From Trades to Turbines: The Art and Science of Wind Energy Resource Assessment

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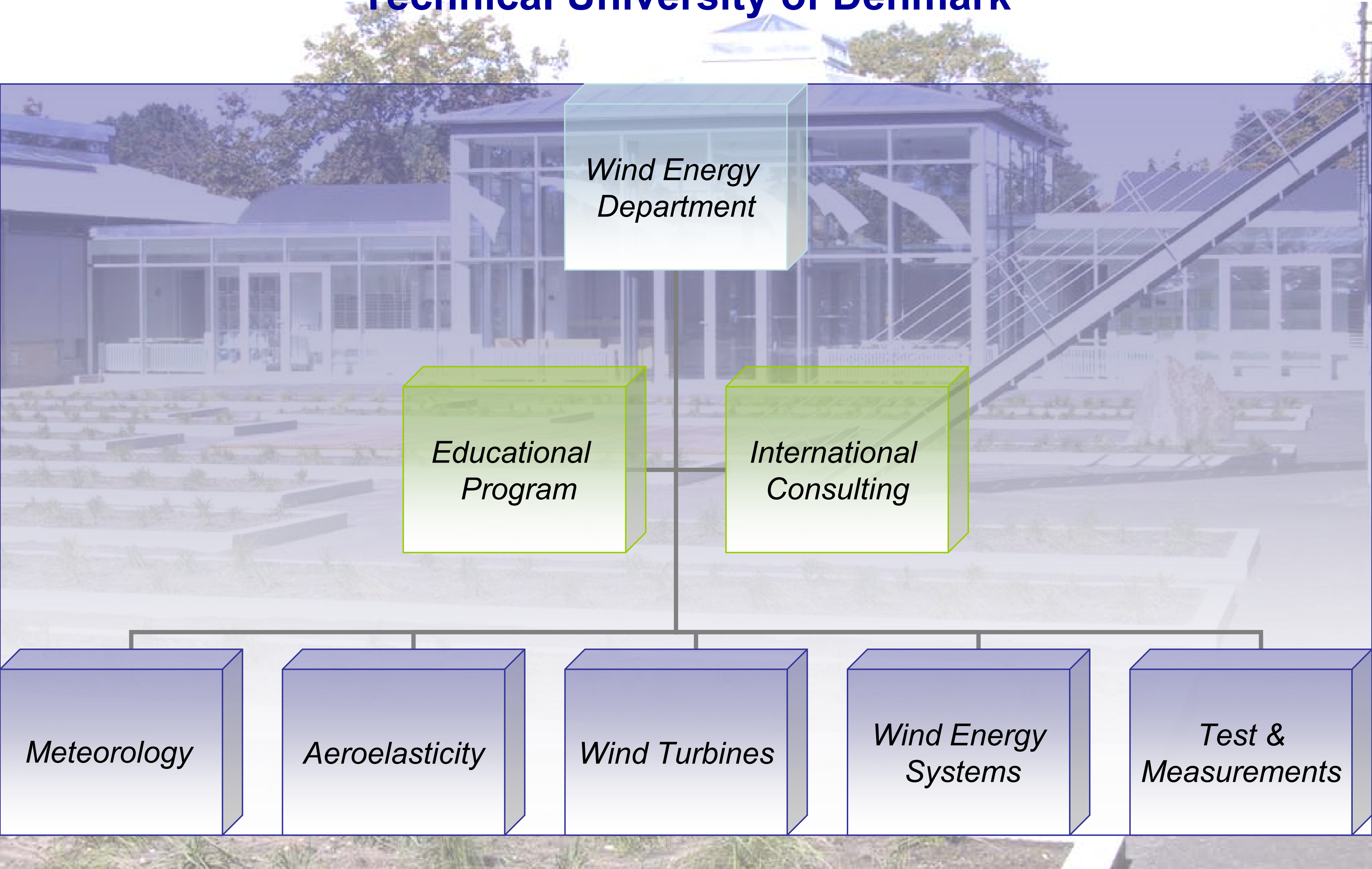


Outline

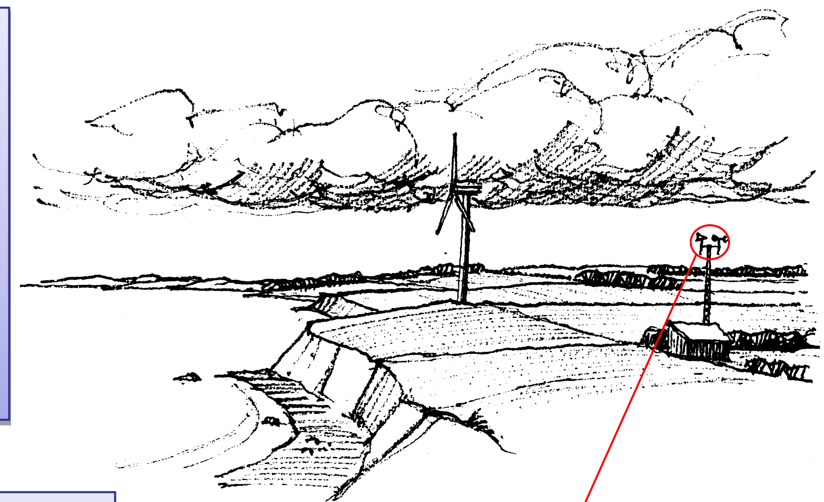
- Introduction
- Wind power resource assessment
- Observational wind atlases
- Numerical wind atlas – statistical-dynamical downscaling
- Examples of recent wind atlases – going the extra step
- Preview of future work: dynamical downscaling
- Final comments

