On the interaction of wind energy with climate and weather

Dan Barrie

October 7th, 2010

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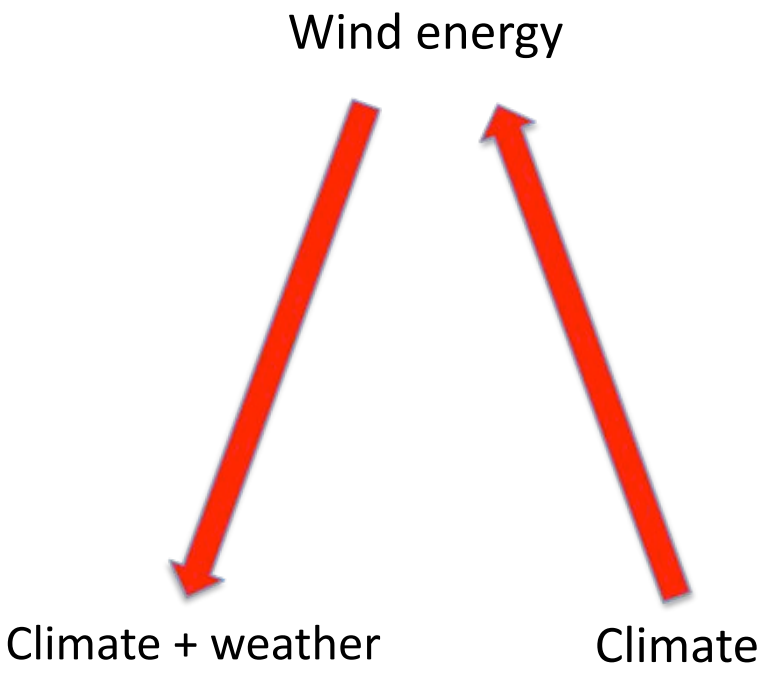
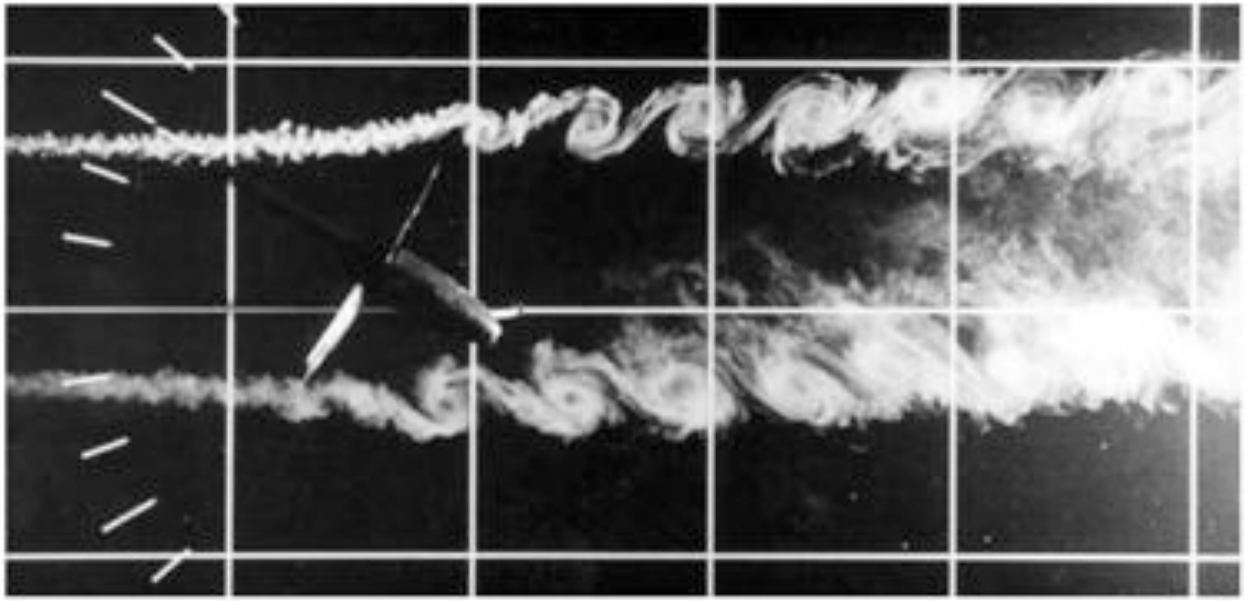
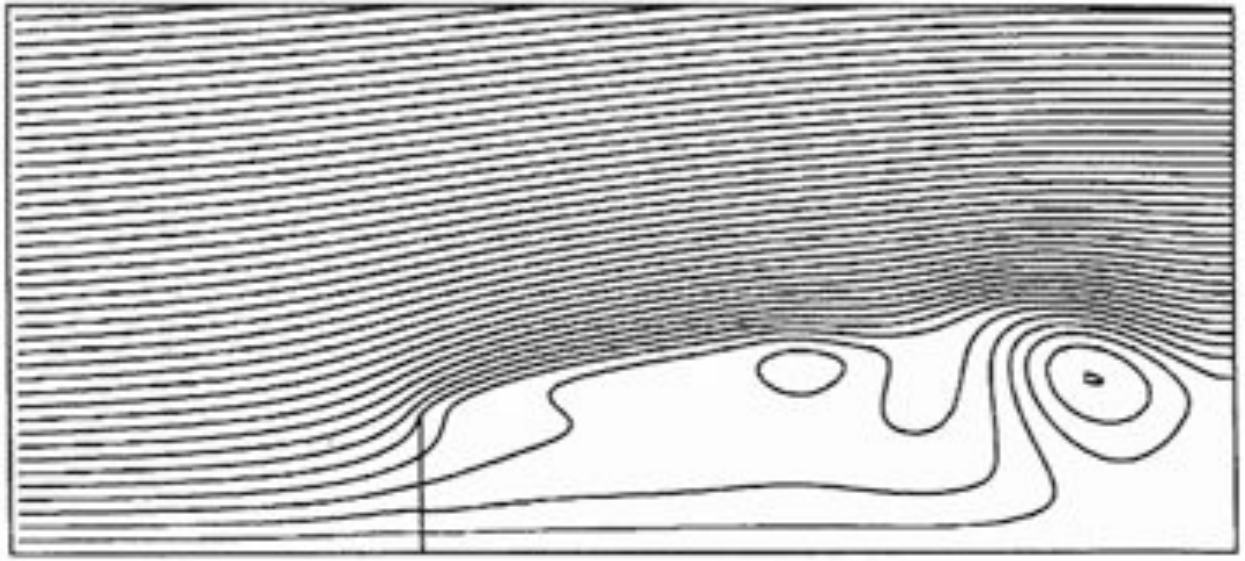
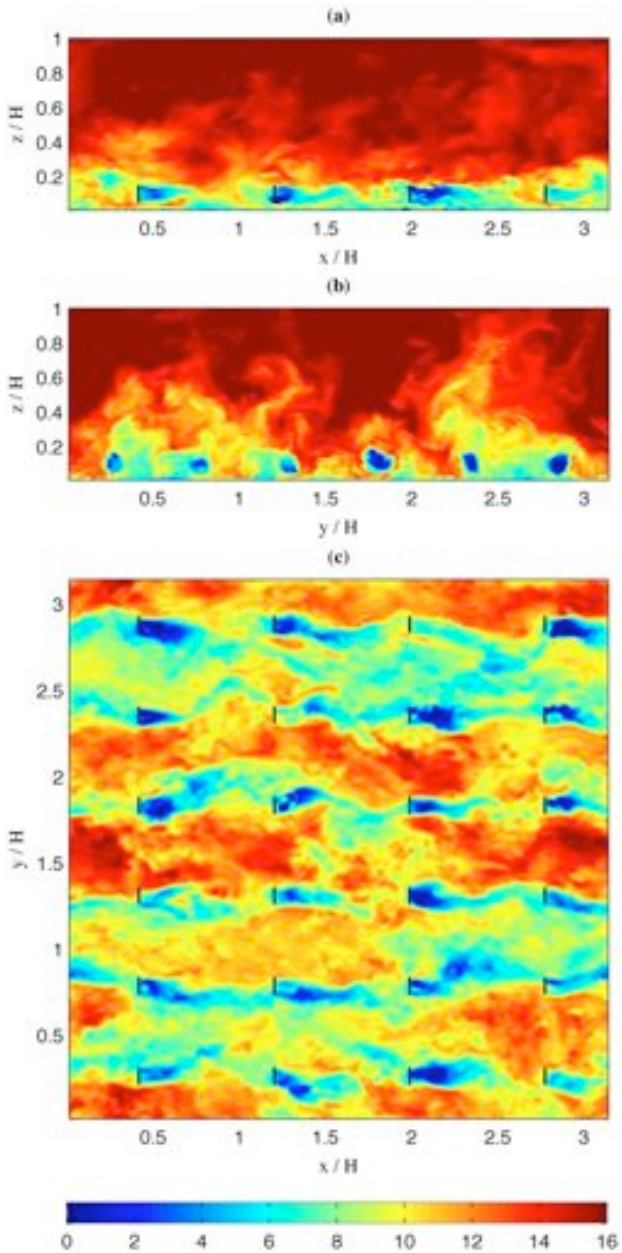

Wind energy
Climate + weather
Climate

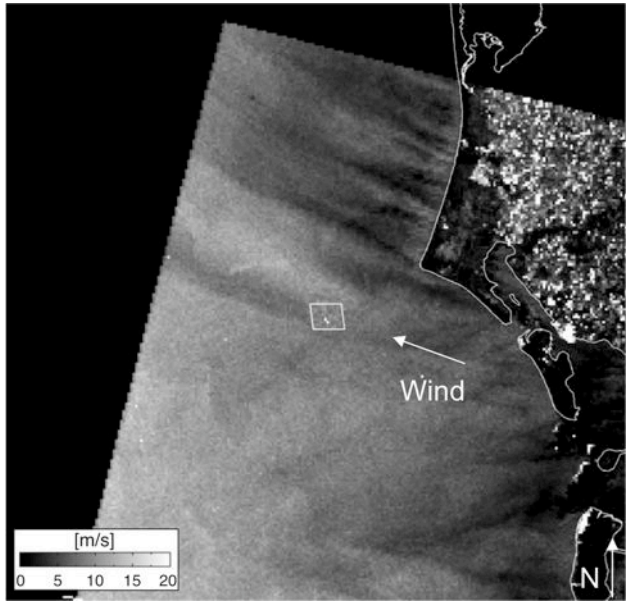


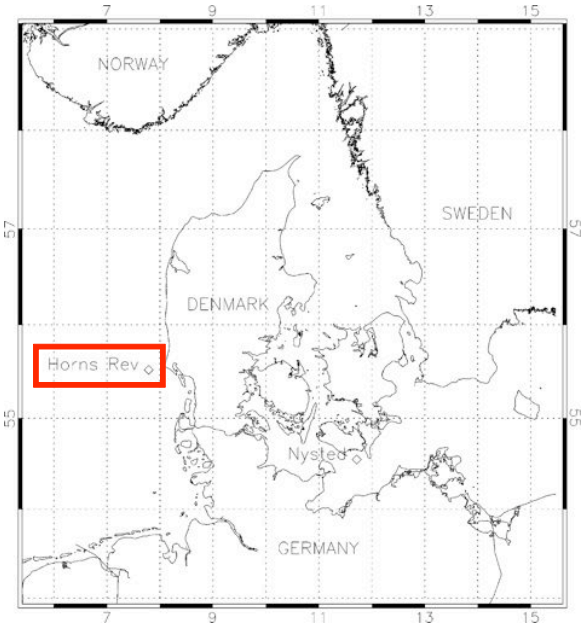


Medici: “Wind turbine wakes – control and vortex shading”, 2004
Vermeer et al.: “Wind turbine wake aerodynamics”, 2003

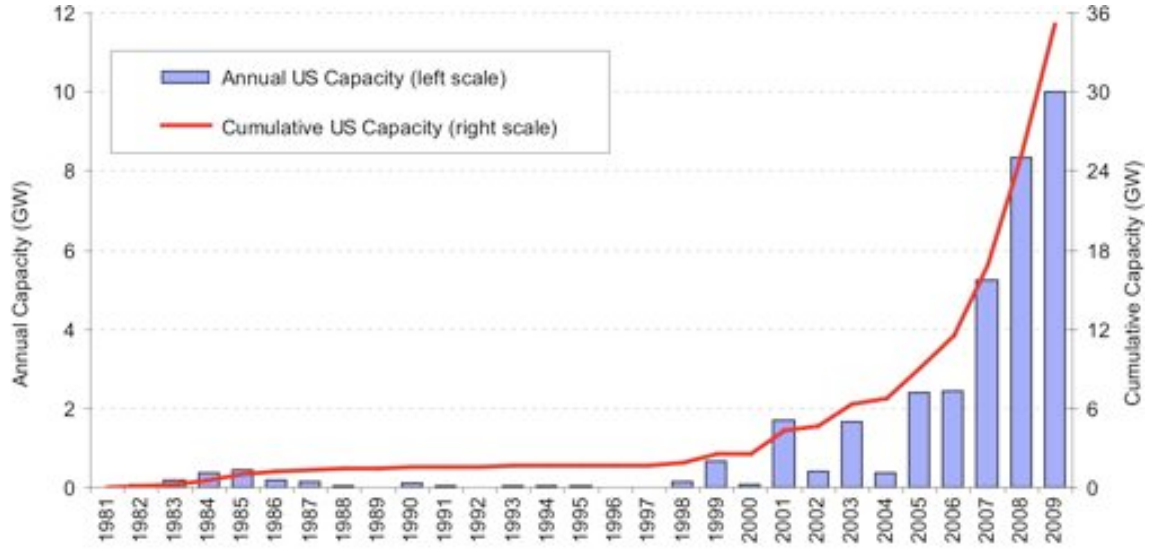


Calaf et al.: “Large eddy simulation of fully developed wind-turbine array boundary layers”, 2010



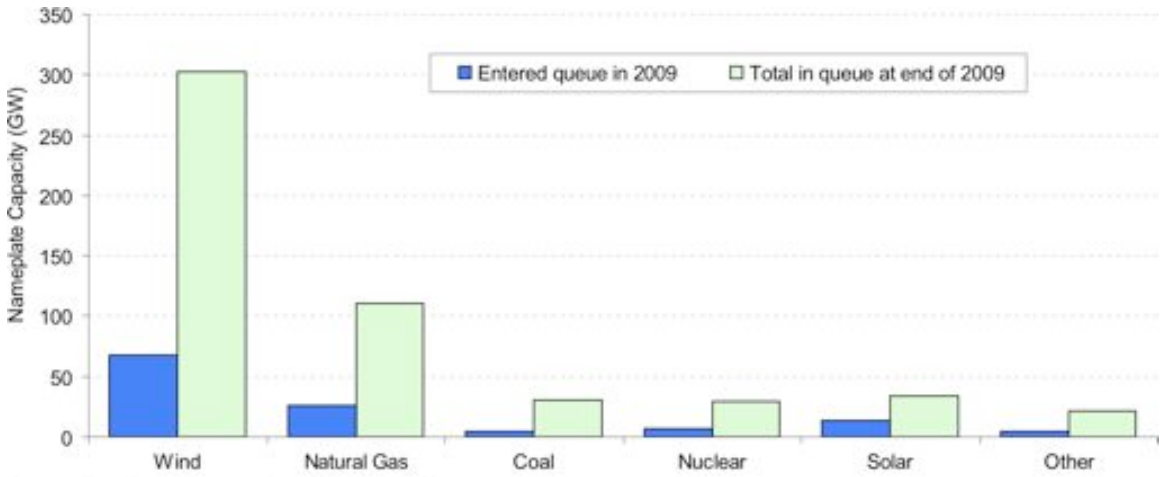


Christiansen and Hasager: “Wake effects of large offshore wind farms identified from satellite SAR”, 2005



