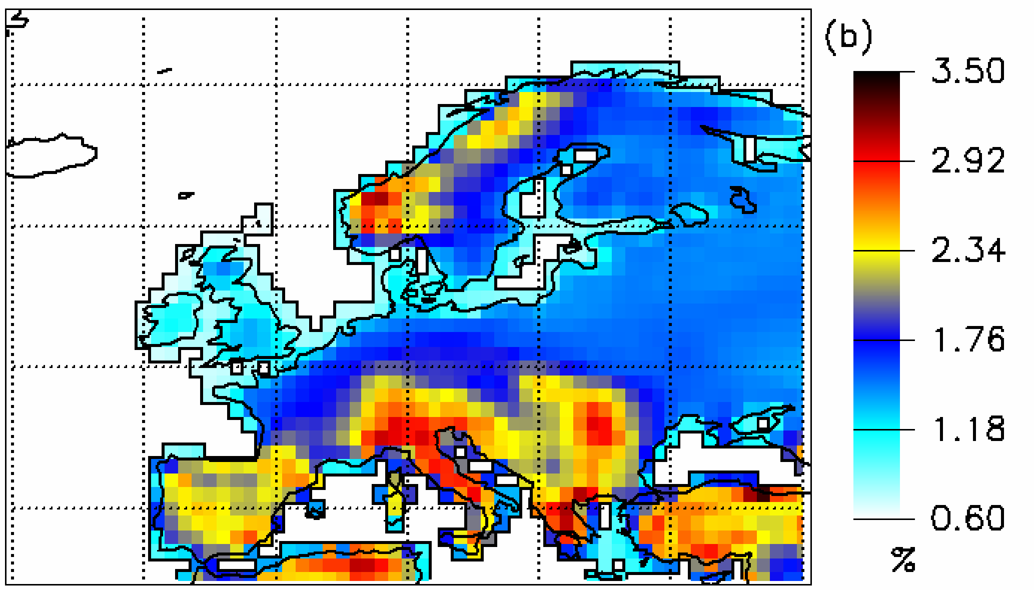
Exponent: 2.8

4. Static networks

All continental areas + 1 °
coastline
in an ideal network (no losses)
identical turbines at each
gridpoint
1325 gridpoints



Average wind power →
Best areas: Atlantic coast



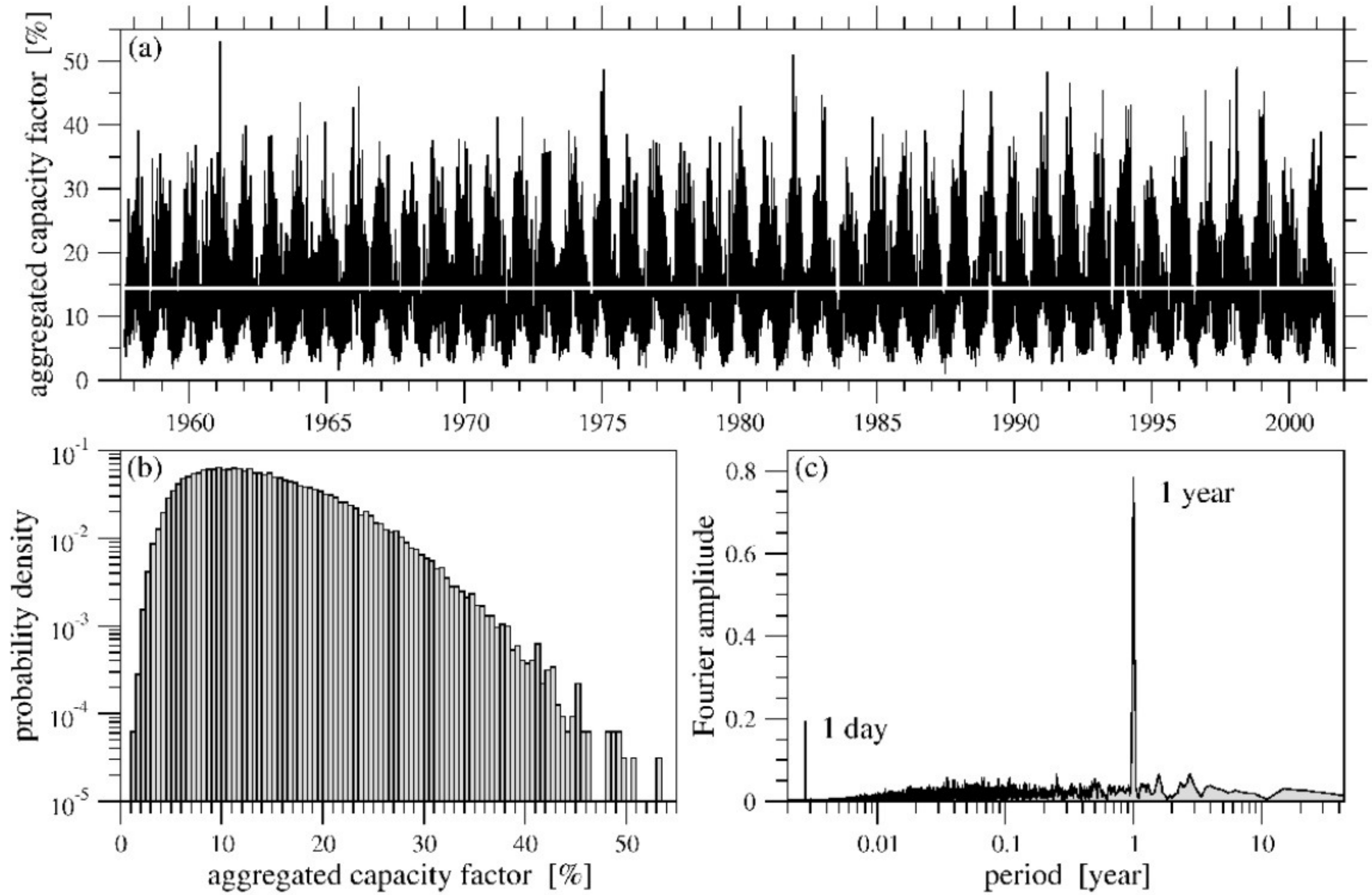
Coefficient of variation of wind power →

High variability,
Distribution is strongly non-Gaussian

4. Static networks

Fully connected network: *aggregated capacity factor*

average 14.4 %, standard deviation: 6.8%



4. Static networks

Fully connected network:

• huge idle capacities (low wind sites)
• great fluctuations

Limited areas:

Great Britain

Average aggregated capacity factor: 41.0 (±25.9) %

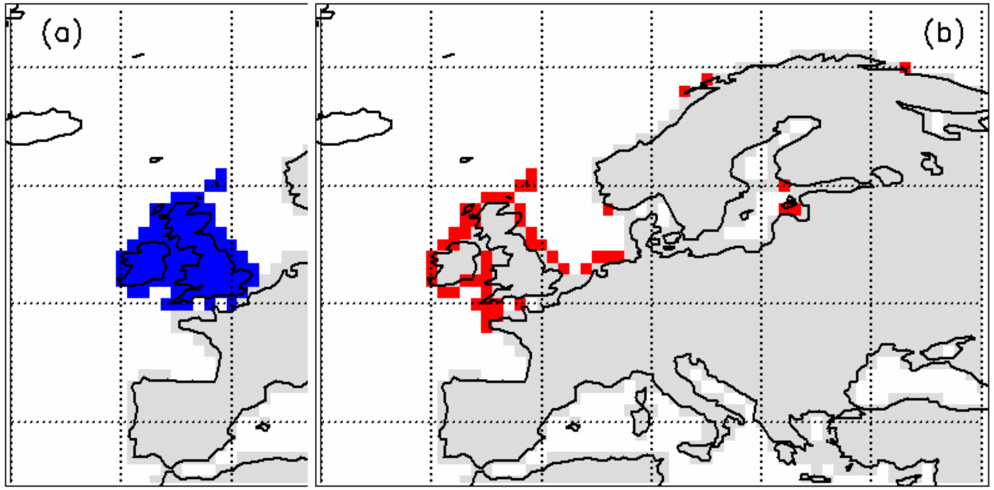
• higher output
• higher fluctuations

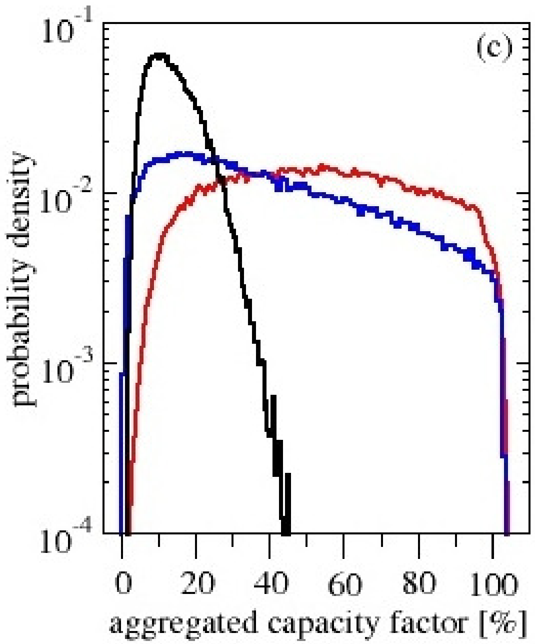
„Base network"

50 sites: most frequently at rated power

Average aggregated capacity factor: 53.8 (±24.3) %

• high output
• low output less probable (←distant sites)



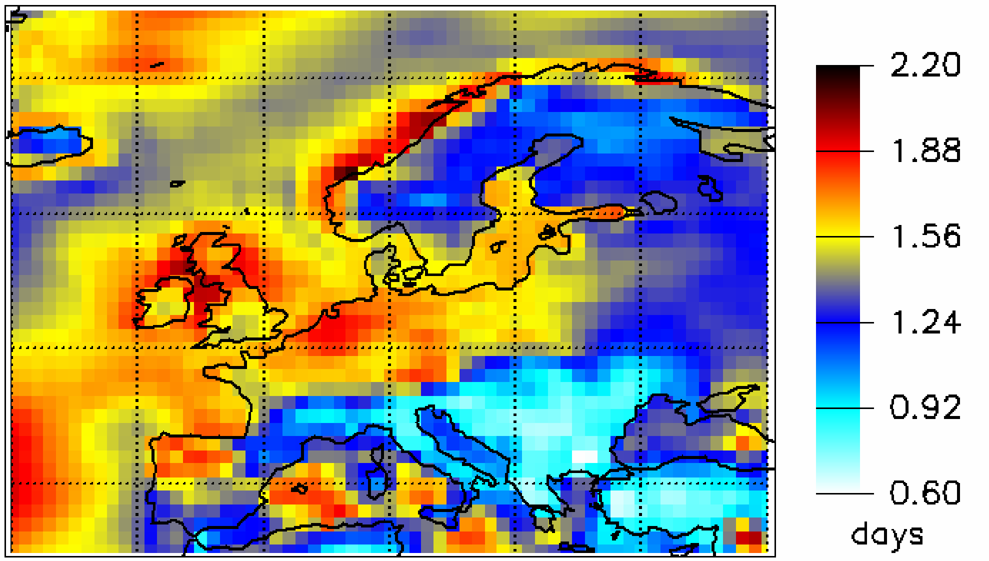


4. Static networks

Reasons:

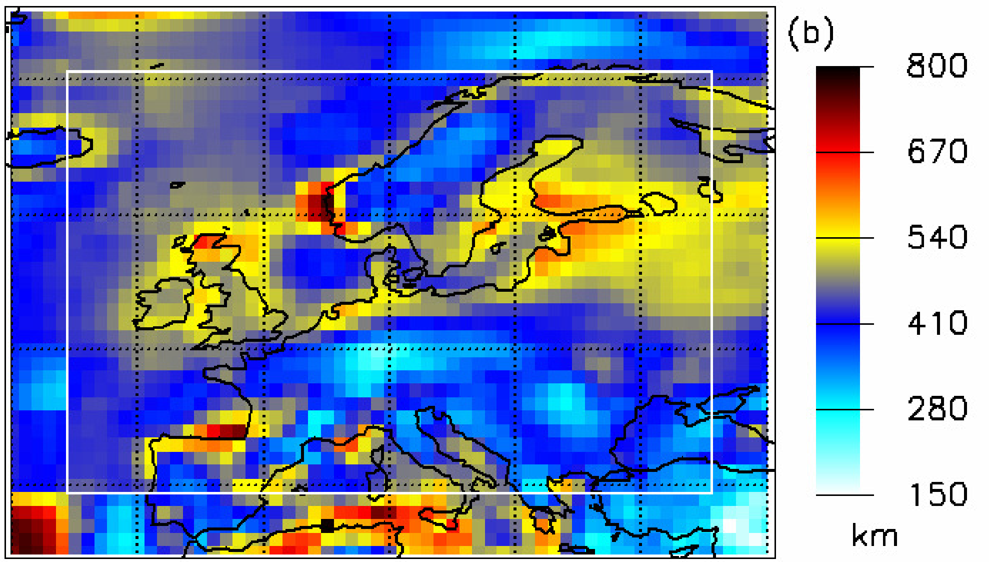
Characteristic time of autocorrelations →
(exp. decay)

short correlations



Characteristic length of spatial correlations →
(exp. decay)

large areas are strongly correlated



4. Static networks

Reasons:

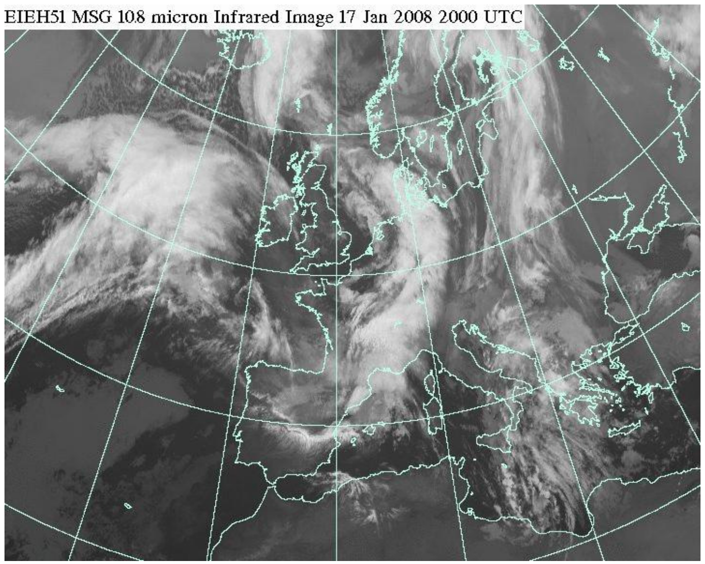
Another test: Random configurations with fixed number of gridpoints

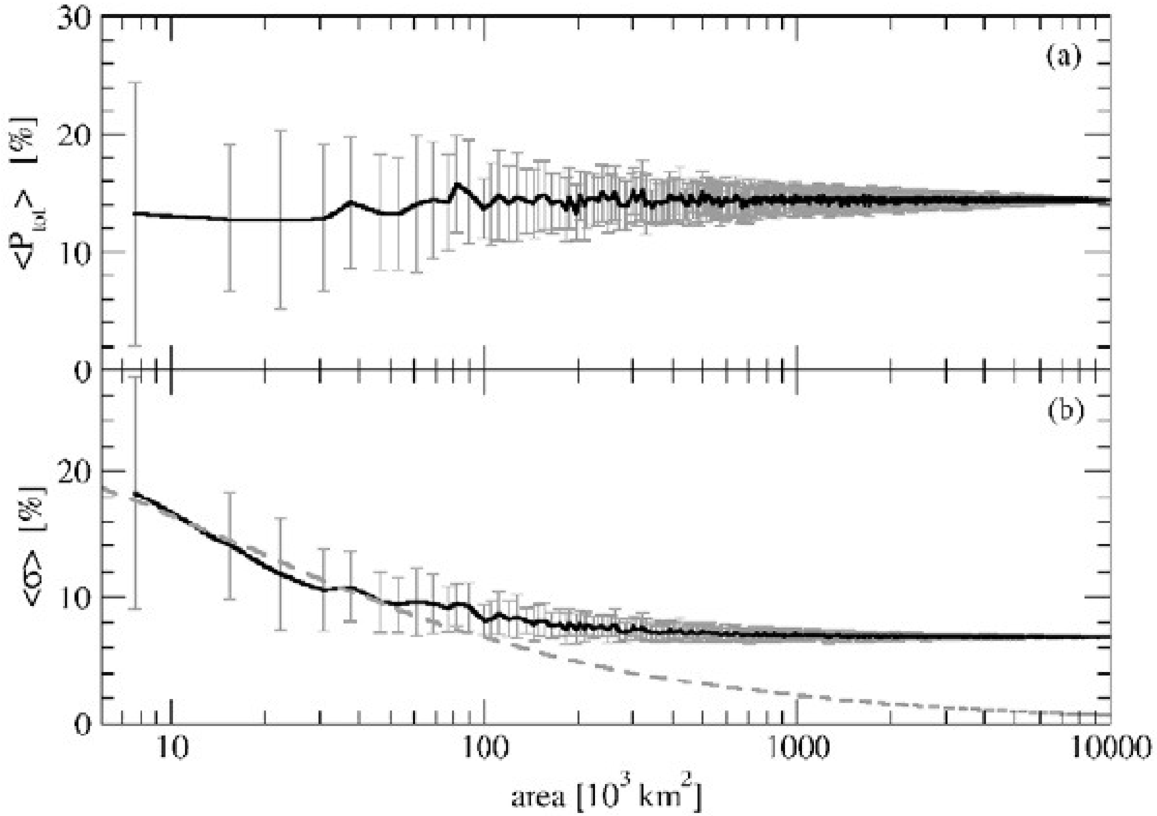
ensemble averages of *average output* and *standard deviation of the output*

Spatial correlations → individual gridpoints: not independent variables

↑

Weather systems



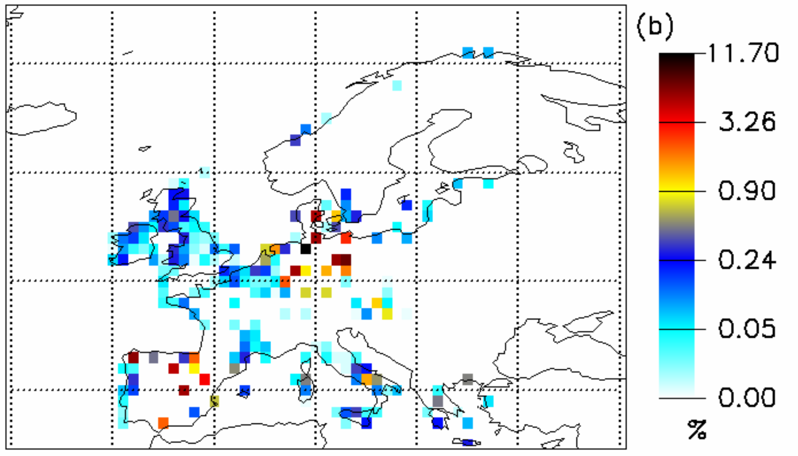


4. Static networks

Diverse networks:
Different capacity limits (different set of turbines) at different gridpoints

Each gridpoint: weight w_i $\sum_{i=1}^{1325} w_i = 1 \quad , 0 \le w_i \le 1$

Optimal distribution of weights: fluctuations of aggregated power minimal (coeff. of var.)
Problem: constrained nonlinear optimization in 1325 dimensions
Iterative Monte Carlo algorithm