The problem

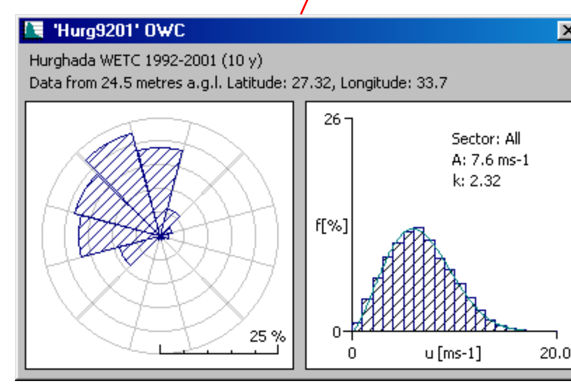
Determining the wind resources accurately is important and difficult

Main parameters governing wind power economics:

- Investment costs
- Operation and maintenance costs
- Electricity production / Wind resources
- Turbine lifetime
- Discount rate



- Wind speed, U [m/s]
- Kinetic energy flux, $P = ½\rho U^3$ [W/m²]
- ΔU of 5% (e.g. U=8.0+0.4m/s) ⟹ ΔP of 15%



- Wind resources are in fact more P than U
- Both U and P are statistical distributions
- We measure U (and D) in one point in space, but need it in the entire atmospheric boundary layer

Observational wind atlas

Inputs

- measured time-series of wind speed and direction – observed wind climate
- terrain topography – elevation, roughness and obstacles – digitised maps, SRTM, Google Earth