Source: AWEA project database

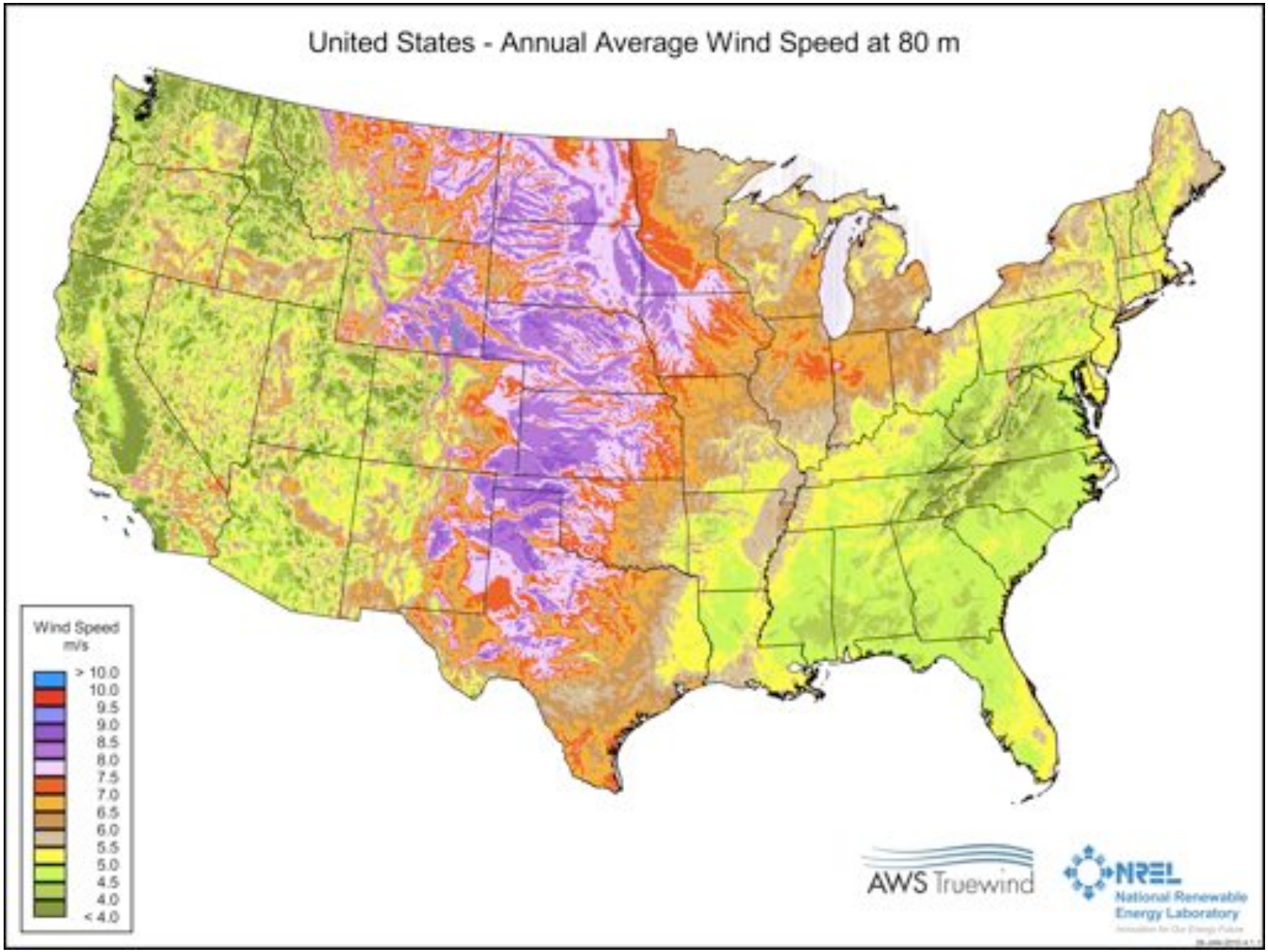
Annual and Cumulative Growth in U.S. Wind Power Capacity



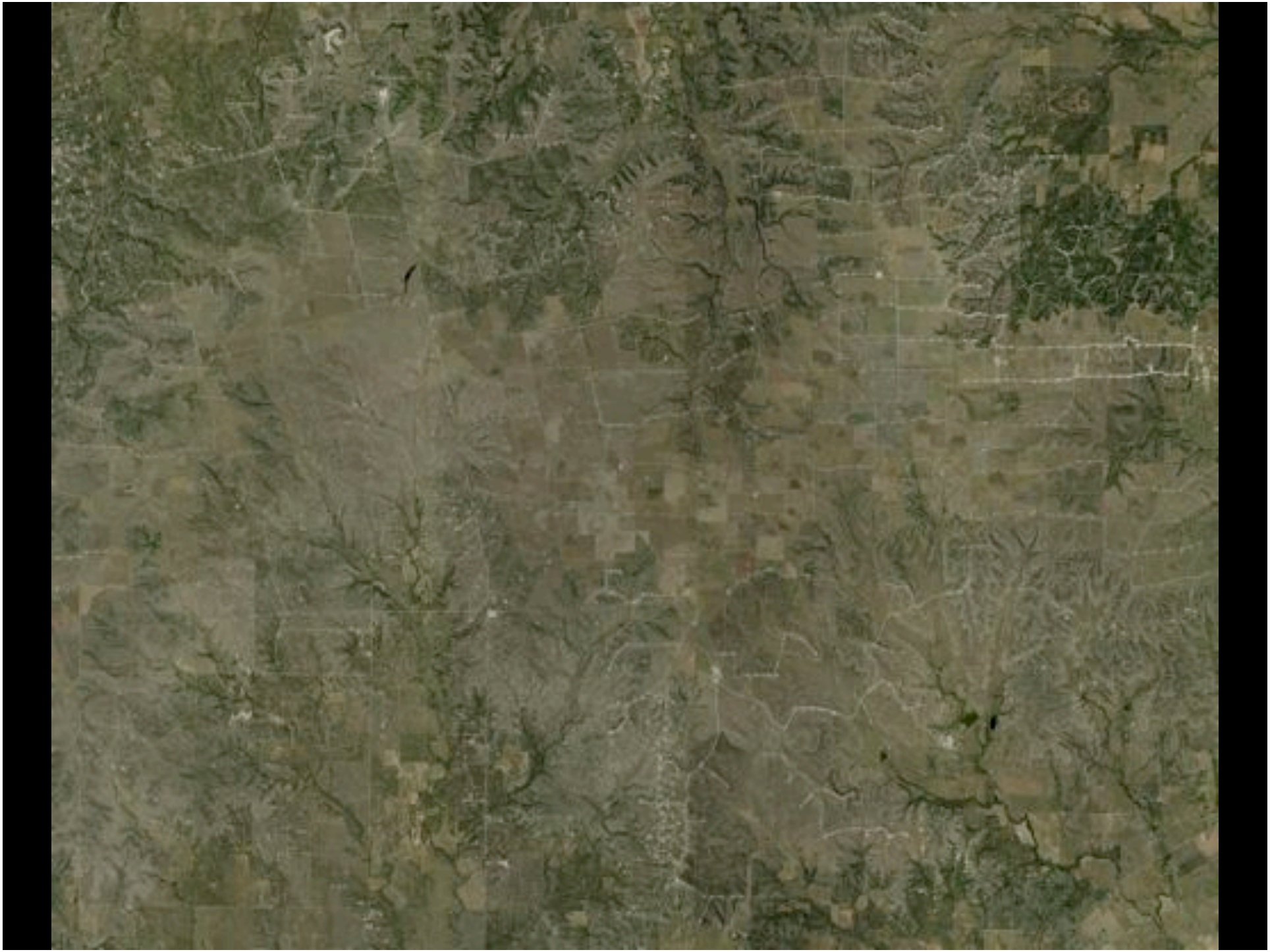
Source: Exeter Associates review of interconnection queues

Nameplate Resource Capacity in 33 Selected Interconnection Queues

Wiser, R., and Bolinger, M.: 2009 wind technologies market report, 2010



http://www.windpoweringamerica.gov/wind_maps.asp



<u>Part I :</u>

Weather response to a large wind turbine array

Model description

Model : Community Atmosphere Model, version 3.0, Eulerian spectral core

Resolution : T42 ~ 2.81°, 26 vertical levels

Ocean component : Climatological sea surface temperatures

Wind farm representation : Heightened surface roughness

Surface roughness estimation via Lettau (1969)

$$z_o = \frac{1}{2} h^* \frac{s_s}{S_L}$$

z_o = surface roughness

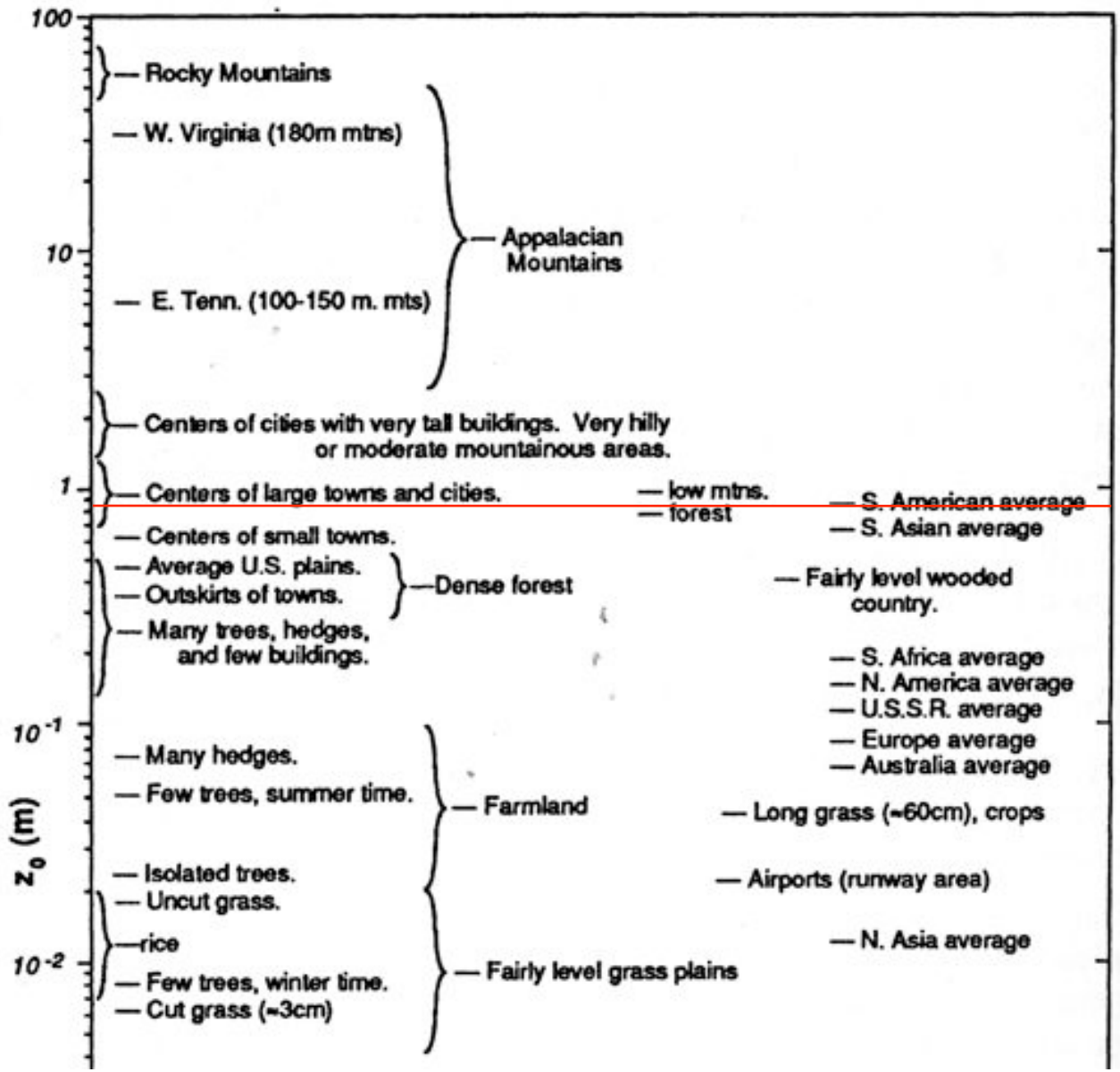
h^* = average vertical extent

s_s = object surface area

S_L = object footprint

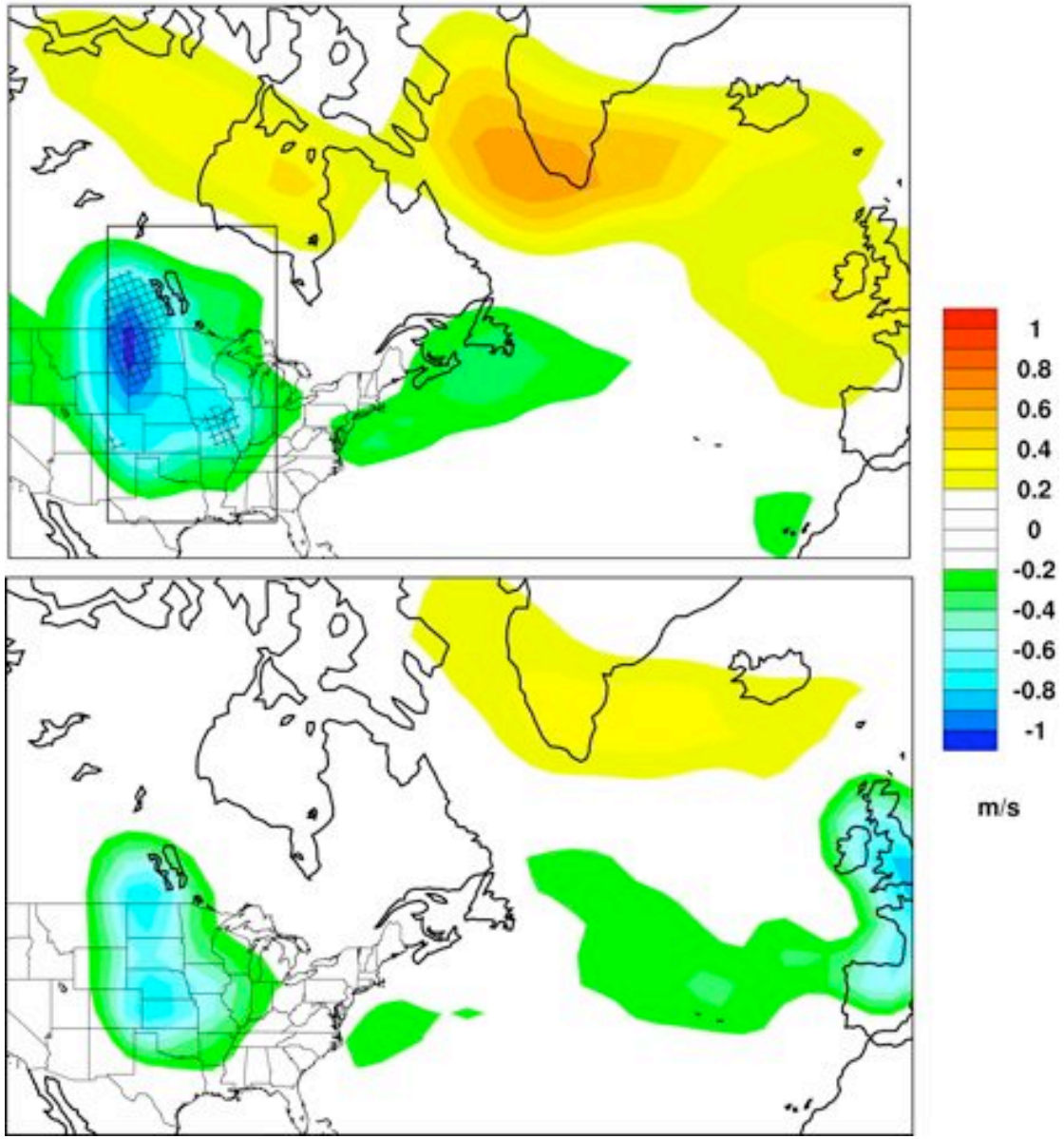
$$z_o = \frac{1}{2}(100m) \cdot \frac{\pi \cdot (56.3m)^2}{(771m)^2} = 0.837m$$

Surface roughness estimation via Lettau (1969)