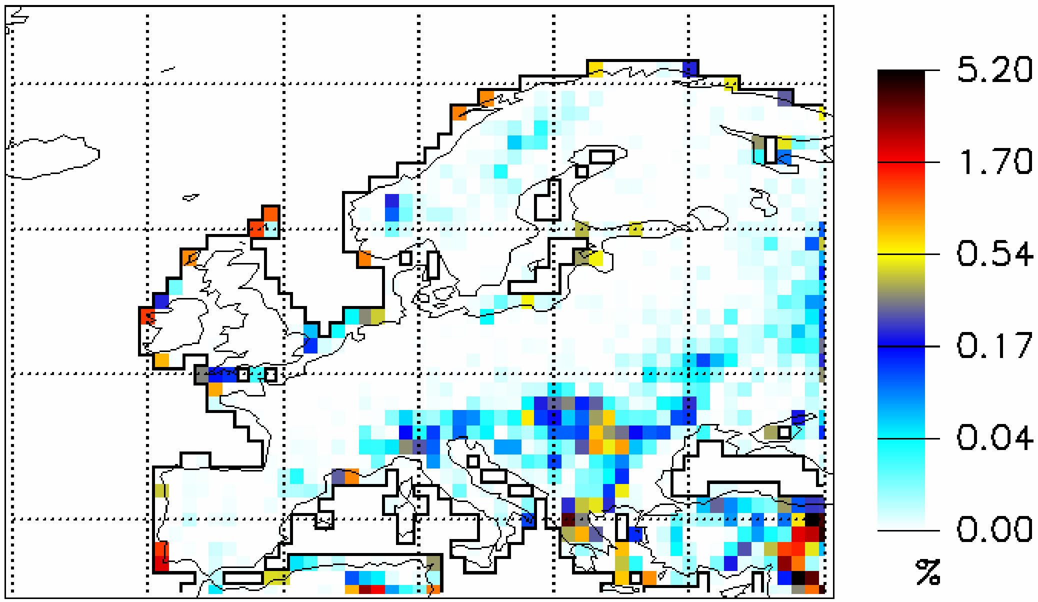


Real setup, October 2007

Results:
Weight distribution →
Average capacity factor:
14.9 (±4.2) %

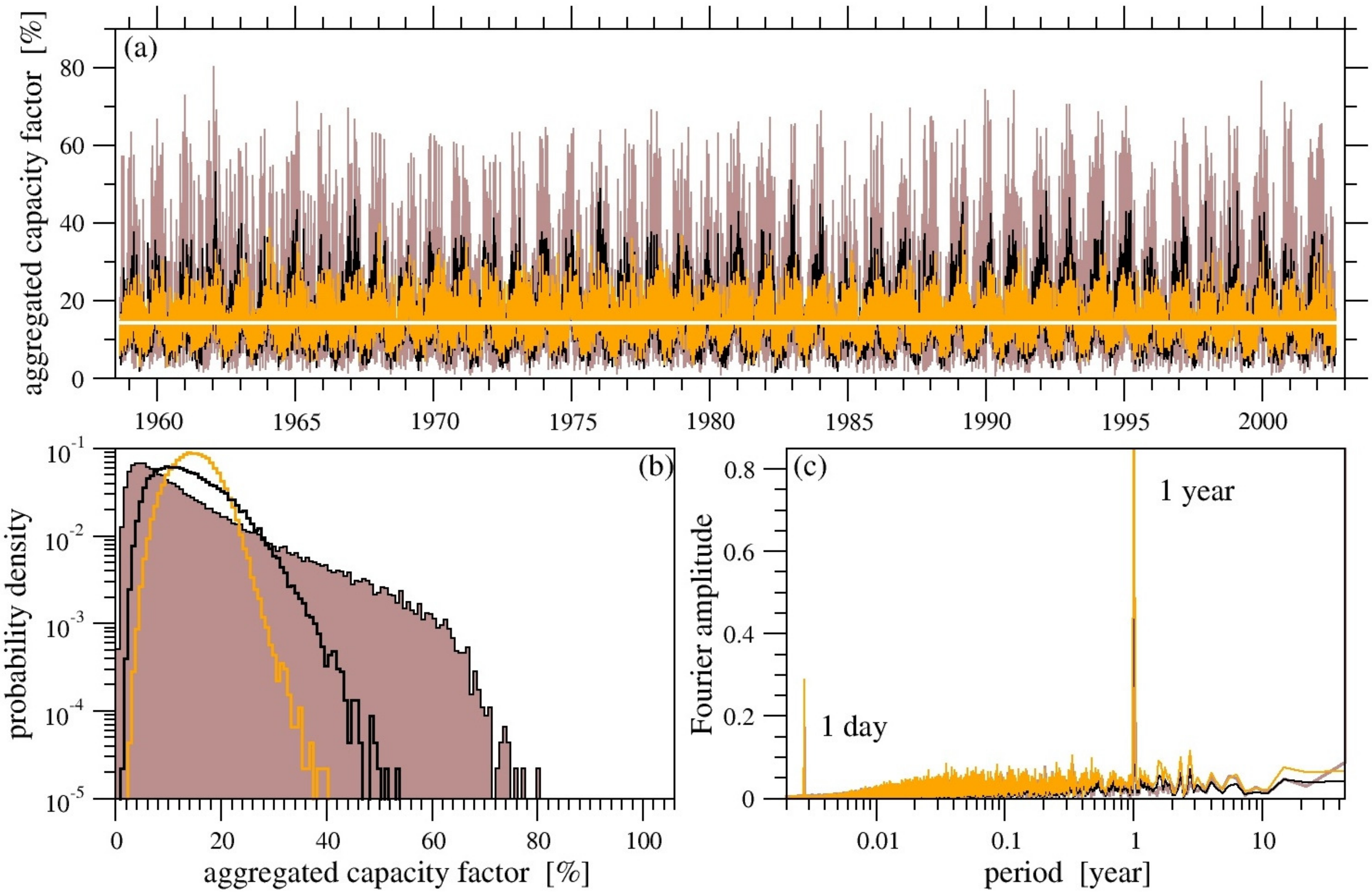
(14.4 (±6.8) %
for uniform weights)

Smaller fluctuations



4. Static networks based on real wind farm data

Average: all ~14%, st.dev.: 12.4% (real), 6.8% (uniform), 4.2% (optimized)



4. Dynamic networks

Full dynamic control

Target:

aggregated power output of the network should be constant at a modest level: 50 sites (out of 1325; 3.8 %) at rated power

- ideal network (no losses)

Strategy:

sites at rated power are connected
(preferably from the „base network”)