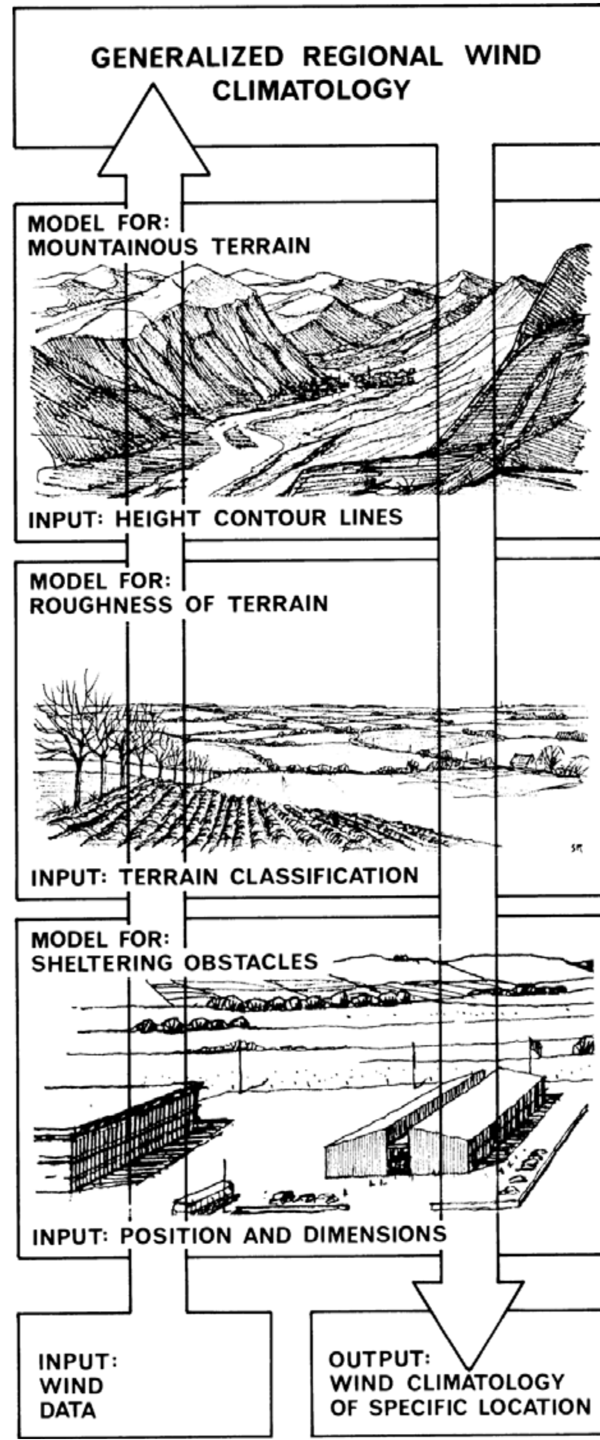
Outputs

- generalised *regional wind climate* for the specific location

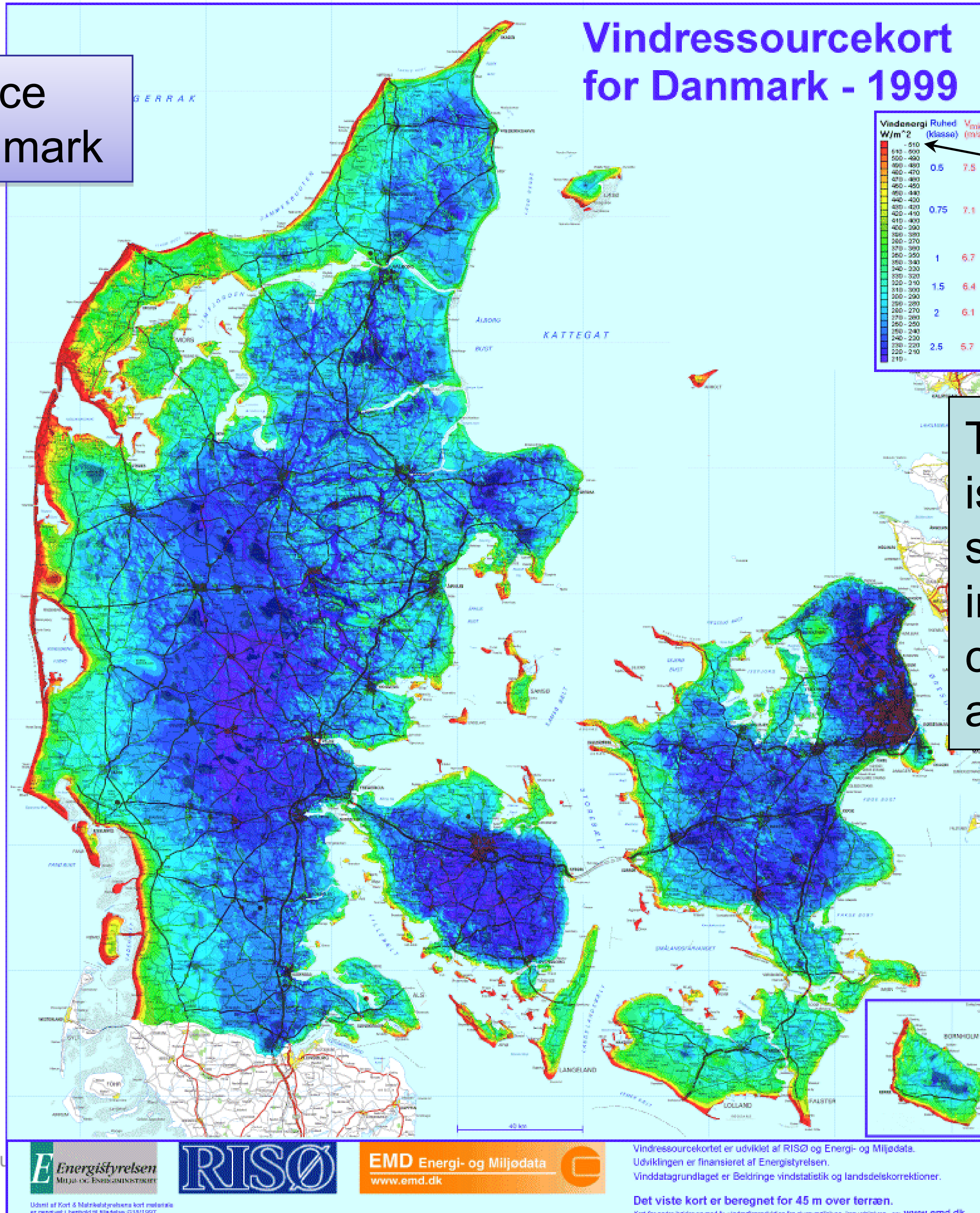
Applications

- energy production estimate for wind farms in the region near the meteorological station

- This Regional Wind Climate is the hypothetical wind climate for an ideal, featureless and completely flat terrain with a uniform surface roughness, assuming the same overall atmospheric conditions as those of the measuring position.



Wind resource map for Denmark



~500 W/m²
Mean wind
~7.5 m/s

The wind atlas is more than a simple map – input "wind climate" files are also provided