Stull: "An introduction to boundary layer meteorology", 1988

Zonal wind anomaly at 993mb

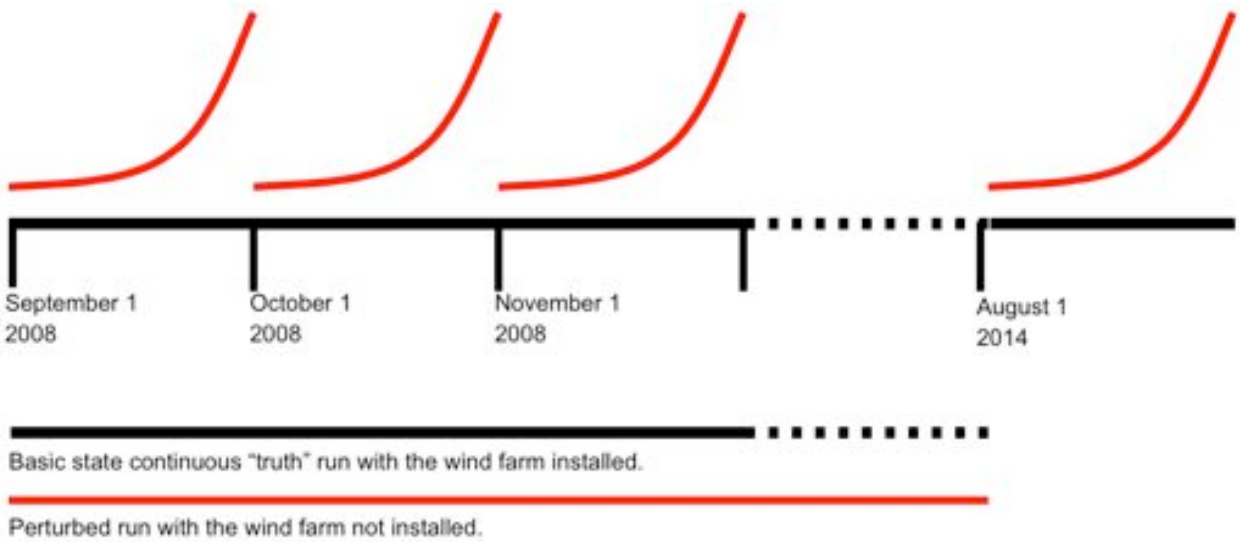


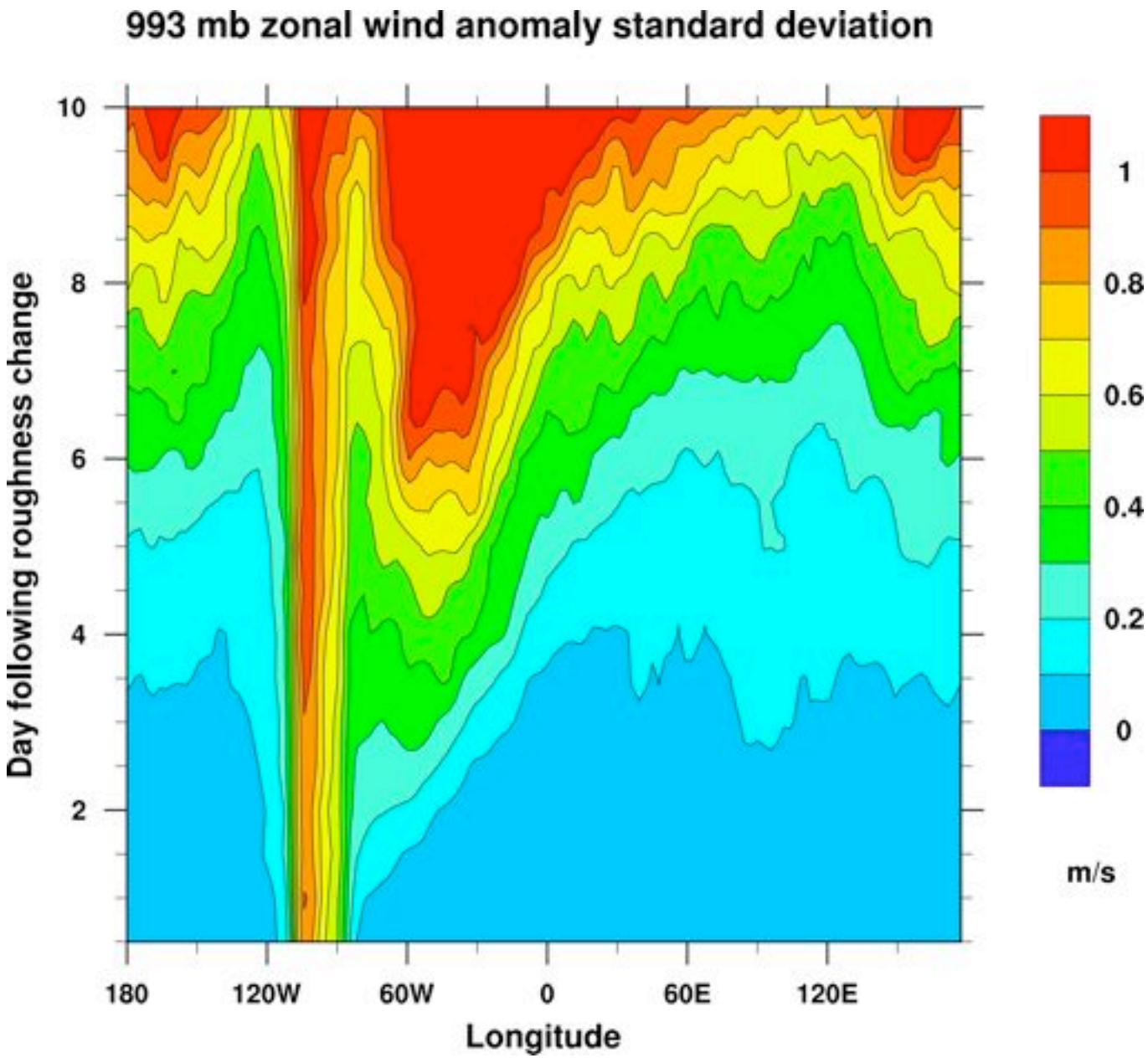
Barrie and Kirk-Davidoff: "Weather response to a large wind turbine array", 2010
Kirk-Davidoff and Keith: "On the Climate Impact of Surface Roughness Anomalies", 2008

Model experiments

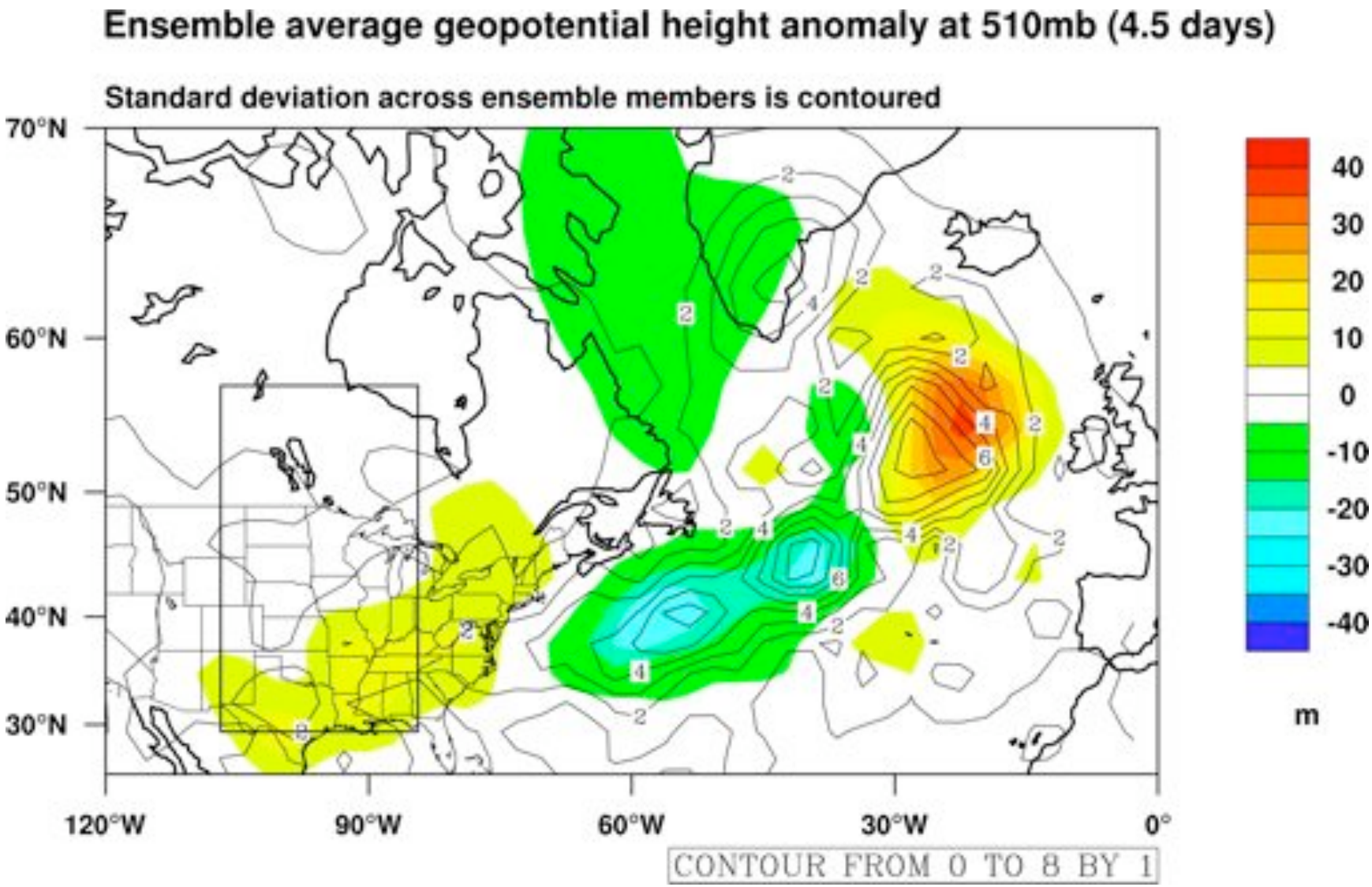
Control run : 6 years, 72 case studies (1 per month) **with** wind farm

Case studies : Branch run of each case study **without** wind farm





Barrie and Kirk-Davidoff: "Weather response to a large wind turbine array", 2010



Barrie and Kirk-Davidoff: "Weather response to a large wind turbine array", 2010

Part II :

Wind farm parameters: studies with a simplified model

Model description

Model : Weather Research and Forecasting model, Held-Suarez configuration (Newtonian cooling, Rayleigh damping)

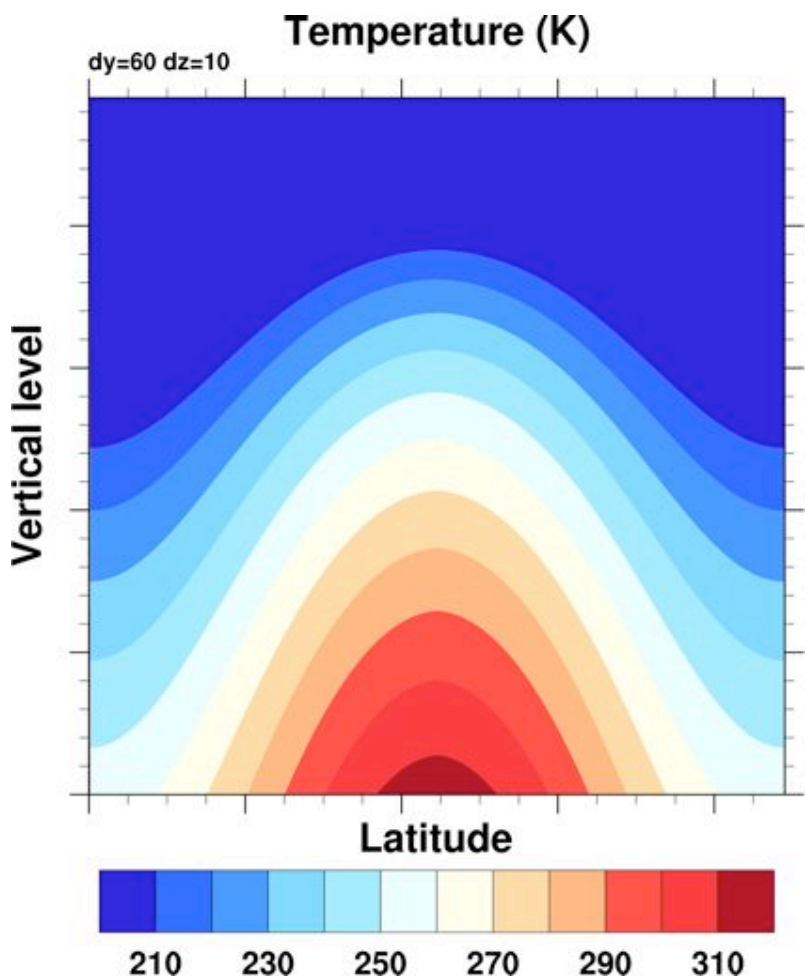
Resolution : 2.8125° x 2.5°, 40 vertical levels

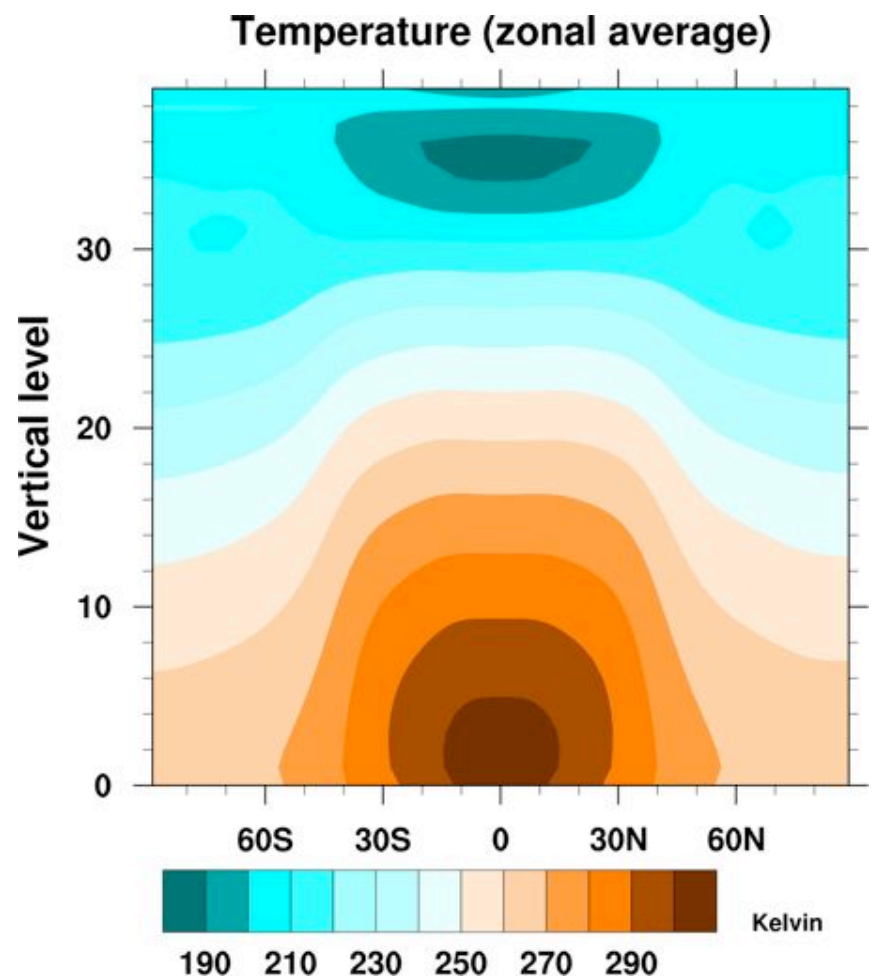
Simplifications : No topography or water

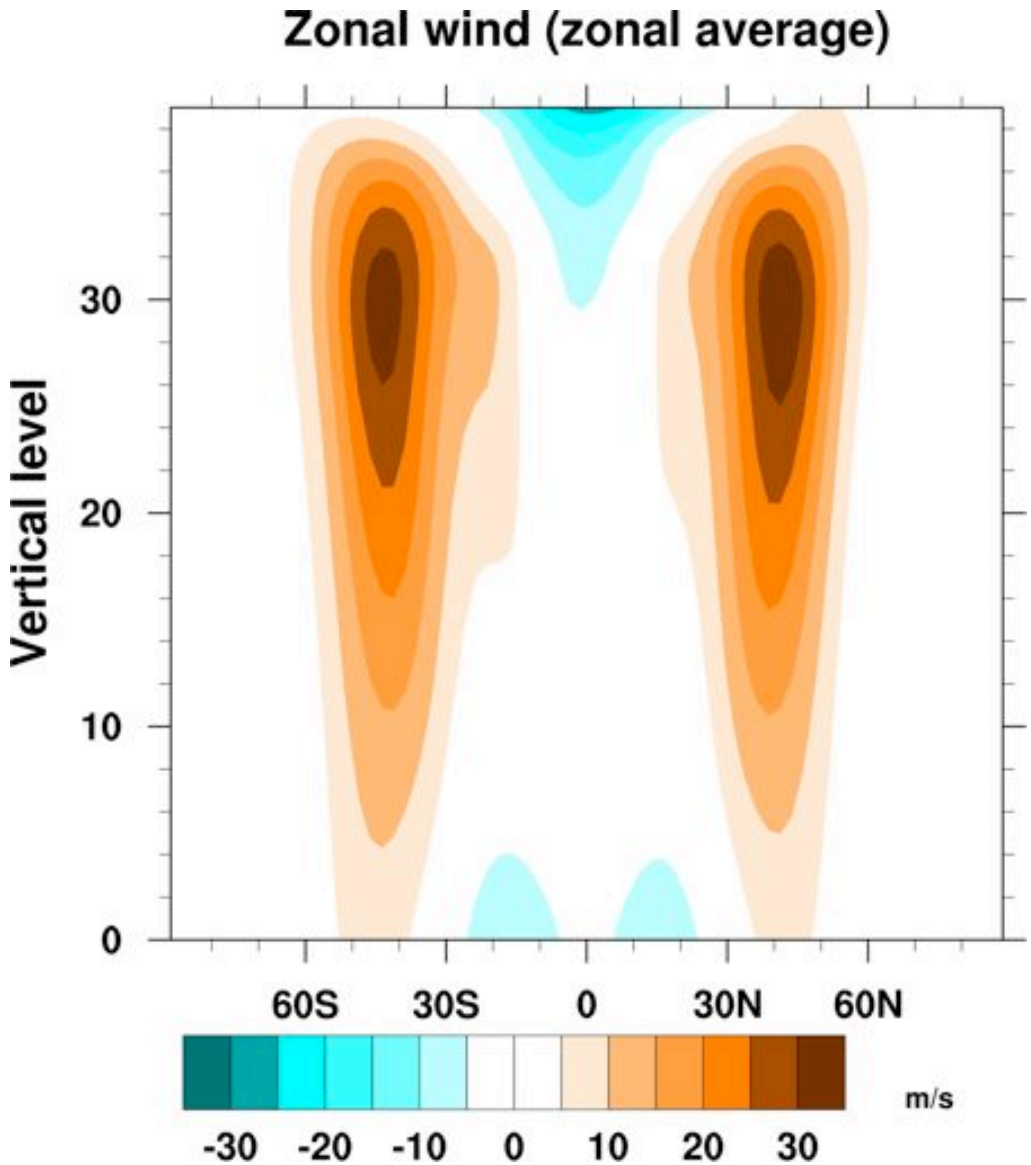
Initial condition : Isothermal atmosphere at rest