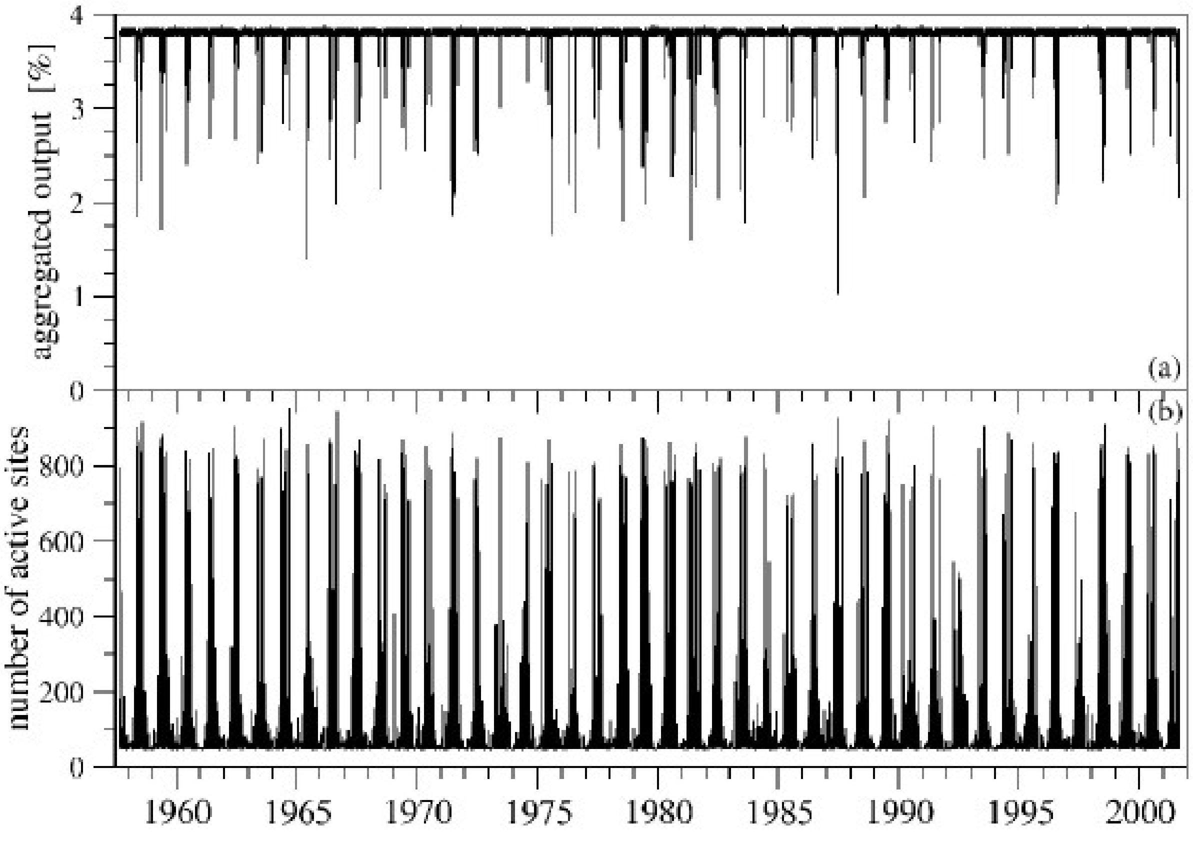
if insufficient: best sites are connected
(in the order of instantenous power)

4. Dynamic networks

Full dynamic control

Results:

- Target cannot be sustained (sudden breaks, low wind scenarios)
- The whole continent should be connected (still insufficient)



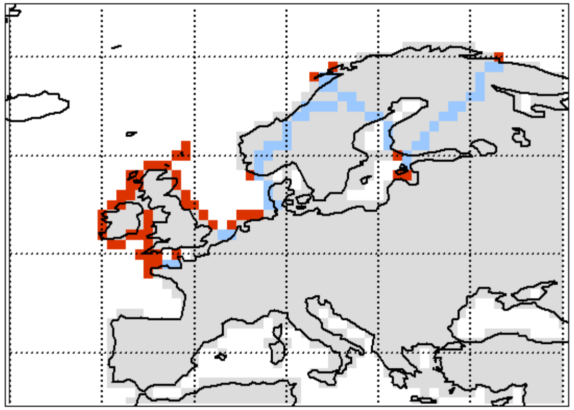
4. Dynamic networks

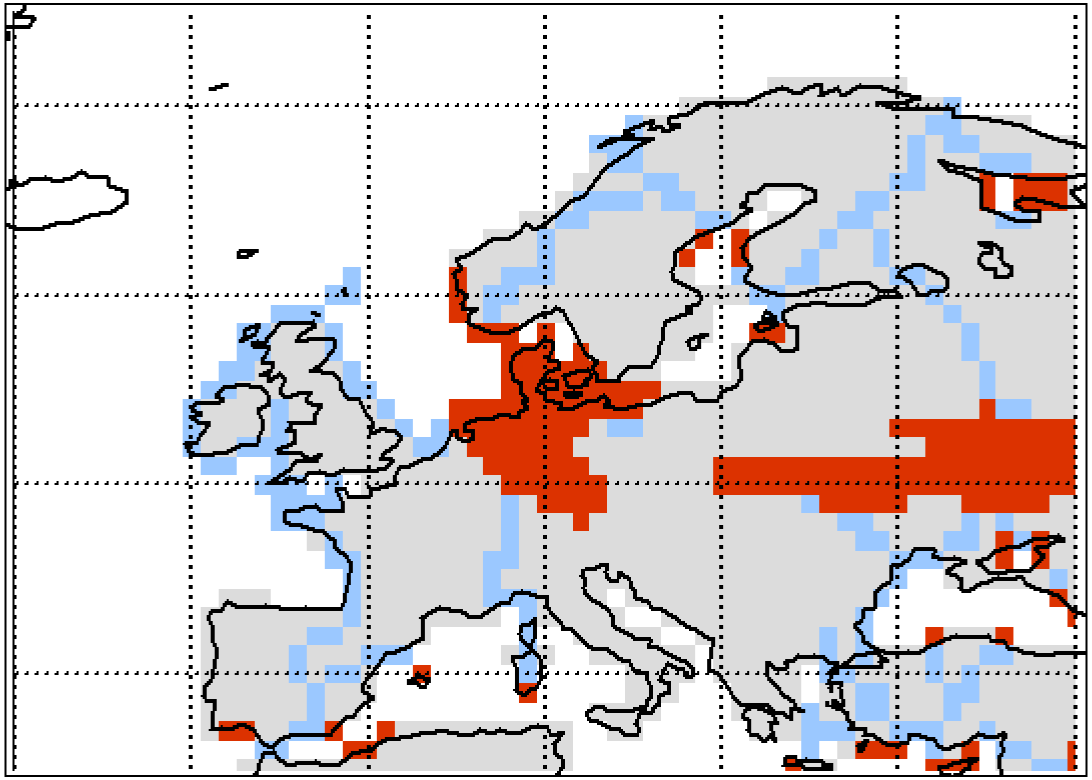
Full dynamic control

Results:

Active sites (red) and the network (blue)