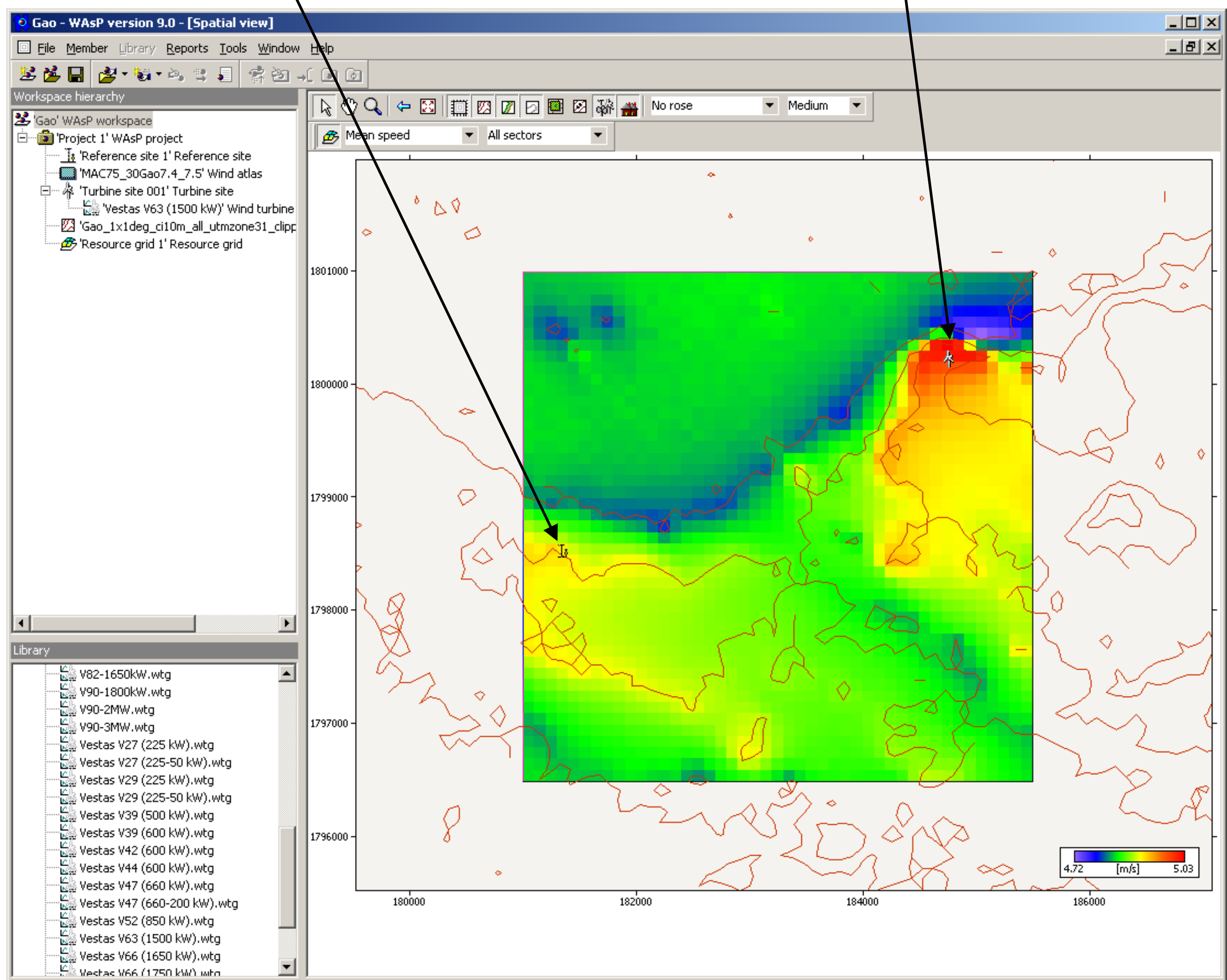
Wind atlas study for Mali

WAsP showing a resource map for an area around the Gao measurement site at 100 m resolution.

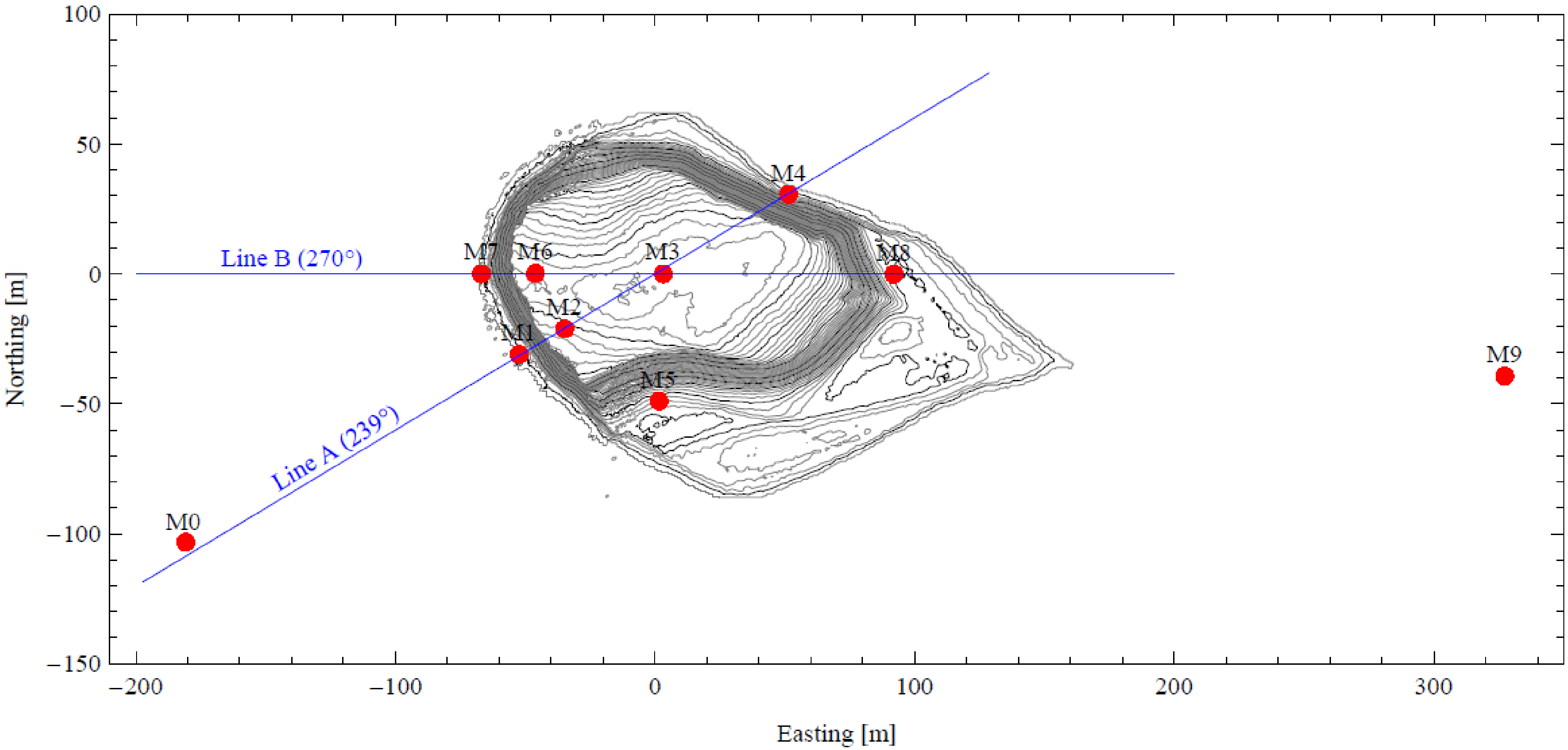
WAsP calculates wind resource for new sites and heights above ground level.