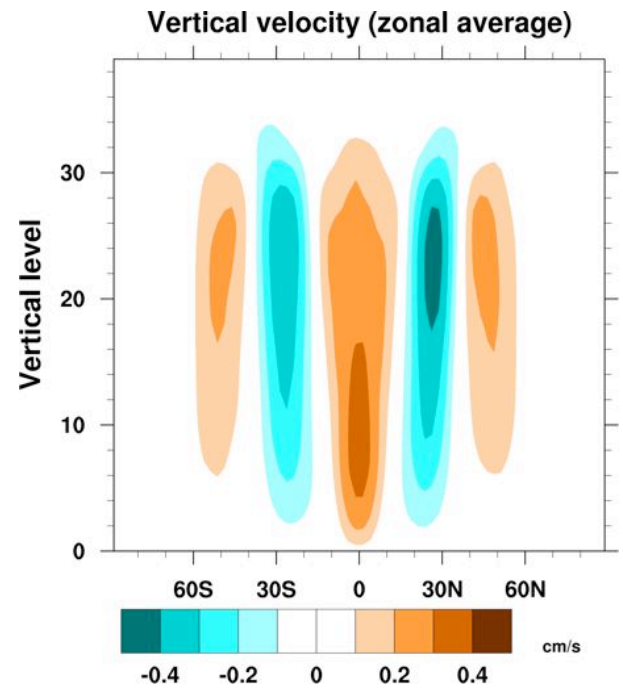
Wind farm representation : Heightened Rayleigh damping in the lowest model layer

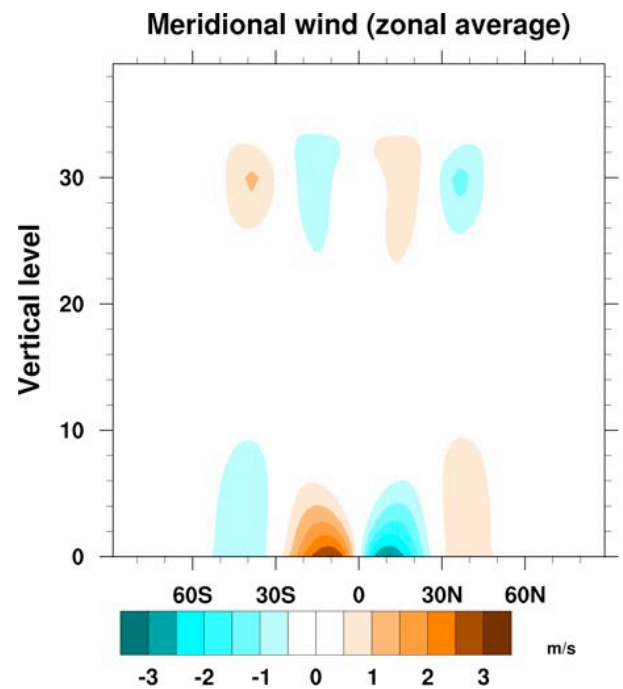
$$T_{eq} = \max\left\{200, \left[315 - \underbrace{(\Delta T)_y \sin^2\phi}_{TERM1} - \underbrace{(\Delta\theta)_z \log\left(\frac{p}{p_o}\right)\cos^2\phi}_{TERM2}\right]\underbrace{\left(\frac{p}{p_o}\right)^k}_{TERM3}\right\}$$






Zonal wind (zonal average)
Vertical level
30
20
10
0
60S
30S
0
30N
60N
m/s
-30
-20
-10
0
10
20
30


Vertical velocity (zonal average)
Vertical level
30
20
10
0
60S
30S
0
30N
60N
cm/s
-0.4
-0.2
0
0.2
0.4


Meridional wind (zonal average)
Vertical level
30
20
10
0
60S
30S
0
30N
60N
m/s
-3
-2
-1
0
1
2
3

Model experiments

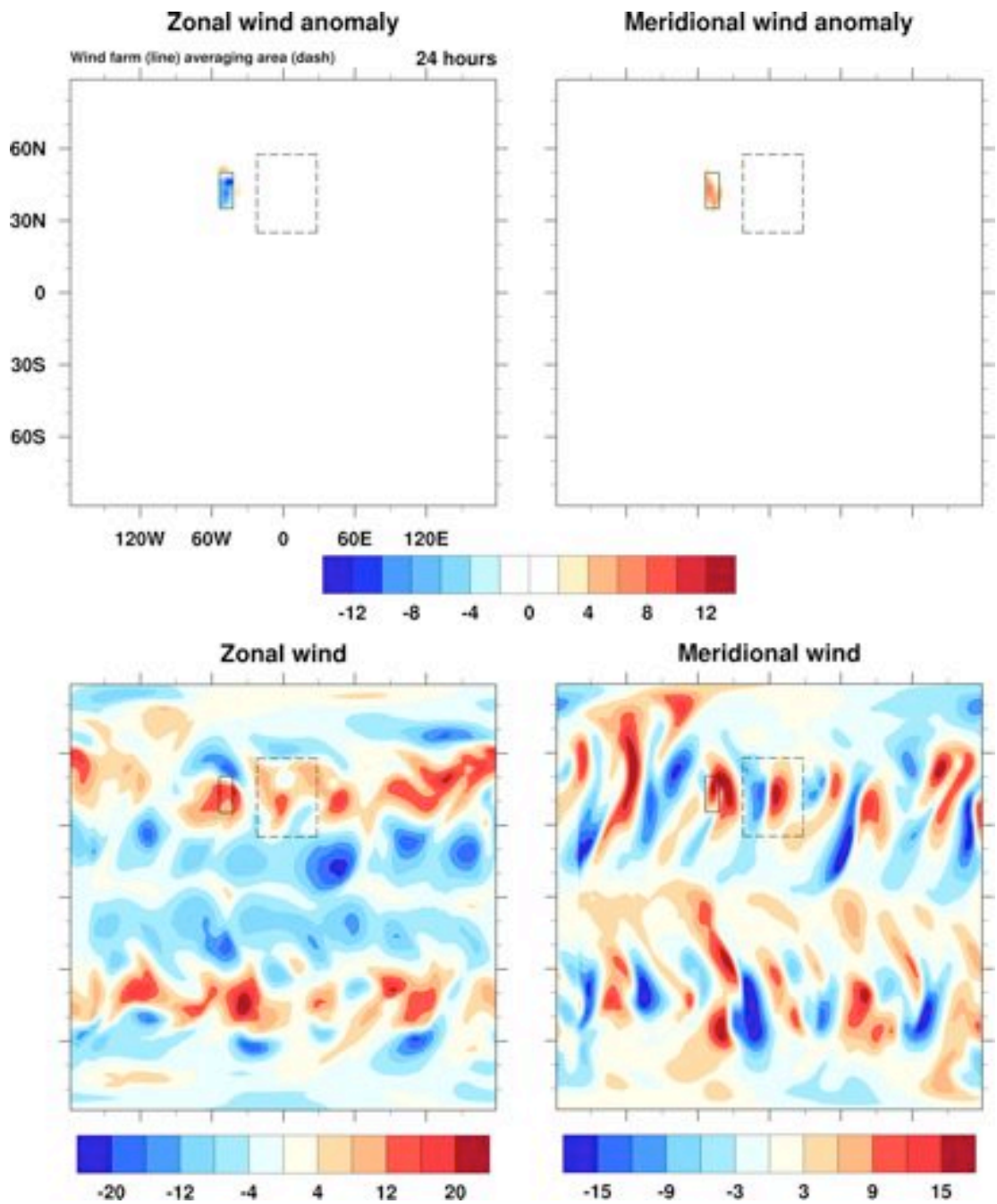
Five wind farm parameters were altered:

- Size
- Position
- Magnitude of damping
- Atmospheric static stability
- Jet stream strength

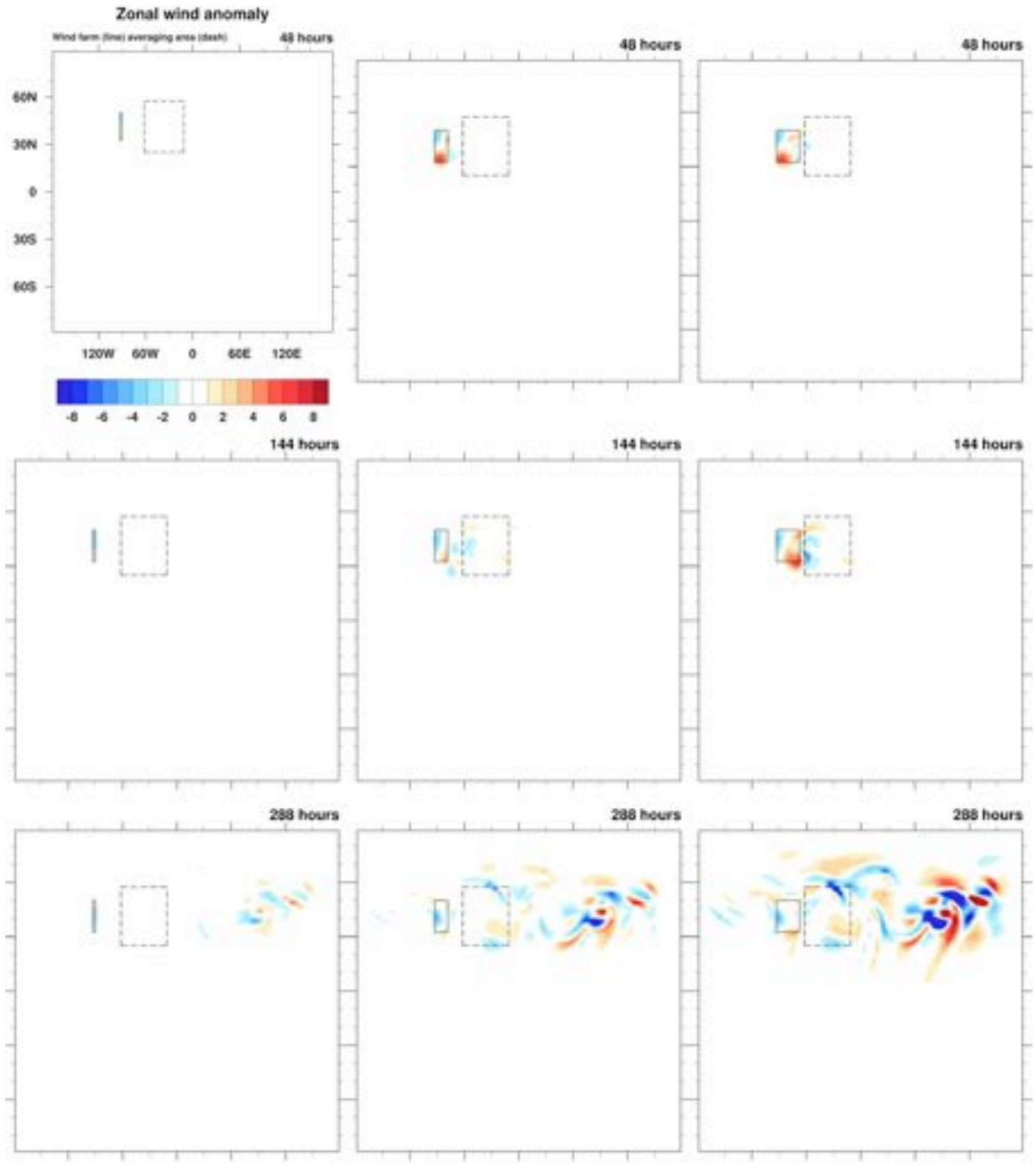
Model spin-up : >200 days

Model runs : 14 days for each parameter value initialized with identical initial conditions

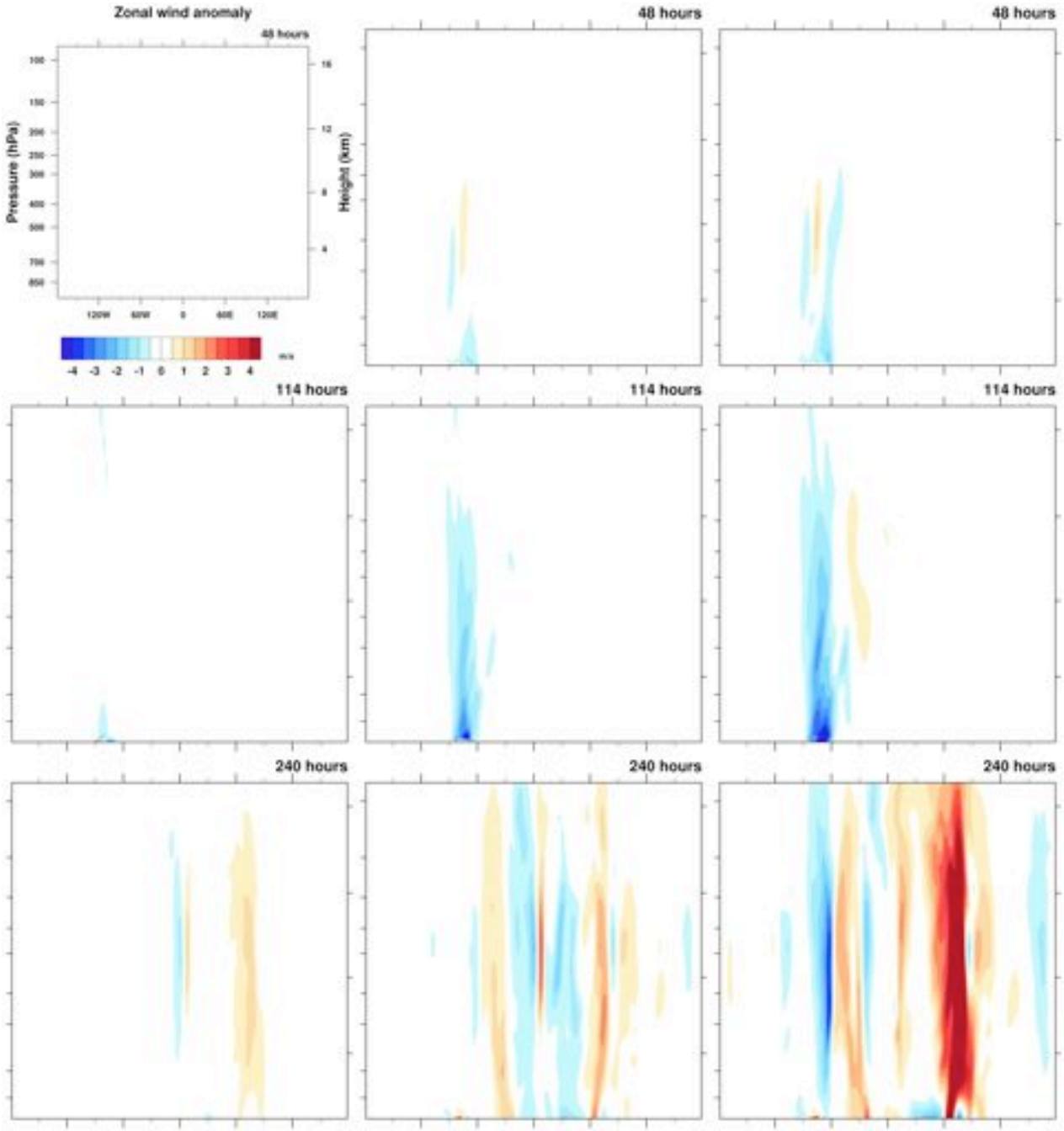
Static stability/jet ensembles : 7 member ensemble, each member initialized with initial conditions separated by 40 days


Zonal wind anomaly
Wind farm (line) averaging area (dash)
24 hours
Meridional wind anomaly
60N
30N
0
30S
60S
120W
60W
0
60E
120E
-12
-8
-4
0
4
8
12
Zonal wind
Meridional wind
-20
-12
-4
4
12
20
-15
-9
-3
3
9
15