base network →



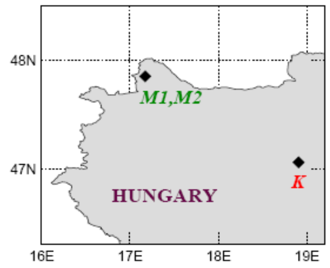


4. Case study: matching consumption – wind power supply

Wind power supply

Turbines at Mosonszolnok and Kulcs

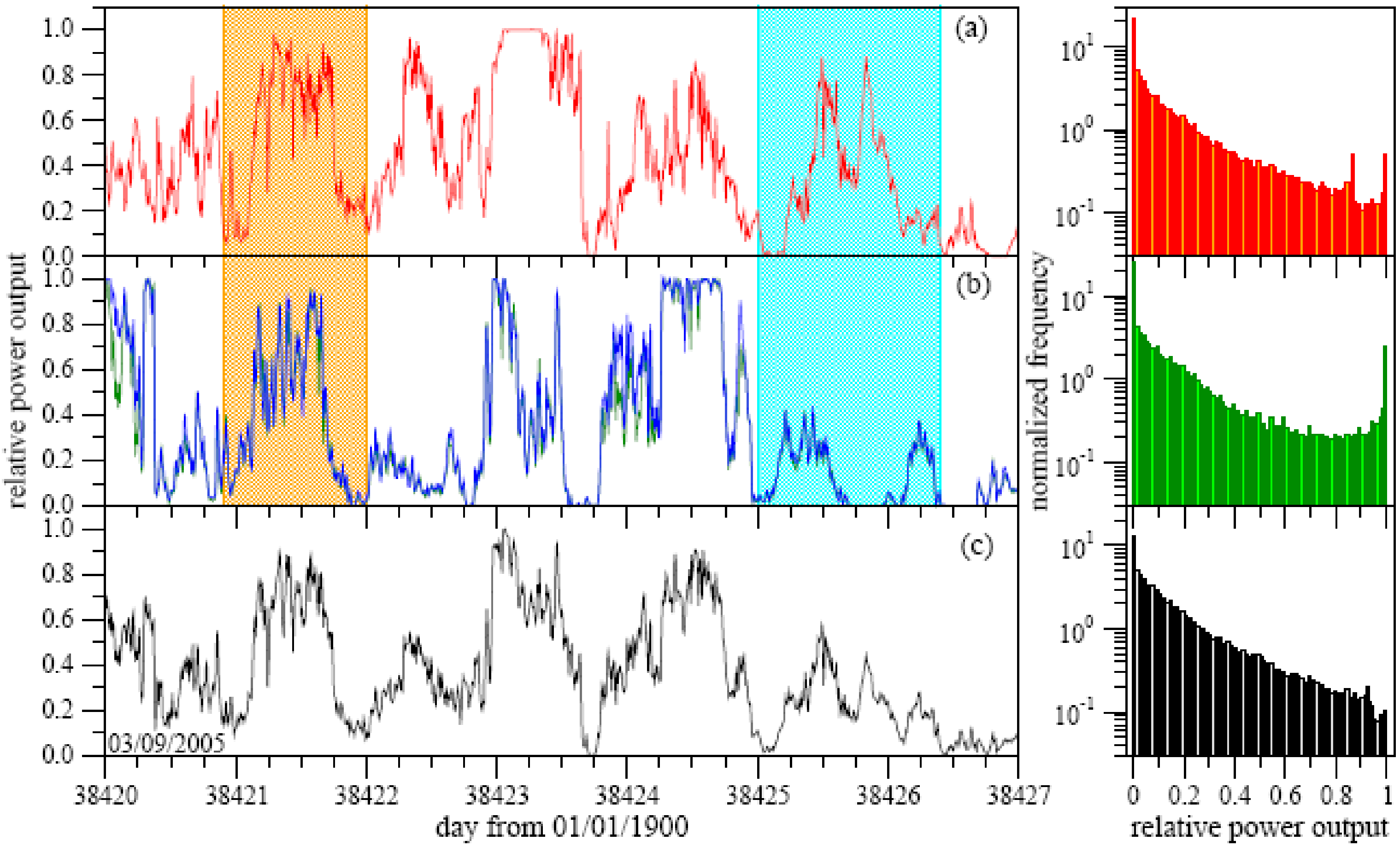
- Correlation between the two sites: 0.52
- Spectra dominated by continuum



Kulcs (K)

Mosonsz. (M)

combined (0.5K+0.5M)

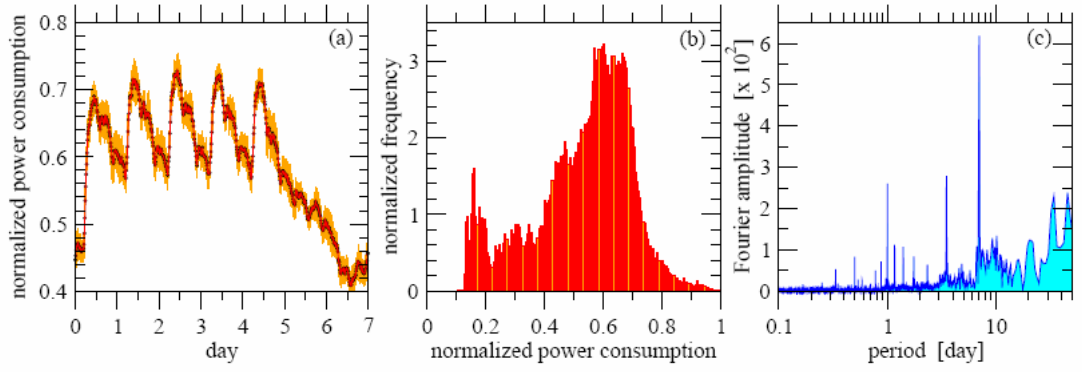


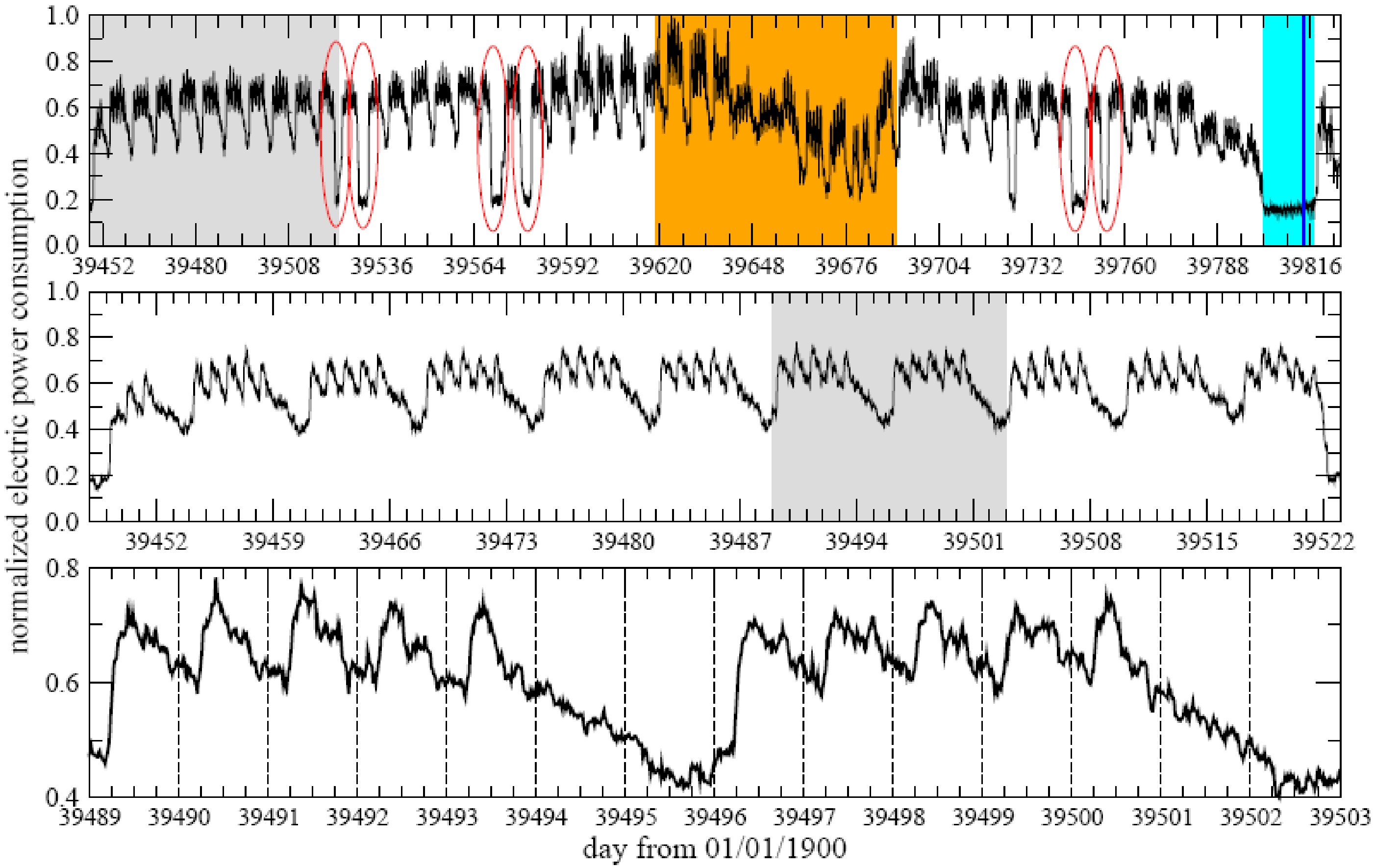
4. Case study: matching consumption – wind power supply