Gao met. station

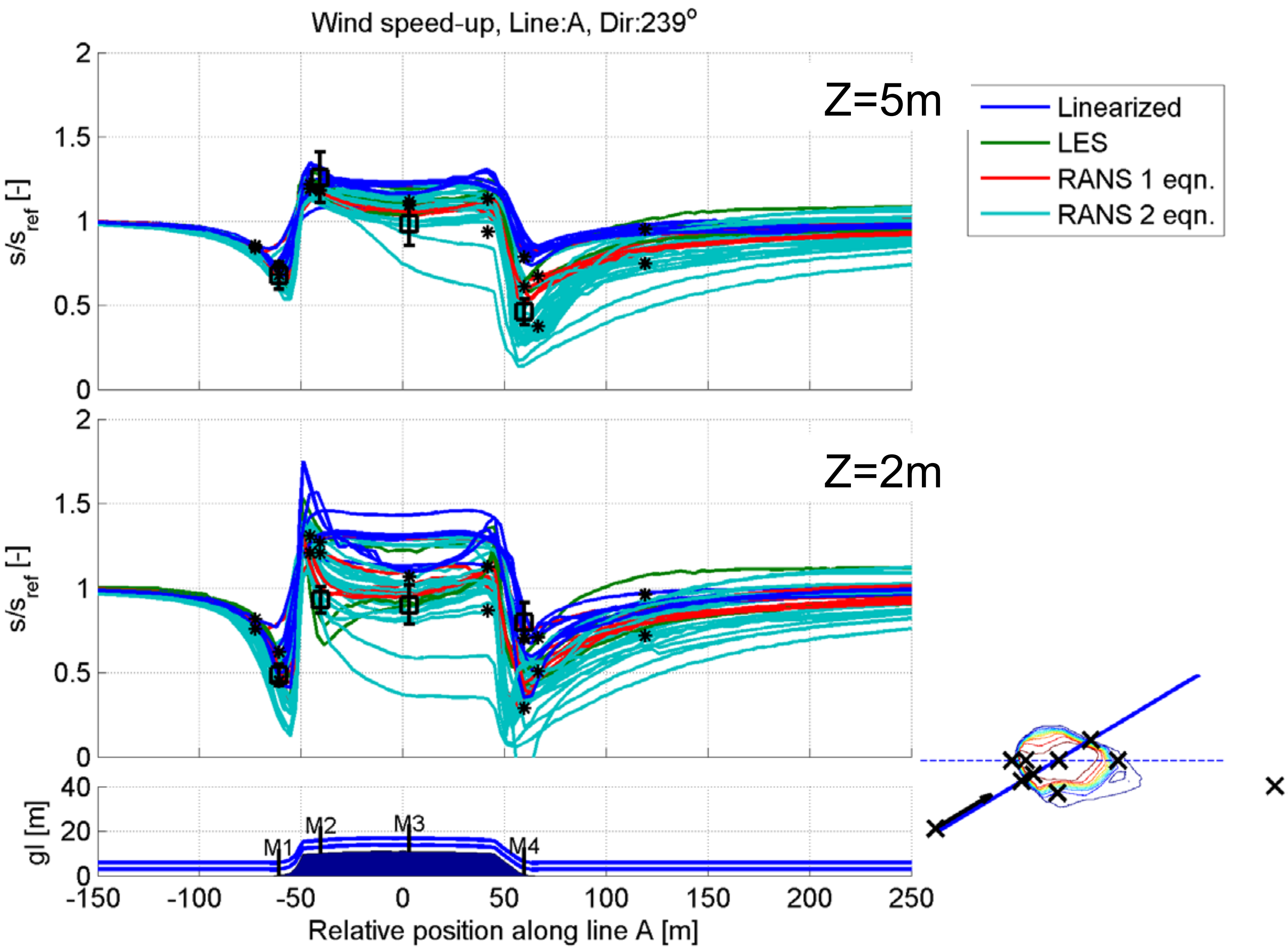
better turbine site



Verification on micro-scale models
CFD were used to find the 10 positions



Speed-up along line A

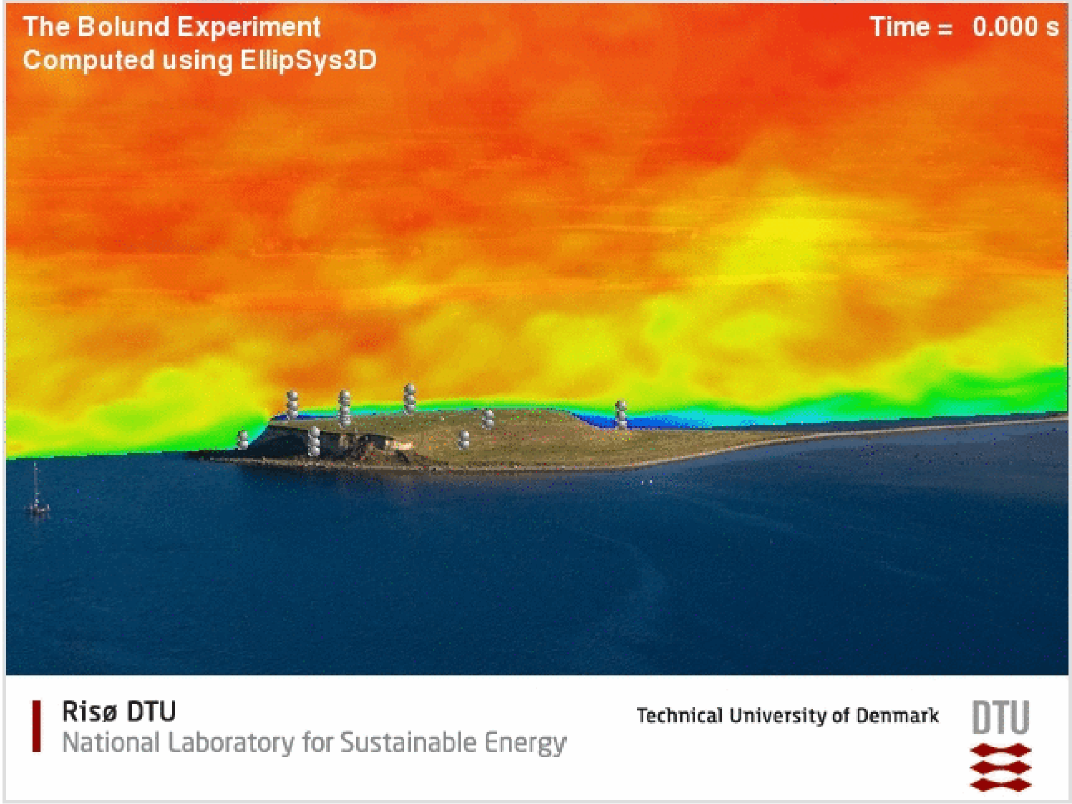


Conclusions on CFD
The Blind Comparison

1. Uncertainty of less than 3% - We have a long way! CFD guides would help somewhat.

2. Recommendation: RANS is today's main workhorse, LES has not matured yet.