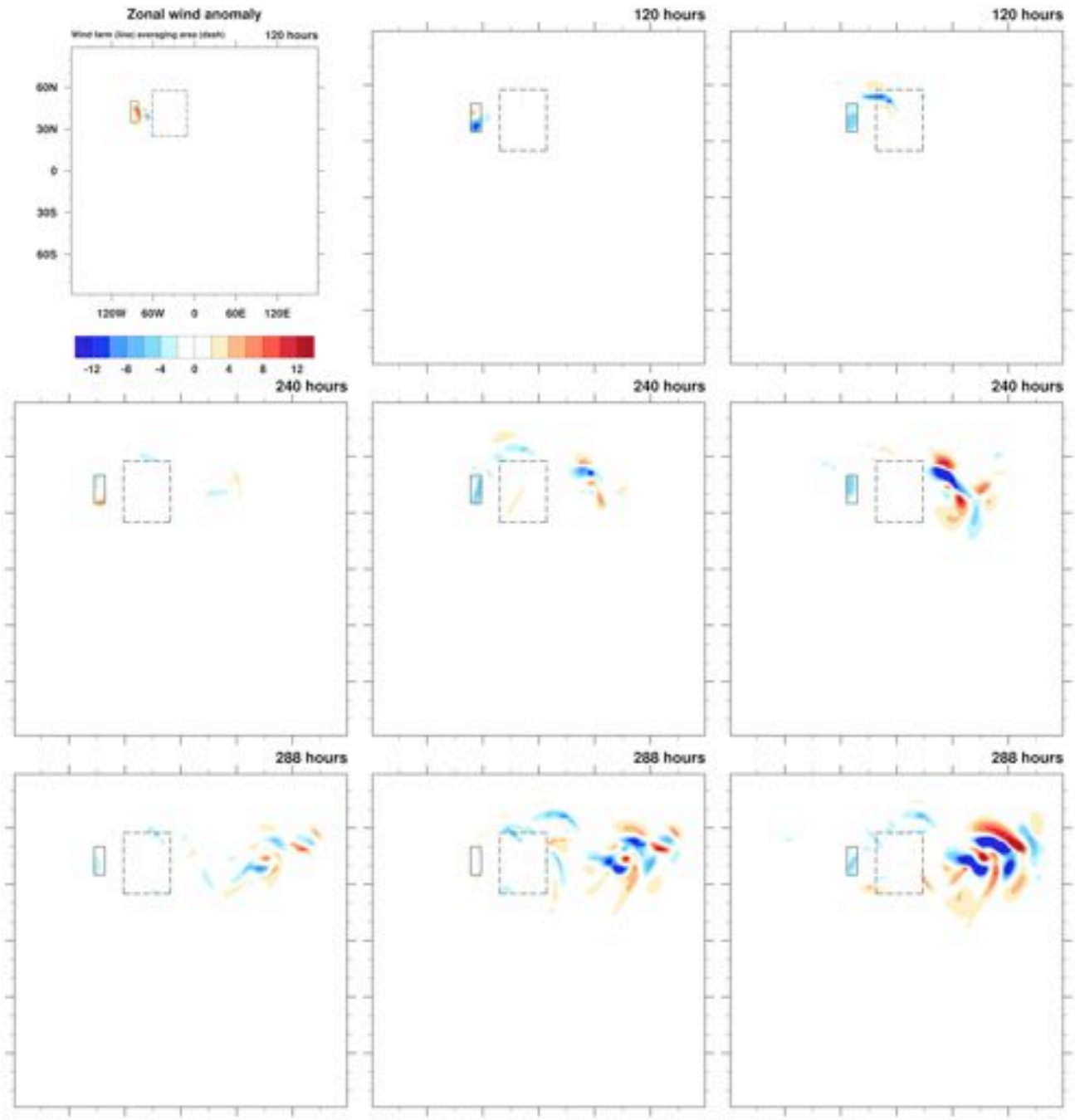
Size – streamwise



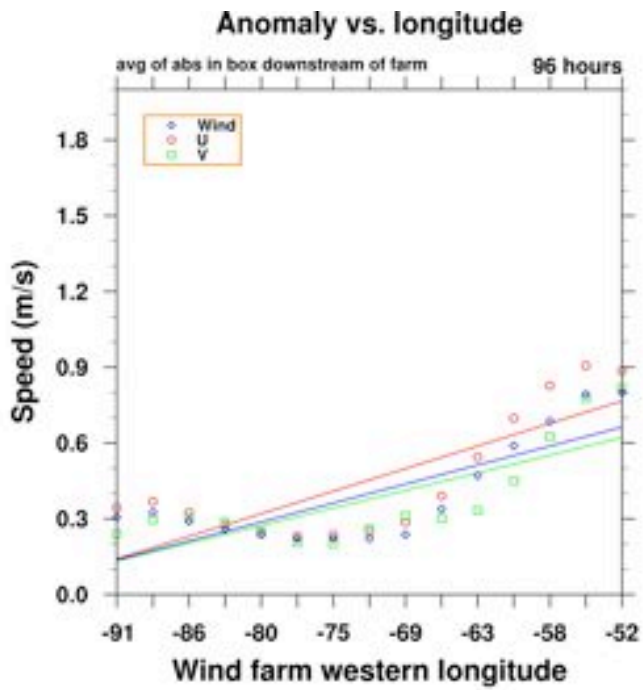
Size – streamwise

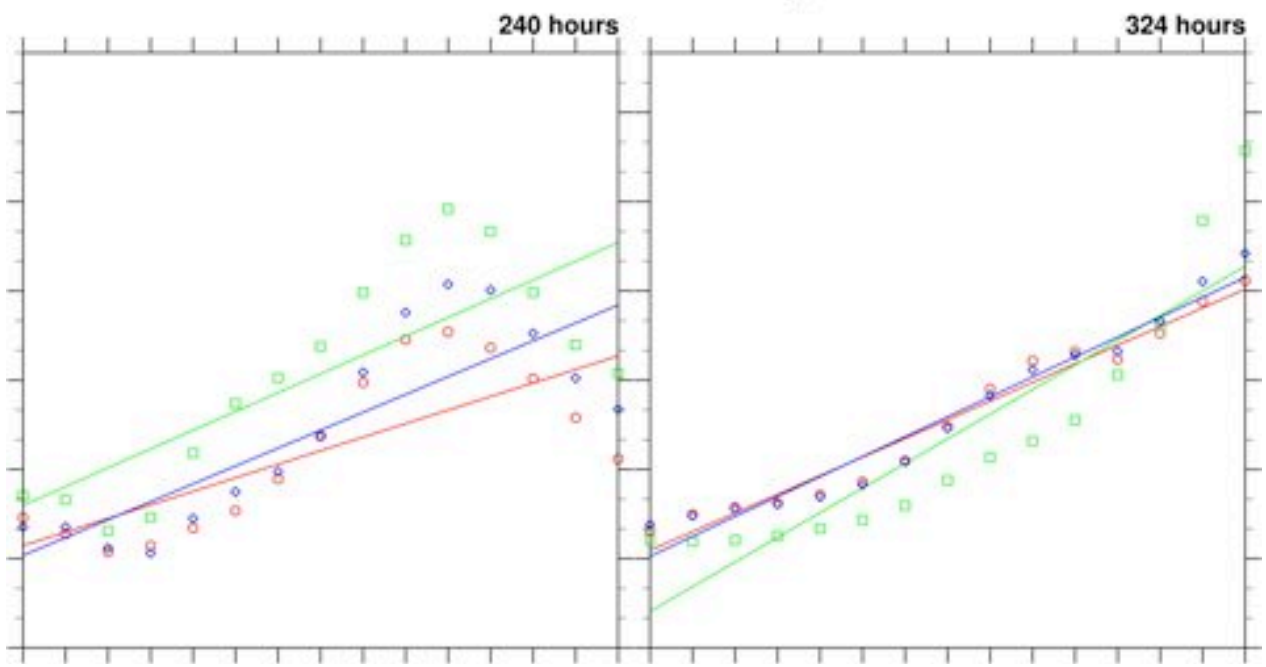


Position – streamwise

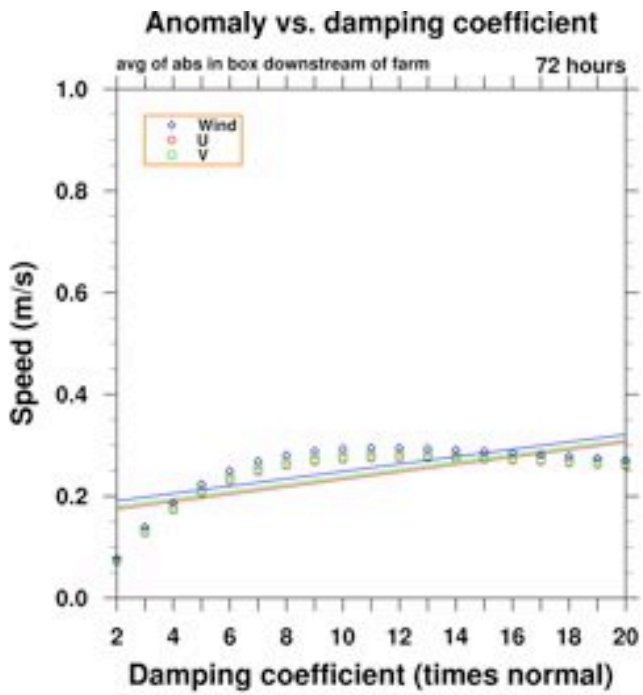


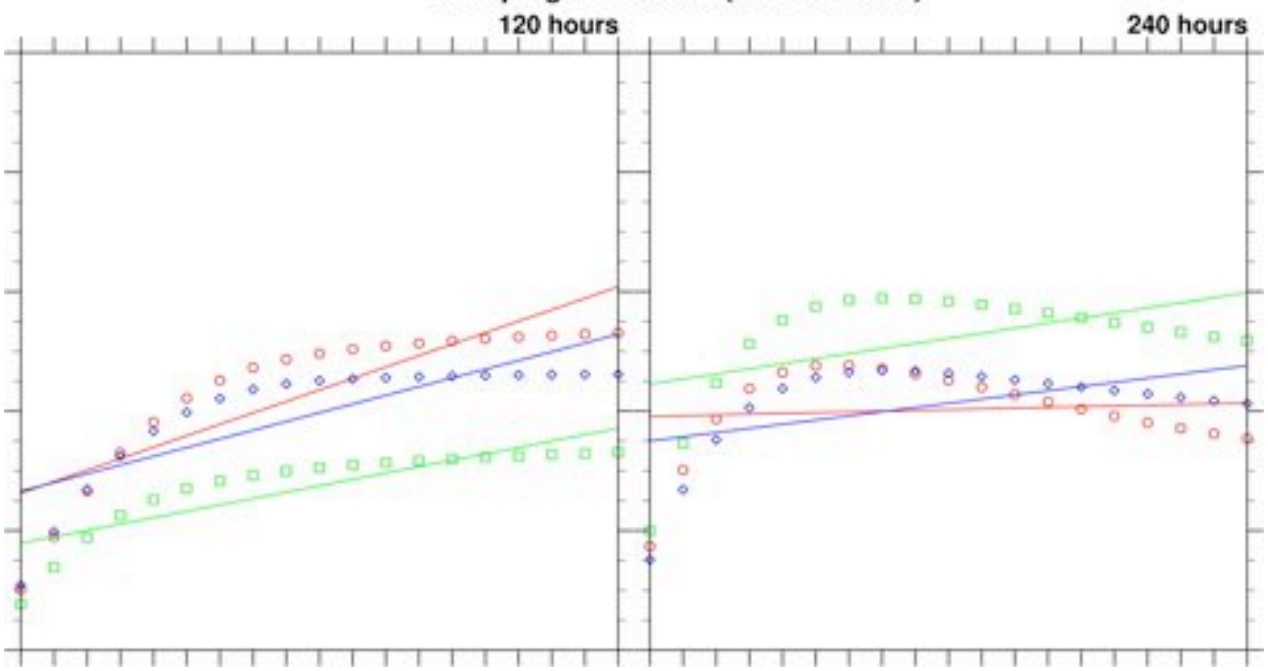
Position – streamwise



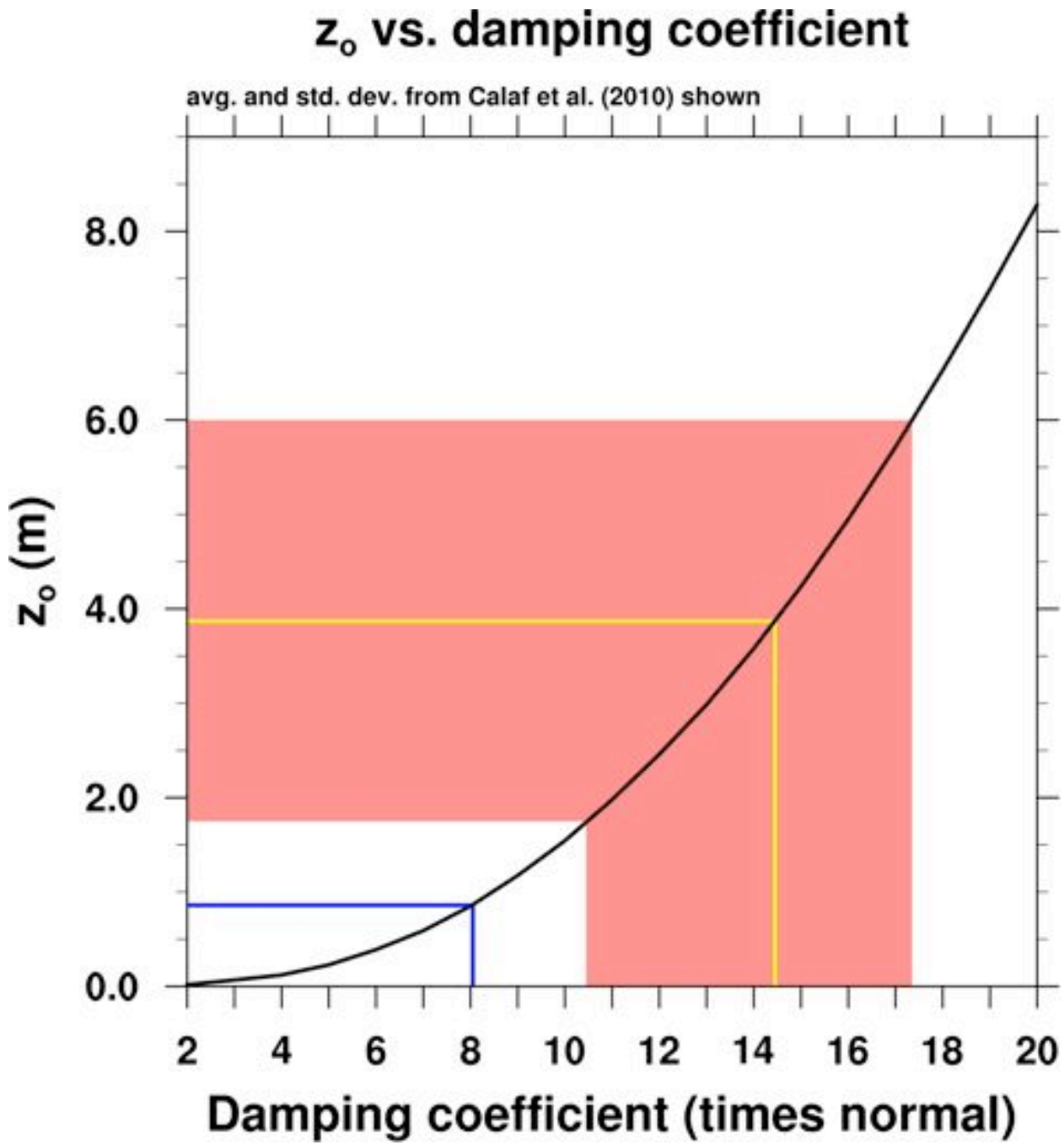


Damping


Anomaly vs. damping coefficient
avg of abs in box downstream of farm
72 hours
Wind
U
V
Speed (m/s)
1.0
0.8
0.6
0.4
0.2
0.0
2
4
6
8
10
12
14
16
18
20
Damping coefficient (times normal)


120 hours
240 hours

Damping


z_o vs. damping coefficient
avg. and std. dev. from Calaf et al. (2010) shown
8.0
6.0
4.0
2.0
0.0
z_o (m)
2
4
6
8
10
12
14
16
18
20
Damping coefficient (times normal)

Static stability experiment

Static stability (vertical temperature gradient) controlled by term 2 in the equilibrium temperature profile equation :

$$T_{eq} = \max\left\{200, \left[315 - \underbrace{(\Delta T)_y \sin^2\phi}_{TERM1} - \underbrace{(\Delta\theta)_z \log\left(\frac{p}{p_o}\right)\cos^2\phi}_{TERM2}\right] \underbrace{\left(\frac{p}{p_o}\right)^k}_{TERM3}\right\}$$