Consumption

Great consumer

(factory in Hungary)





4. Case study: matching consumption – wind power supply

Matching supply – demand

$$P_{tot} = F \cdot \frac{C_{av}}{f}$$

Excess wind power (F)

Average consumption (C_{av})

Installed wind power (P_{tot})

Average capacity factor (f)

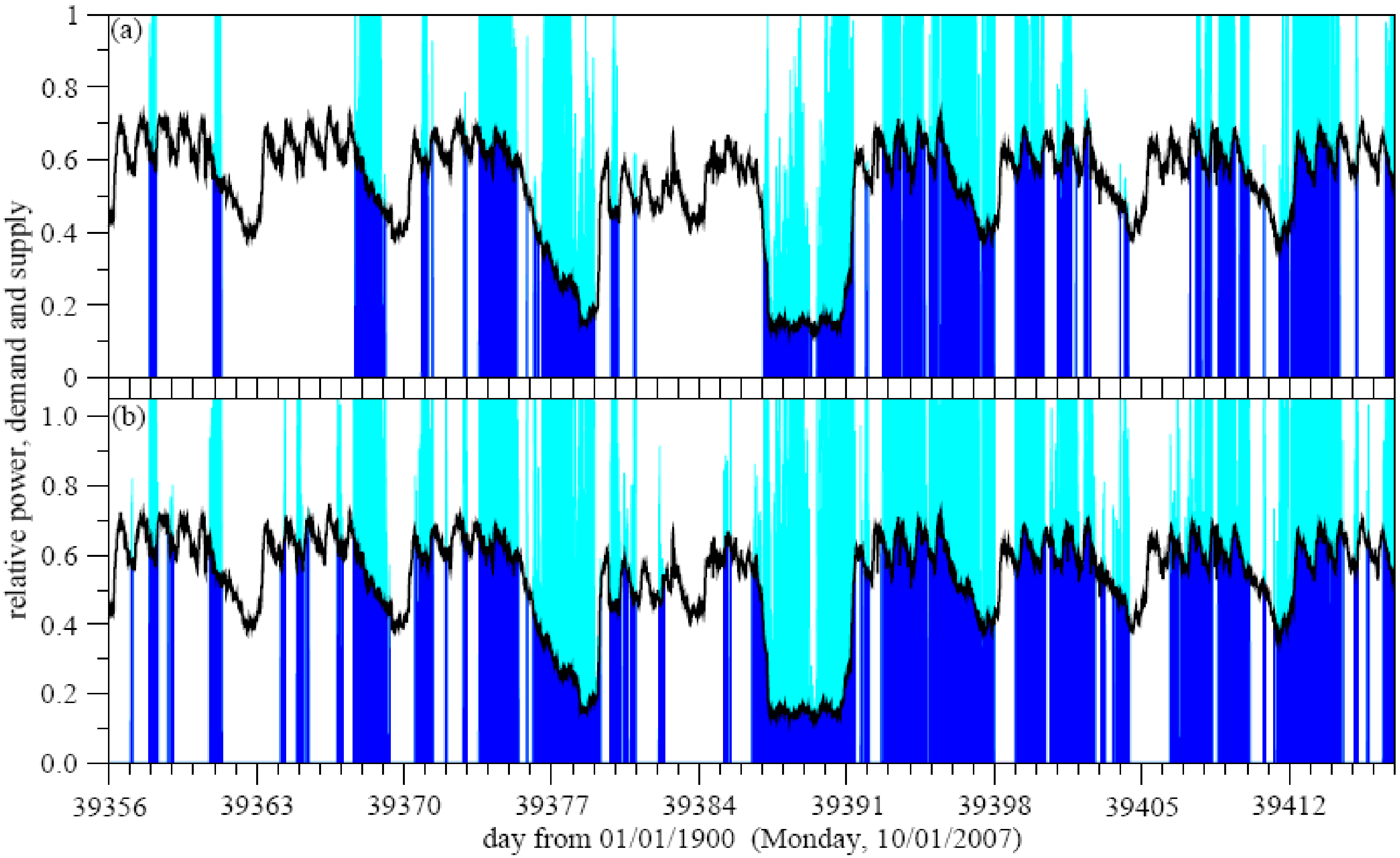
F = 1

on average
supply – demand
exactly match

34% of time suppl.

F = 2

52 % of time suppl.