3. 7 diff. CFD solvers in top 10: The user is more important than the solver.



Numerical wind atlas – mesoscale

When good quality long-term wind observations are not available, the numerical wind atlas method is used.

Inputs

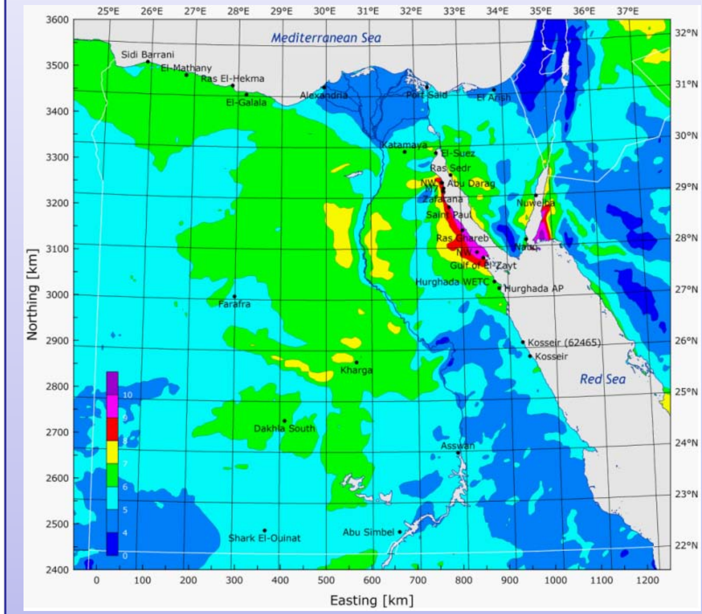
- NCEP/NCAR global reanalysis data-set
- terrain topography – elevation and roughness – satellite and SRTM data