Term 2: Release of latent heat in convective processes

Manipulate $(\Delta\theta)_z$ to control static stability

- Default value = 10
- Large values = increased static stability

Side effect : Jet strength altered

Static stability experiment (continued)

Procedure to conserve jet strength :

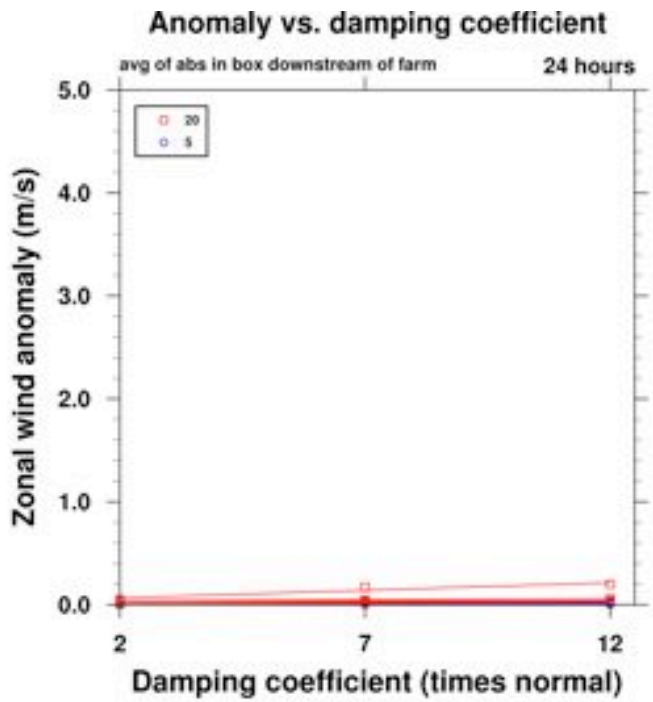
Derive geostrophic wind field from equilibrium temperature profile using thermal wind :

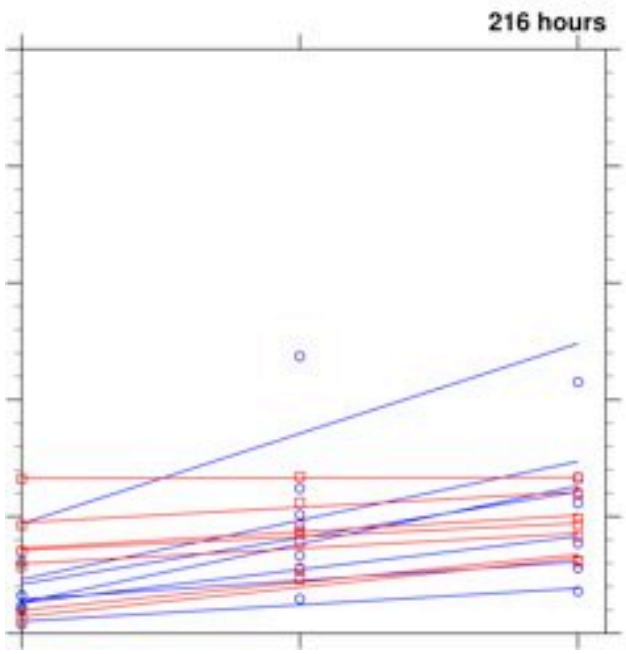
$$V_T = \frac{R}{f} \cdot \ln\left(\frac{p_1}{p_2}\right) \times \nabla_P \overline{T}$$

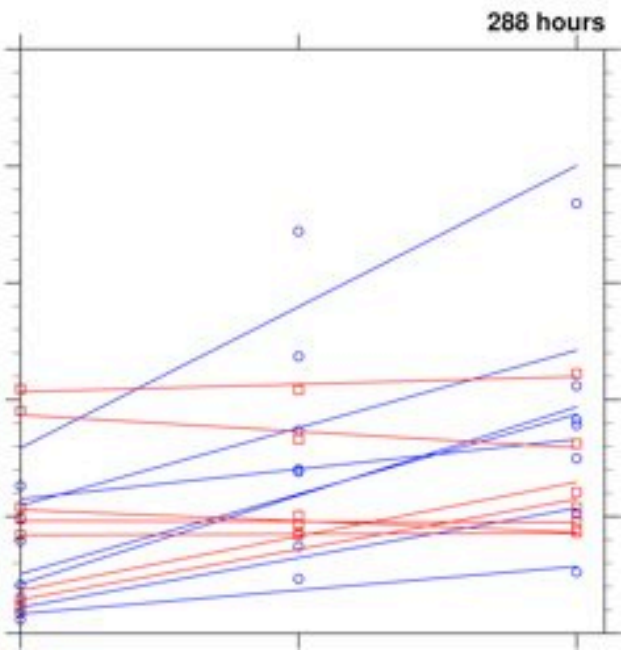
For a given value of $(\Delta\theta)_z$, find corresponding value of $(\Delta T)_y$ that preserves jet strength, using iterative process

Test	$(\Delta\theta)_z$	$(\Delta T)_y$	Notes
1	5	62.88	Decreased stability
2	10	60	Default stability
3	20	53.84	Increased Stability

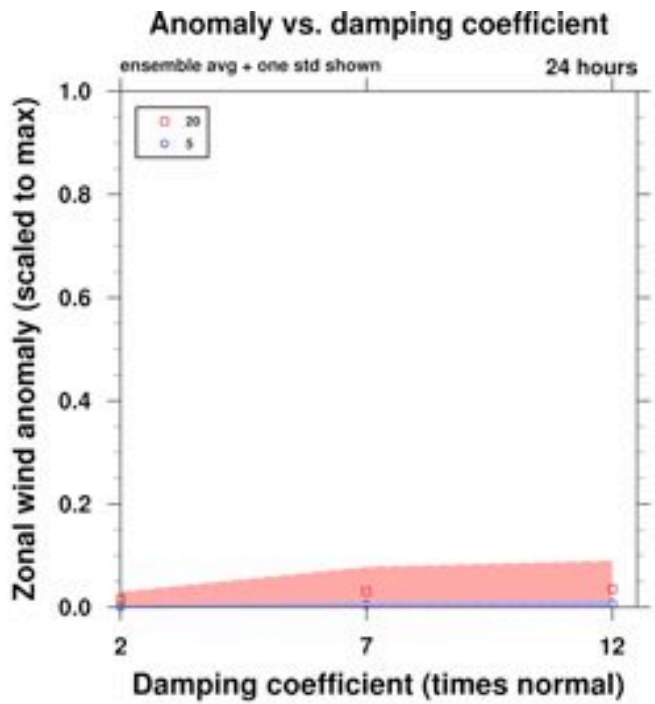
Static stability

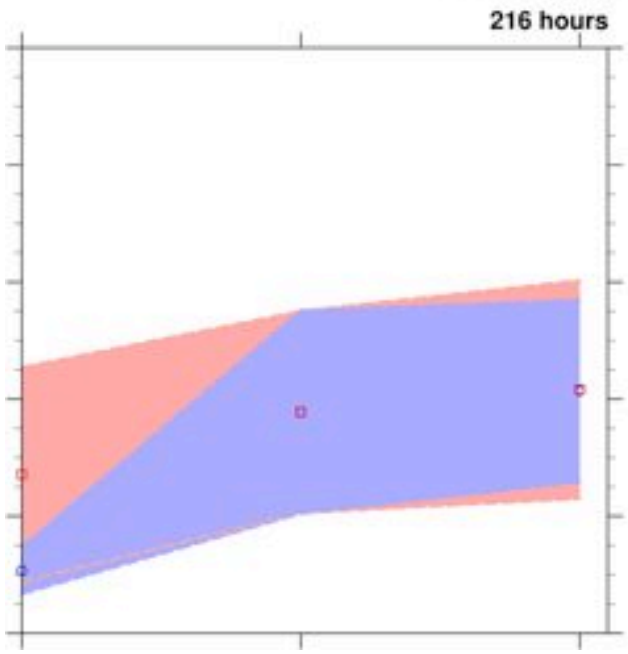


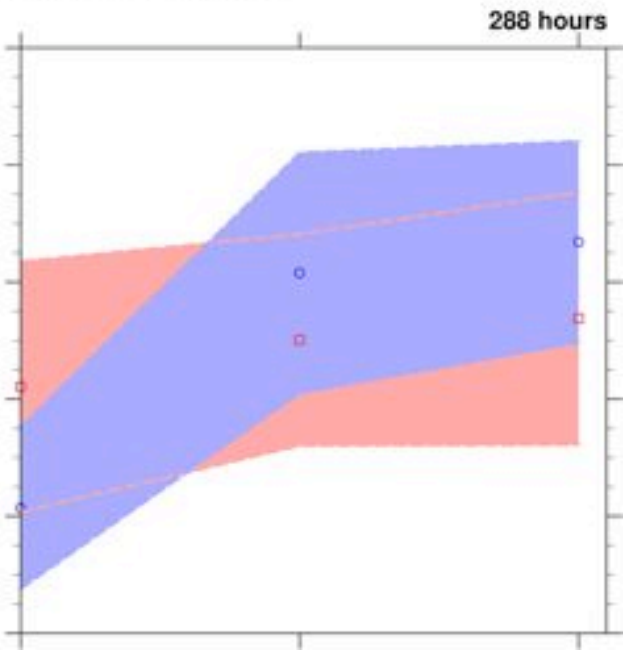




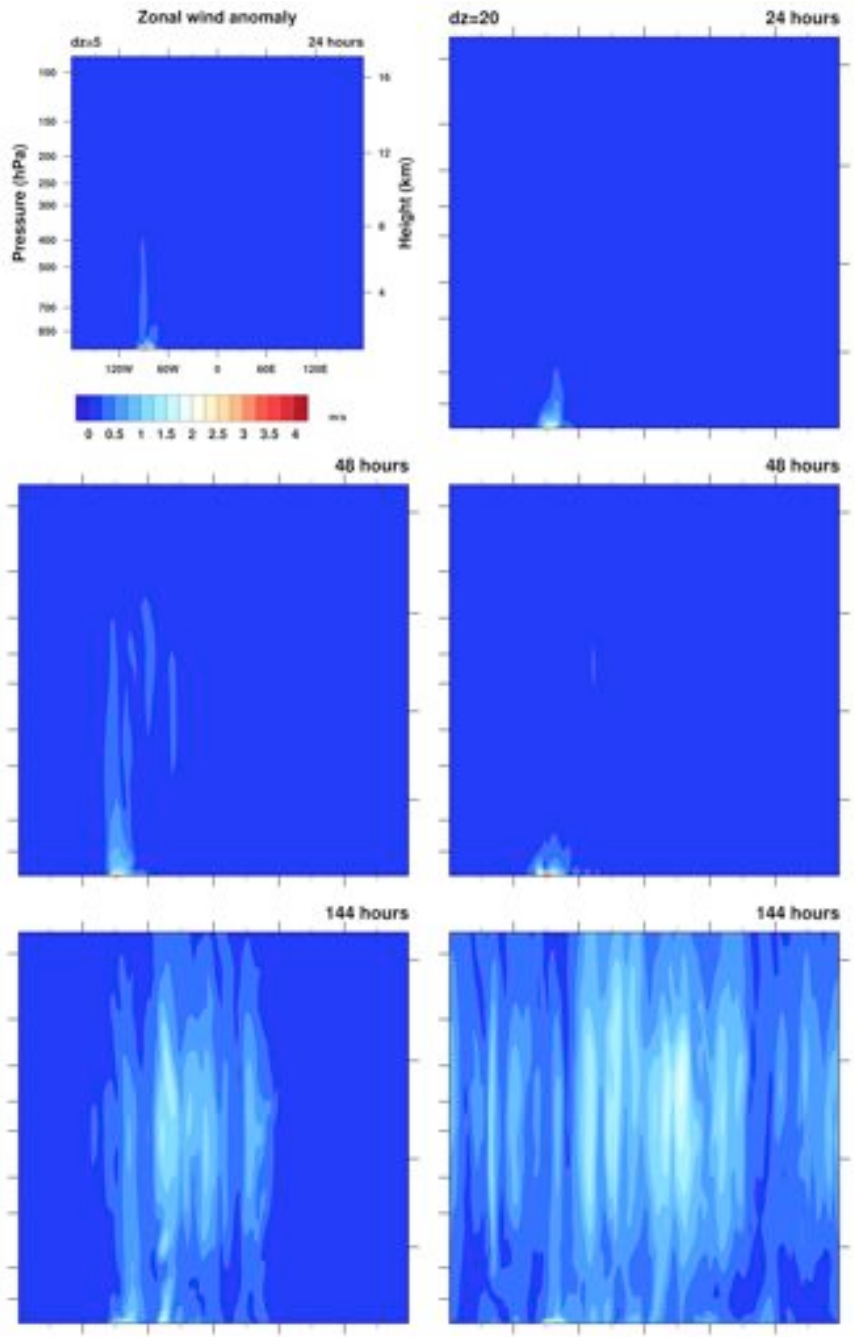
Static stability







Static stability



Jet experiment

Jet strength controlled by term 1 in the equilibrium temperature profile equation :

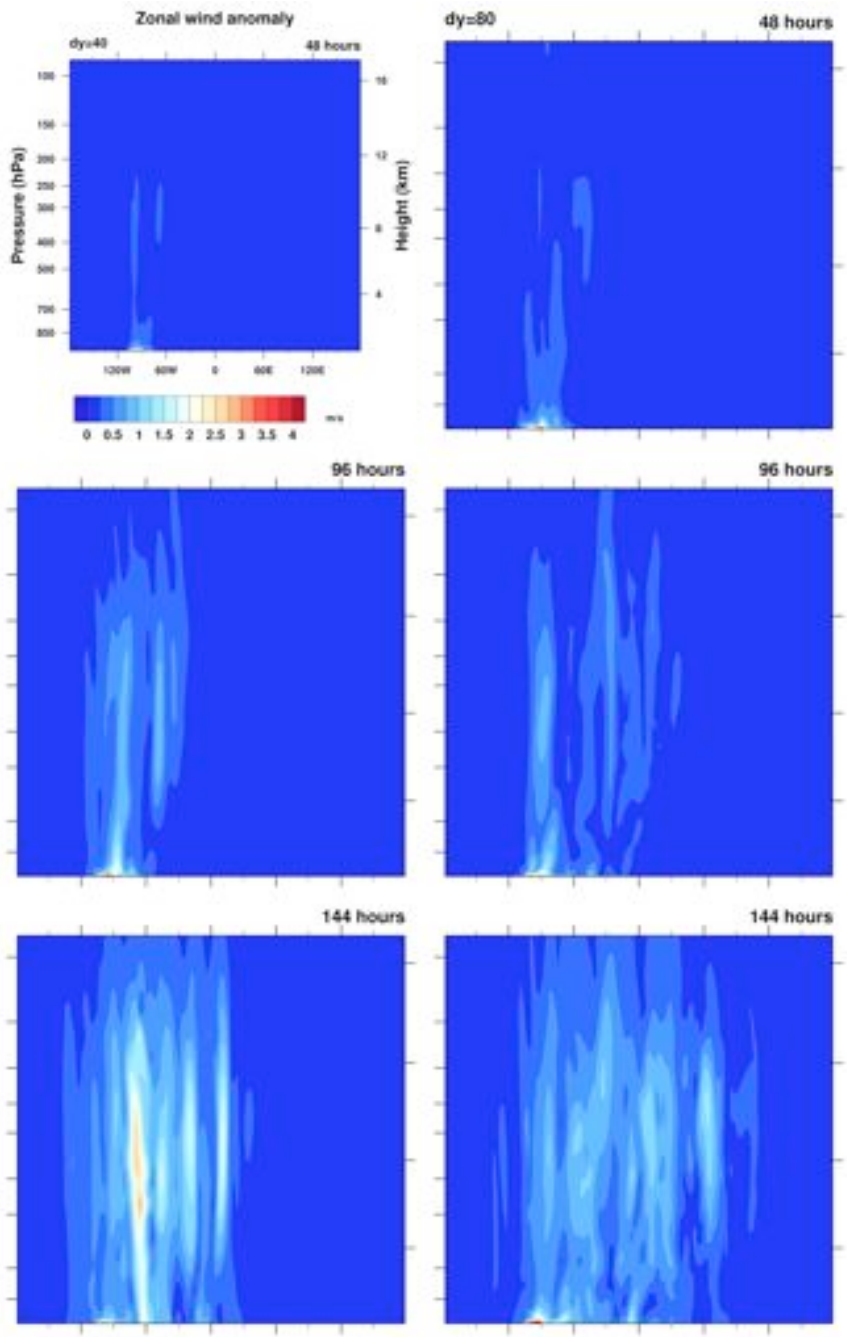
$$T_{eq} = \max\left\{200, \left[315 - \underbrace{(\Delta T)_y \sin^2\phi}_{TERM1} - \underbrace{(\Delta\theta)_z \log\left(\frac{p}{p_o}\right)\cos^2\phi}_{TERM2}\right] \underbrace{\left(\frac{p}{p_o}\right)^k}_{TERM3}\right\}$$