4. Case study: matching consumption – wind power supply

Matching supply – demand

time of supply | excess (rel. to P_{tot}) | missing power

Demand as before

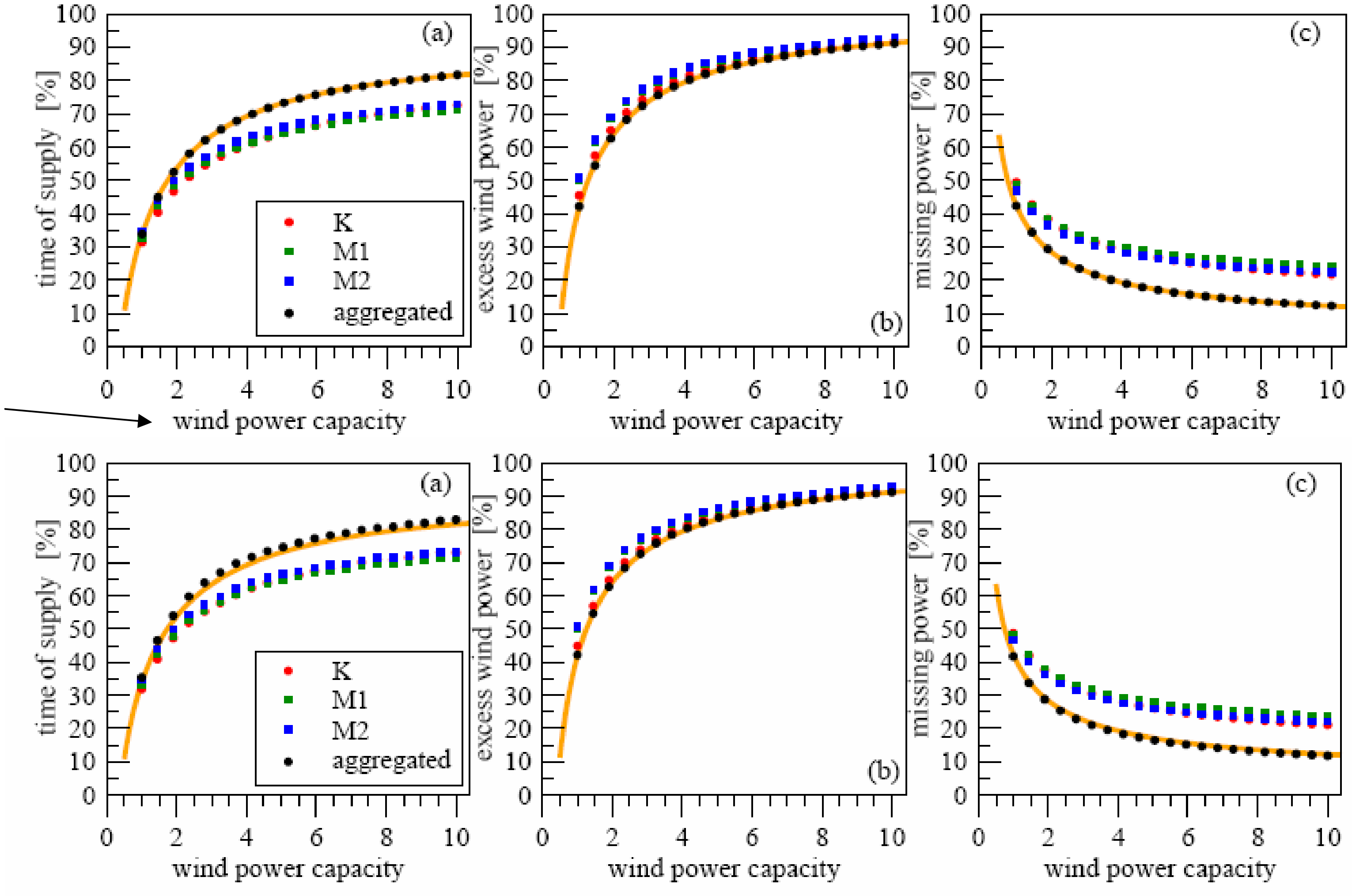
F: 1 - 2

34% - 52%

100% not poss.

Constant demand

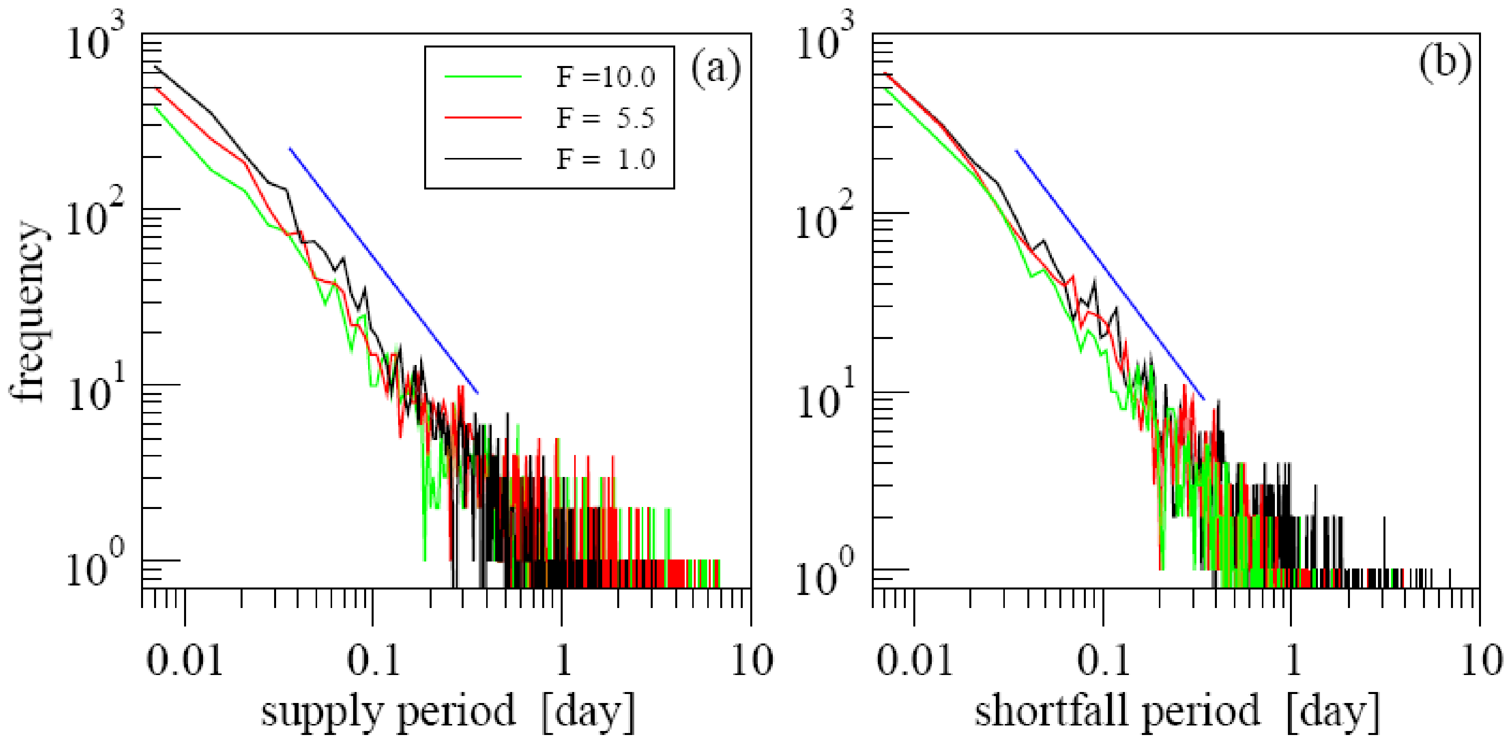
F



4. Case study: matching consumption – wind power supply

Distribution of continuous supply and shortfall periods

- supply periods of >2 hours (~economically feasible): 31 days only
- shortfalls of more days are possible



exponent: -1.4

5. Summary

- Wind seems to be a key energy source of the future, however problems need to be solved (intermittency).
- General description of wind speed histograms – generalized gamma distribution.
- Reanalysis – turbine measurement comparison: acceptable agreement.
- Statistics for various hypothetical wind power networks.
- It does not seem to be possible to achieve stable output using only wind power.

Wind always blows somewhere (?).

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