Term 1: Meridional temperature gradient

Manipulate $(\Delta T)_y$ to control jet

- Default value = 60
- Large values = increased jet strength

Jet


Zonal wind anomaly
dy=40
48 hours
dy=80
48 hours
96 hours
96 hours
144 hours
144 hours
Pressure (hPa)
Height (km)
0 0.5 1 1.5 2 2.5 3 3.5 4

Part III :

The impact of climate change on the United States wind resource

Data

13 Coupled Model Intercomparison Project, Phase 3 model datasets

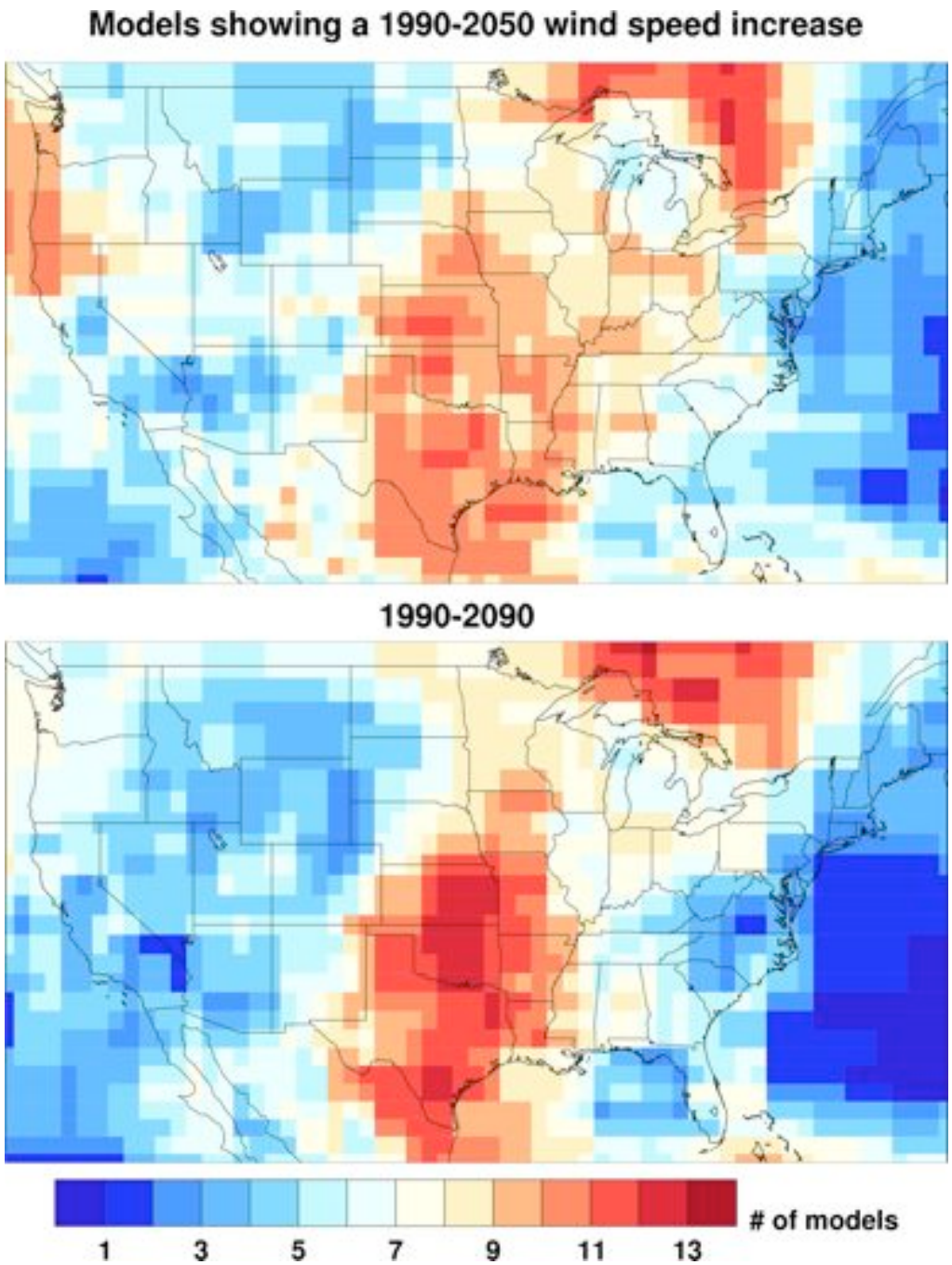
SRES A2 emissions pathway : higher than average emissions growth, lower than recent actual emissions

10 m daily zonal and meridional wind speed fields

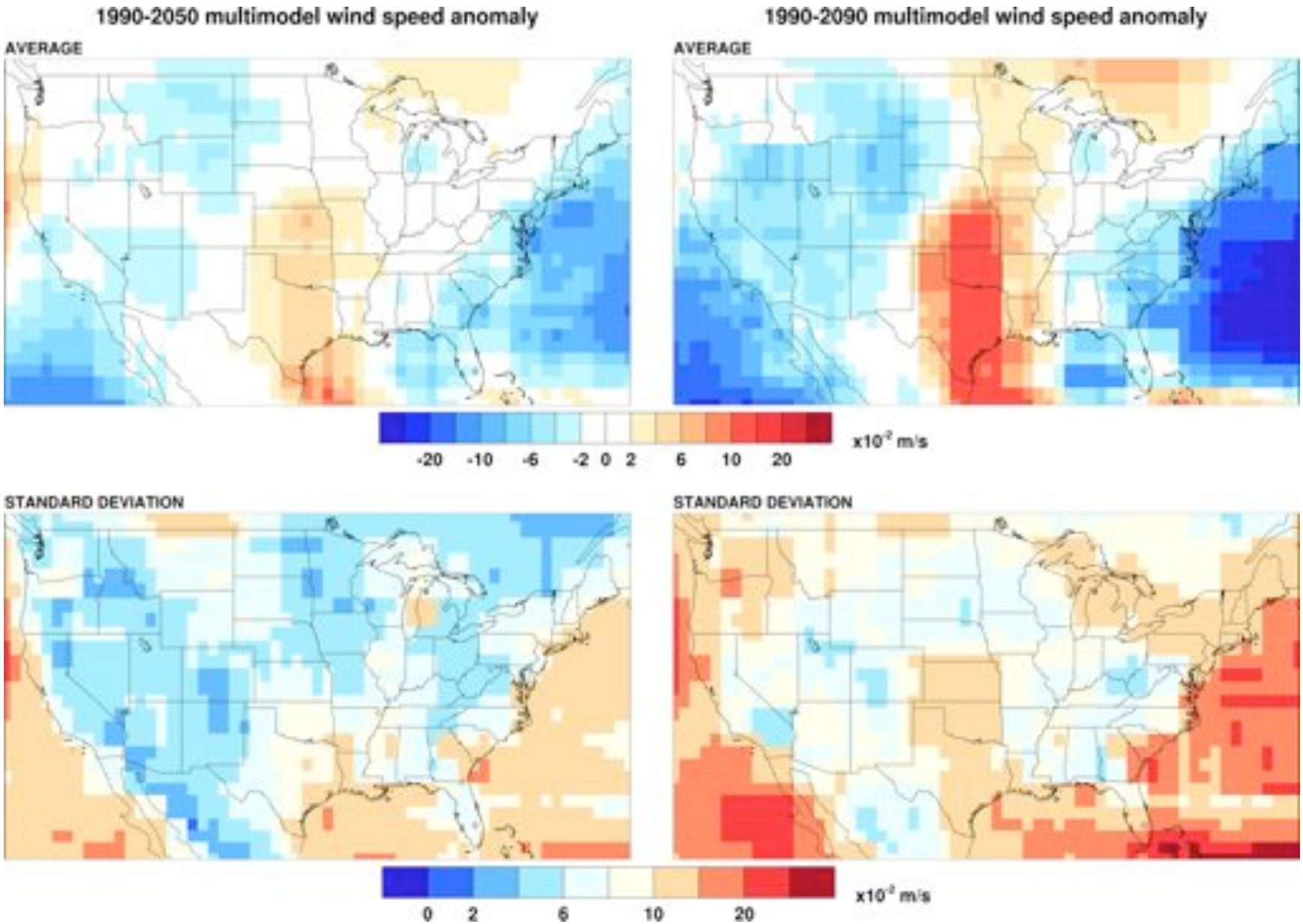
Intermodel resolution range : 45x72 to 160x320

Time periods analyzed : 1990-2000, 2050-2060, 2090-2100

CMIP3


Models showing a 1990-2050 wind speed increase
1990-2090
1
3
5
7
9
11
13
# of models

CMIP3


1990-2050 multimodel wind speed anomaly
1990-2090 multimodel wind speed anomaly
AVERAGE
AVERAGE
-20 -10 -6 -2 0 2 6 10 20
x10⁻² m/s
STANDARD DEVIATION
STANDARD DEVIATION
0 2 6 10 20
x10⁻² m/s

Wind power

Power is proportional to speed cubed:

$$P = \tfrac{1}{2} \cdot \rho \cdot A \cdot v^3 \cdot c_B \cdot c_g$$

Total speed:

$$V = \overline{\left[\sqrt{(u)^2 + (v)^2}\right]}$$

Stationary component of speed:

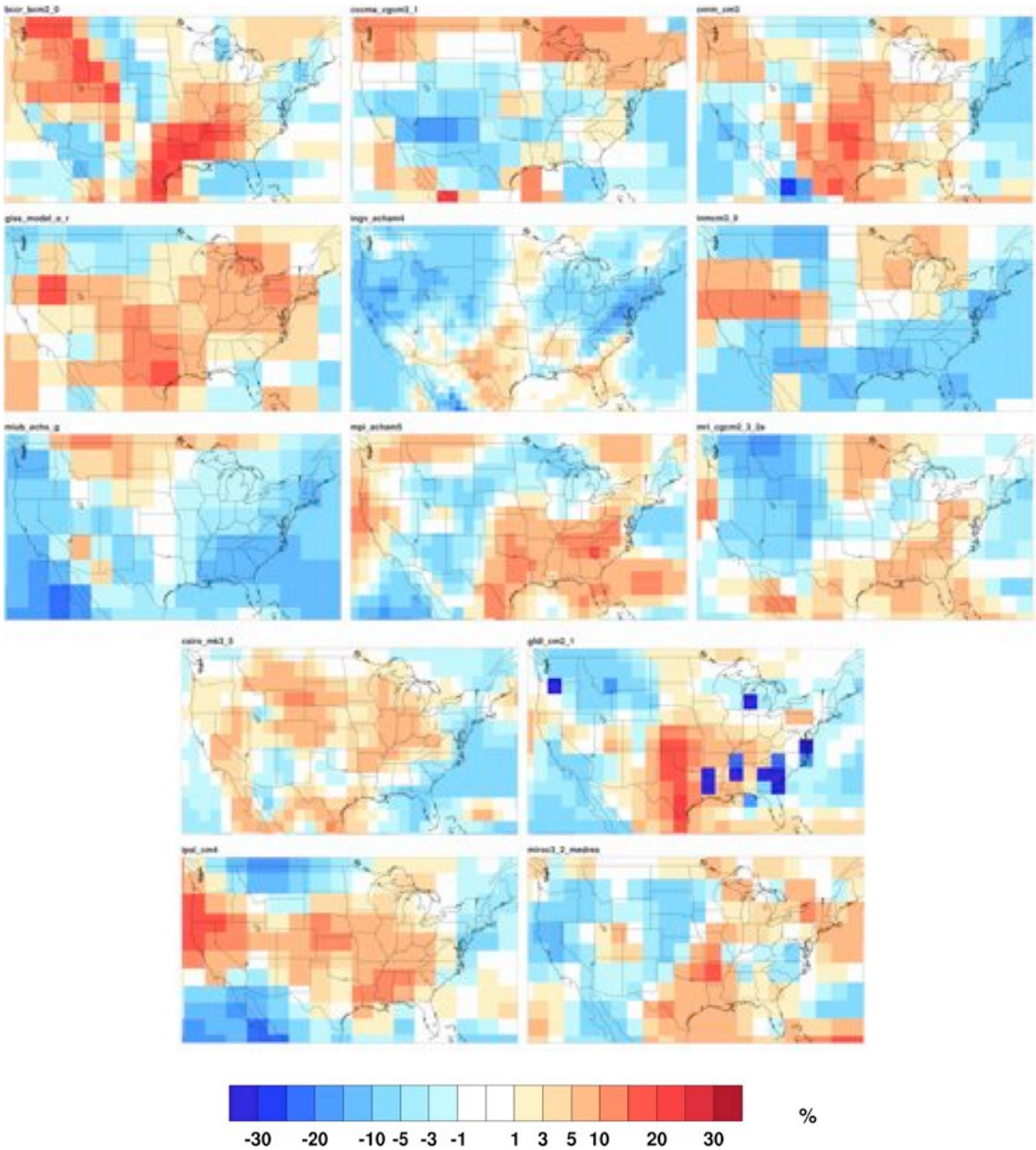
$$V_S = \left[\sqrt{(\bar{u})^2 + (\bar{v})^2}\right]$$

Transient component of speed:

$$V_T = V - V_S$$

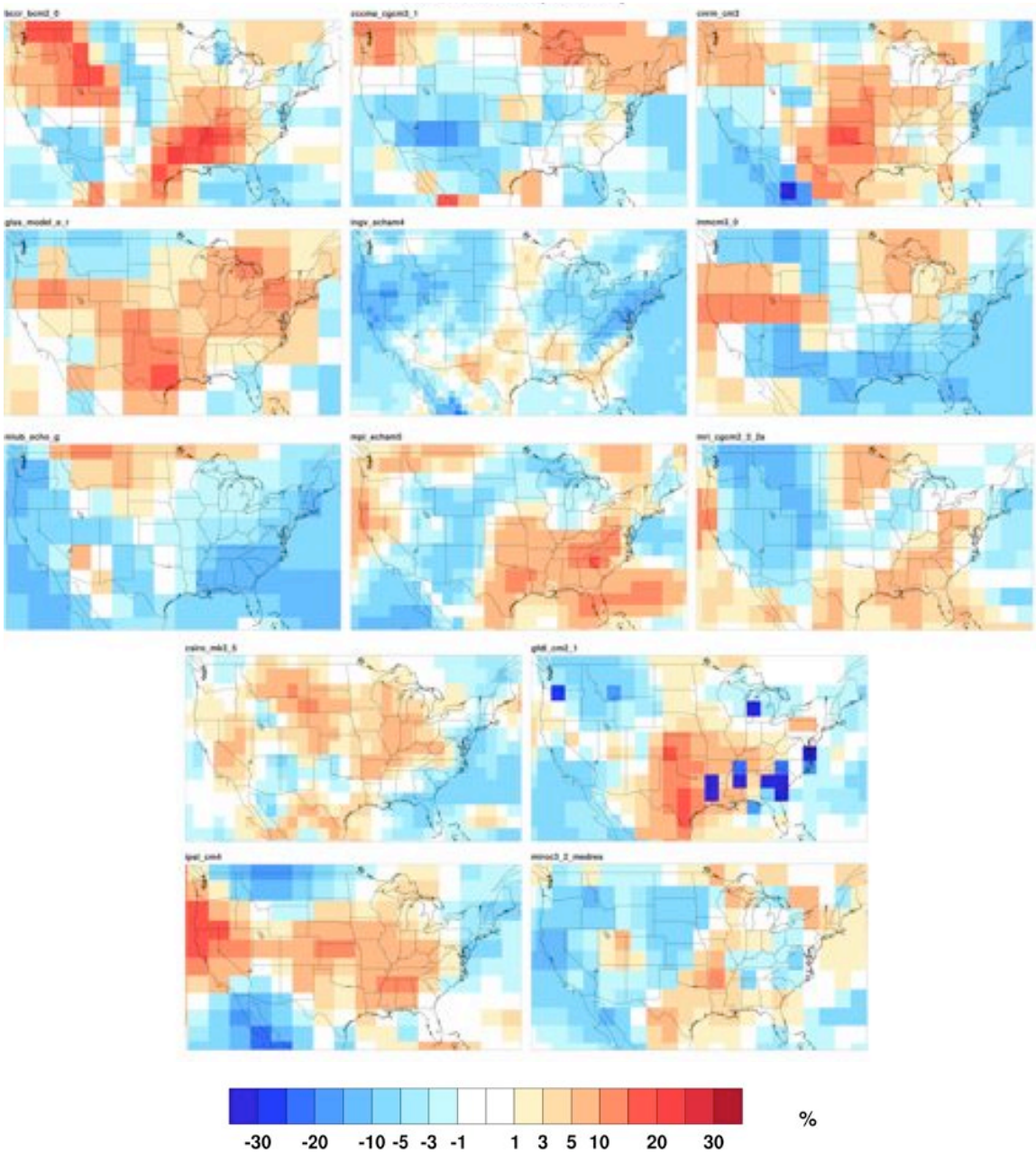
CMIP3

1990s – 2050s total power anomaly



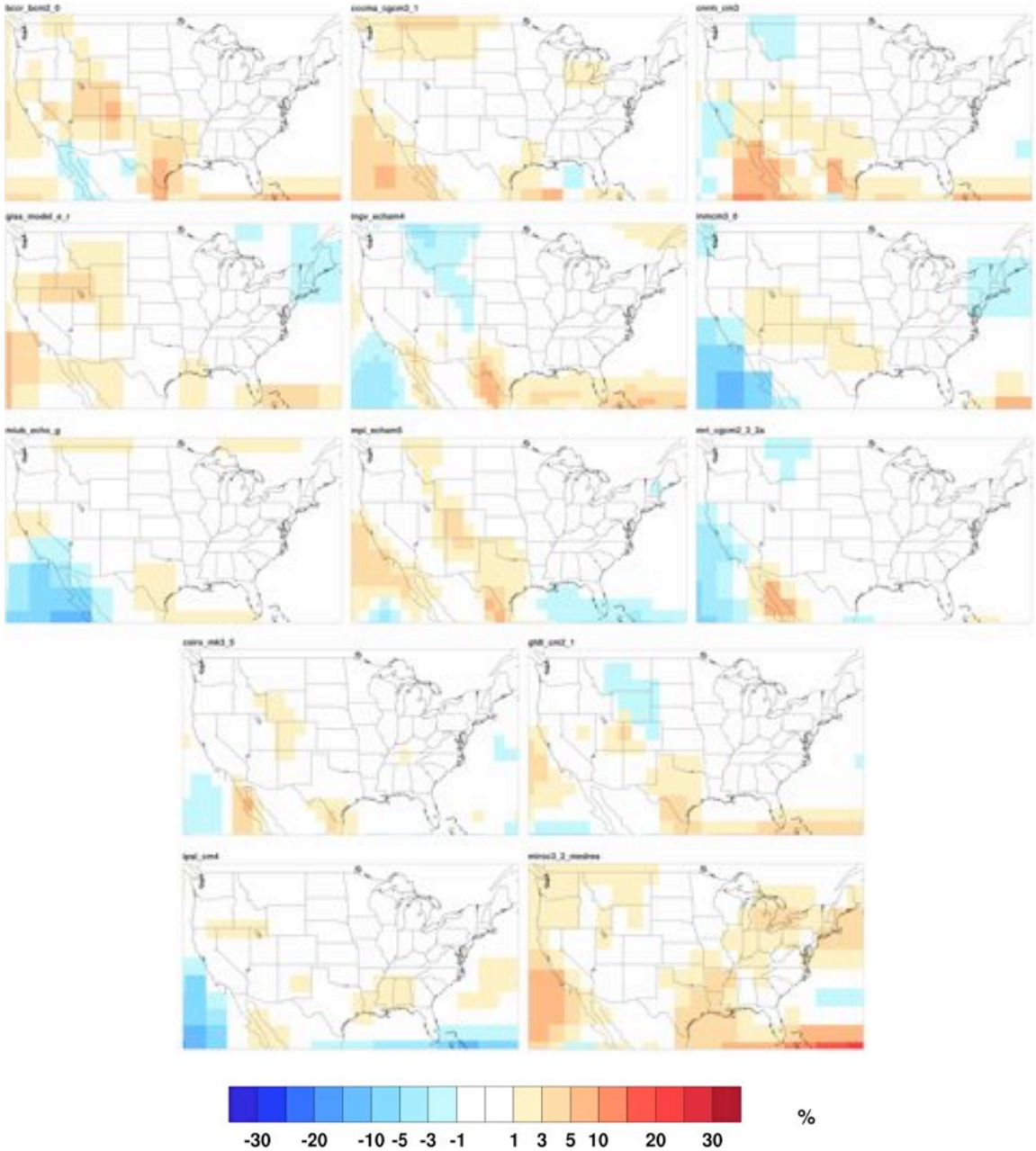
CMIP3

1990s – 2050s transient power anomaly



CMIP3

1990s – 2050s stationary power anomaly



Data

3 North American Regional Climate Change Assessment Program model datasets

SRES A2 emissions pathway

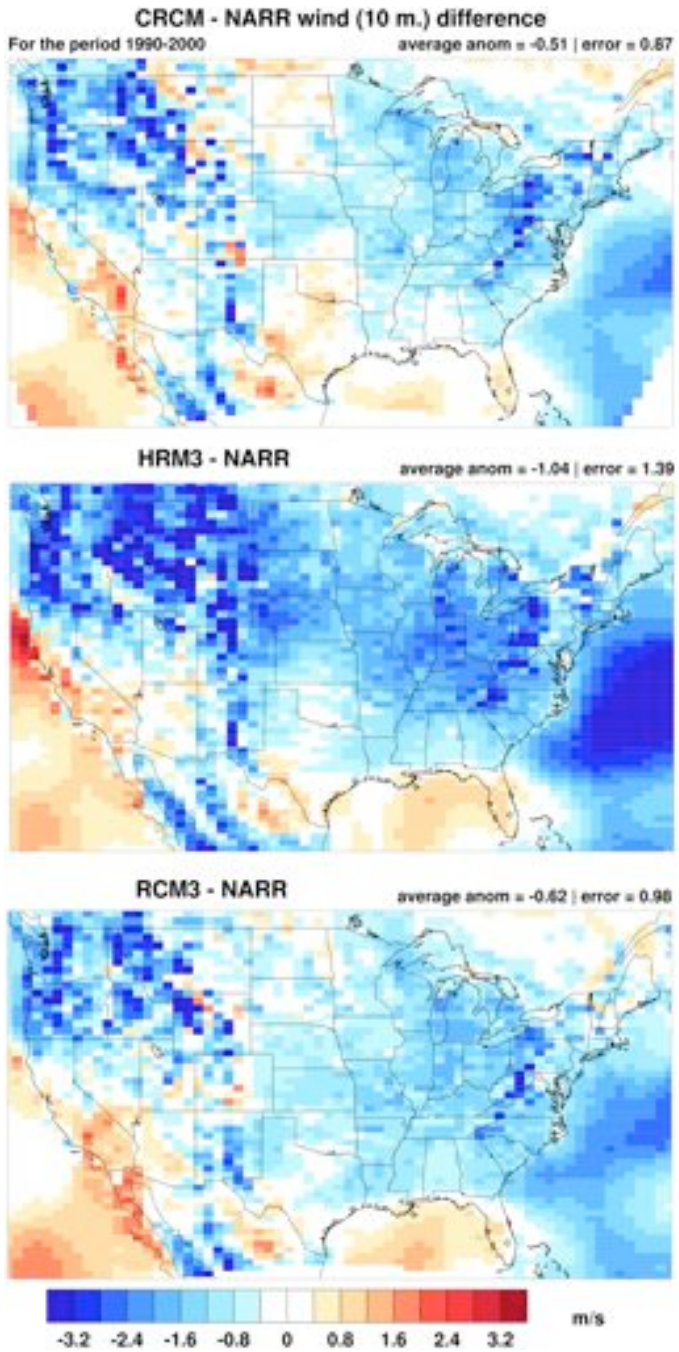
10 m 3-hour zonal and meridional wind speed fields

Model resolution : 50 km

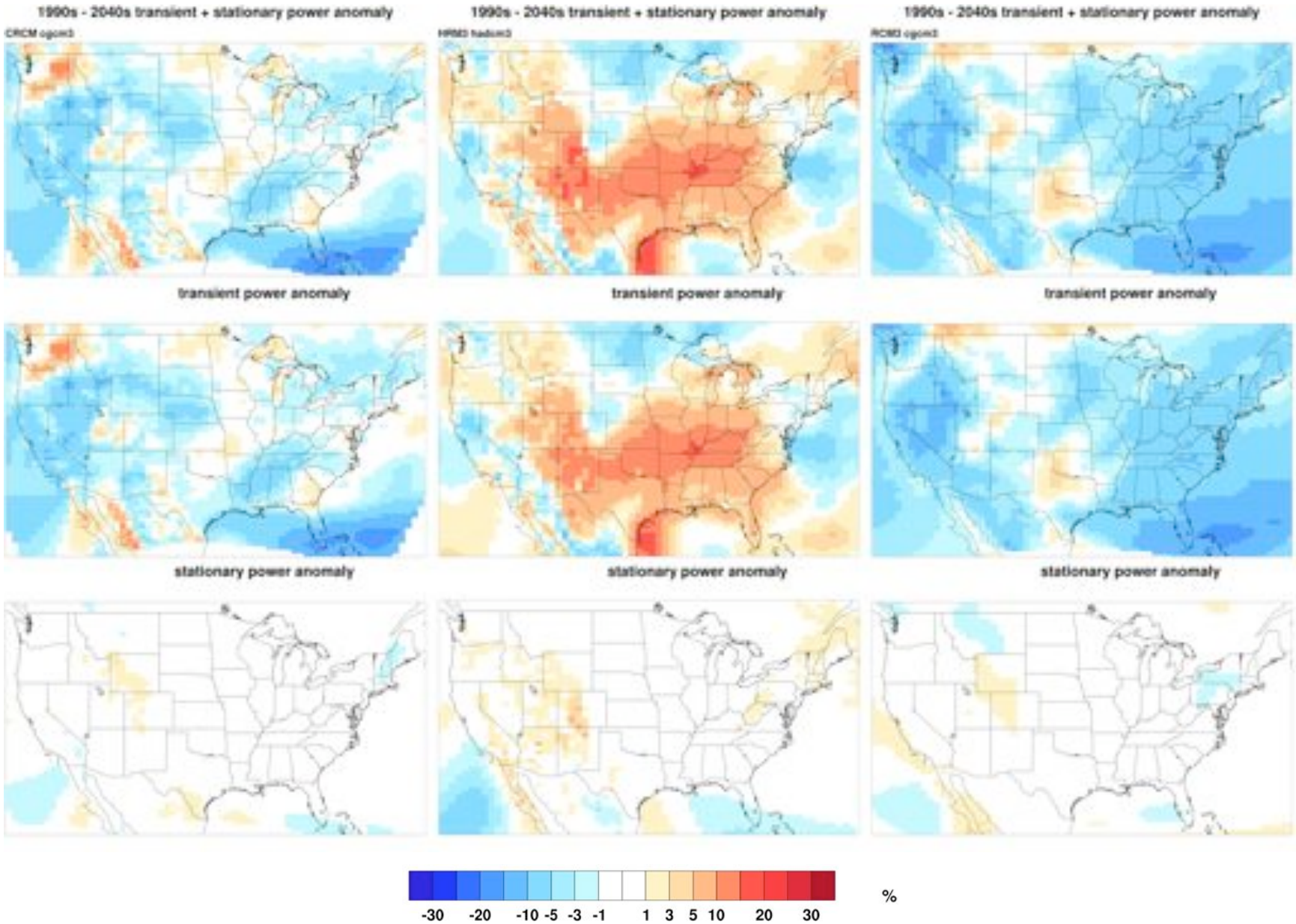
Time periods analyzed : 1990-2000, 2040-2050, 2060-2070

Validation of 1990-2000 against North American Regional Reanalysis data

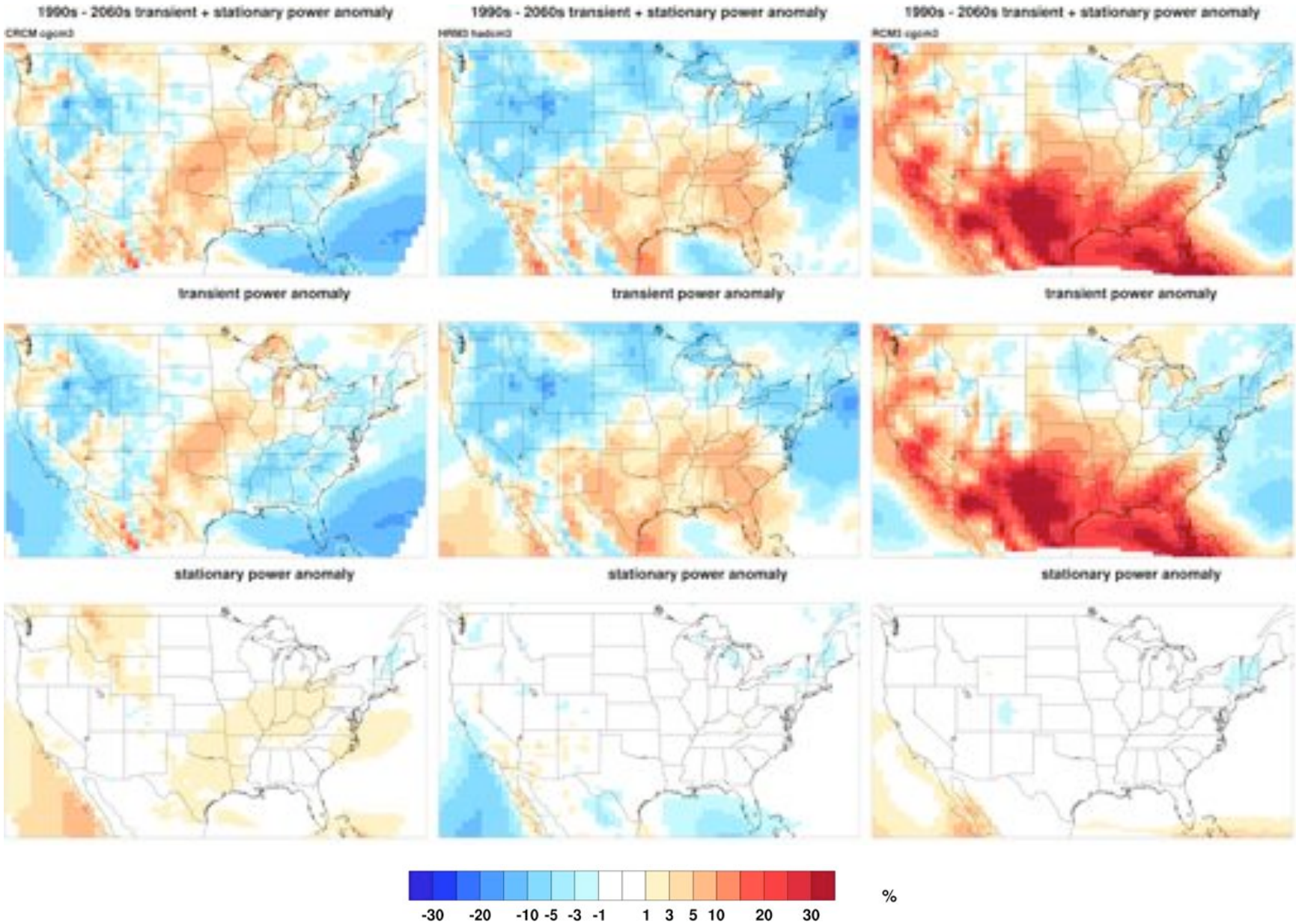
NARCCAP


CRCM - NARR wind (10 m.) difference
For the period 1990-2000
average anom = -0.51 | error = 0.87
HRM3 - NARR
average anom = -1.04 | error = 1.39
RCM3 - NARR
average anom = -0.62 | error = 0.98
-3.2 -2.4 -1.6 -0.8 0 0.8 1.6 2.4 3.2
m/s

NARCCAP


1990s - 2040s transient + stationary power anomaly
1990s - 2040s transient + stationary power anomaly
1990s - 2040s transient + stationary power anomaly
transient power anomaly
transient power anomaly
transient power anomaly
stationary power anomaly
stationary power anomaly
stationary power anomaly
-30 -20 -10 -5 -3 -1 1 3 5 10 20 30
%

NARCCAP


1990s - 2060s transient + stationary power anomaly
1990s - 2060s transient + stationary power anomaly
1990s - 2060s transient + stationary power anomaly
transient power anomaly
transient power anomaly
transient power anomaly
stationary power anomaly
stationary power anomaly
stationary power anomaly
-30 -20 -10 -5 -3 -1 1 3 5 10 20 30
%

Conclusions

- Atmospheric perturbations generated by central United States wind farm grow over North Atlantic

- Wind farm impacts could rival forecast uncertainty in magnitude; impacts may be forecastable

- Downstream impacts increase as wind farm size increases

- Increased static stability suppresses near-farm impacts, encourages remote impacts

- Stronger jet increases downstream range of impacts

Conclusions (continued)

- Climate change due to anthropogenic global warming is projected to enhance central United States wind power resource

- High variability in the intermodel projections

Future work

- Apply fundamental modeling conclusions to detailed weather impacts studies

- Formulate a dynamical framework that describes the transient atmospheric response to the wind farm

- Study CMIP3 and NARCCAP wind speed frequency distributions in greater detail

- Continued study of the NARCCAP data set, which is in nascent stages.

Thank you