Outputs

- generalised *regional wind climate* for large domains

Applications

- planning
- assessment of mesoscale effects at wind farm projects



wind resource map for Egypt: mean wind at 50m AGL

Beneficial features of the numerical wind atlas methods developed at RISØ-DTU

- Classification system
  - statistical-dynamical downscaling methods allow for a much less resource demanding evaluation of climatological wind resources
    - full 30-year period: 263000 hours to be simulated
    - Risø DTU's KAMM/WAsP method: 900 hours (1/290th full period)
    - CMA's WRF method: 14400 hours (1/18th full period)
- Verification method
  - comparison of modelling based results against measurements provides quality check
  - gives an estimate of bias and random errors
- Sensitivity testing and uncertainty estimation
  - exploration of the most important model parameters
  - indicates possible sources of errors and targets areas for improvement
  - may be used to generate associated maps of uncertainty

Downscaling model chain

large-scale

~150 wind classes
~200 km

Reanalysis data
NCEP/NCA
30 years

→ mesoscale modelling →

meso-scale

wind resource maps + generalized wind climate data and maps

~2 – 10 km

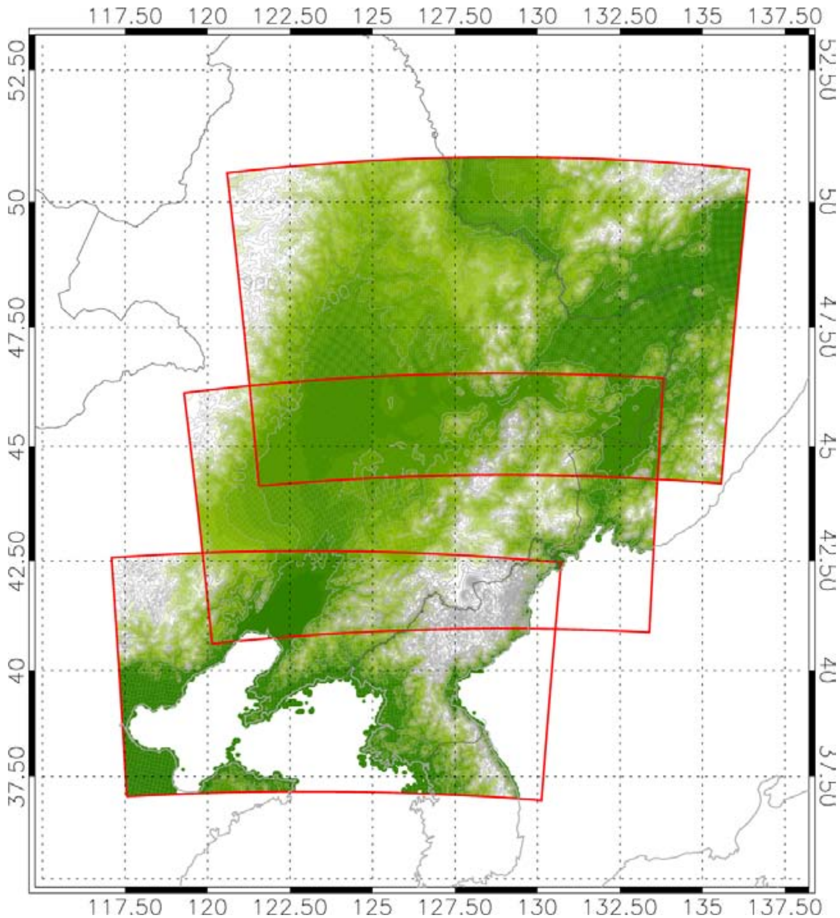
→ microscale modelling →

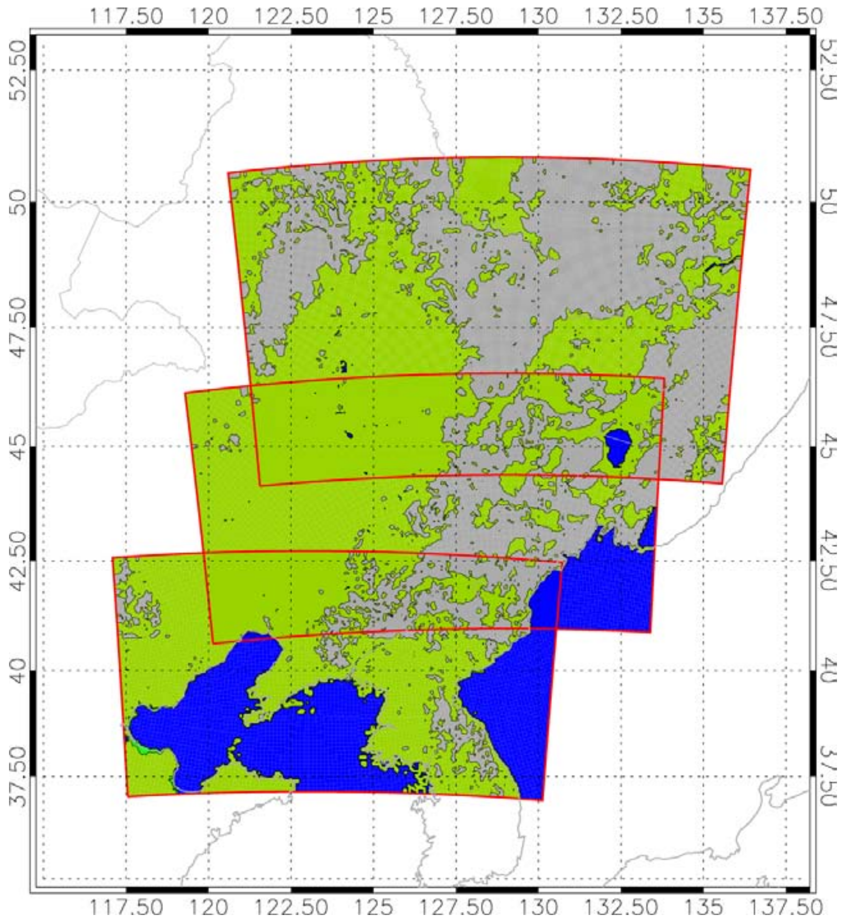
micro-scale

wind resource maps + turbine production + wake modelling, …

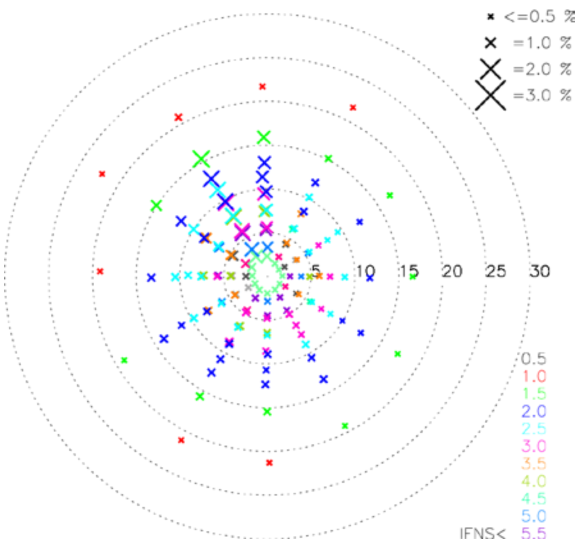
~1 m – 2 km

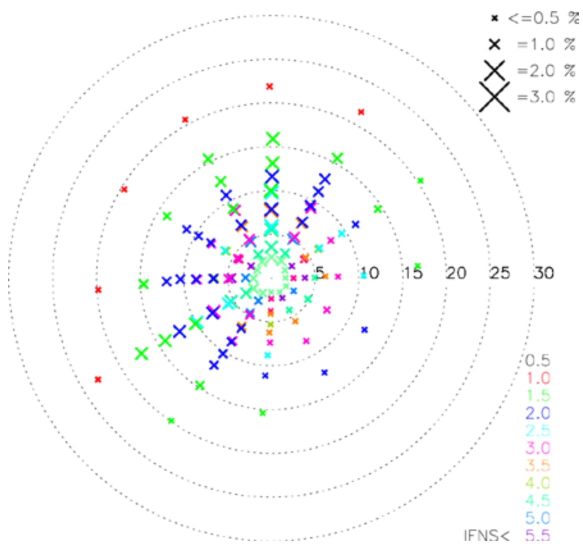
Orography and roughness length

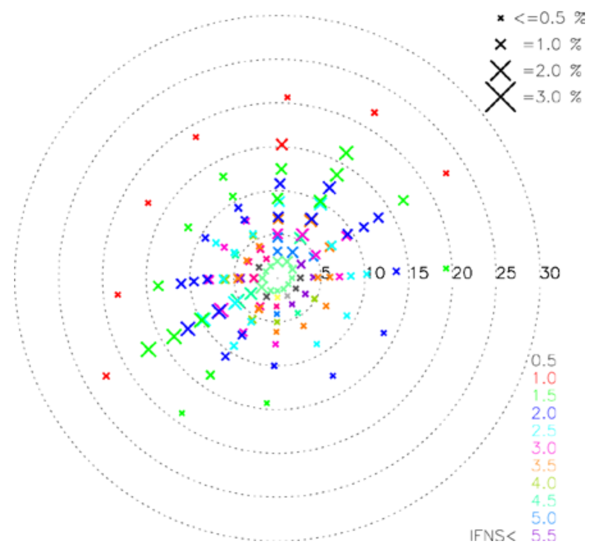




Wind classes of the 3 domains

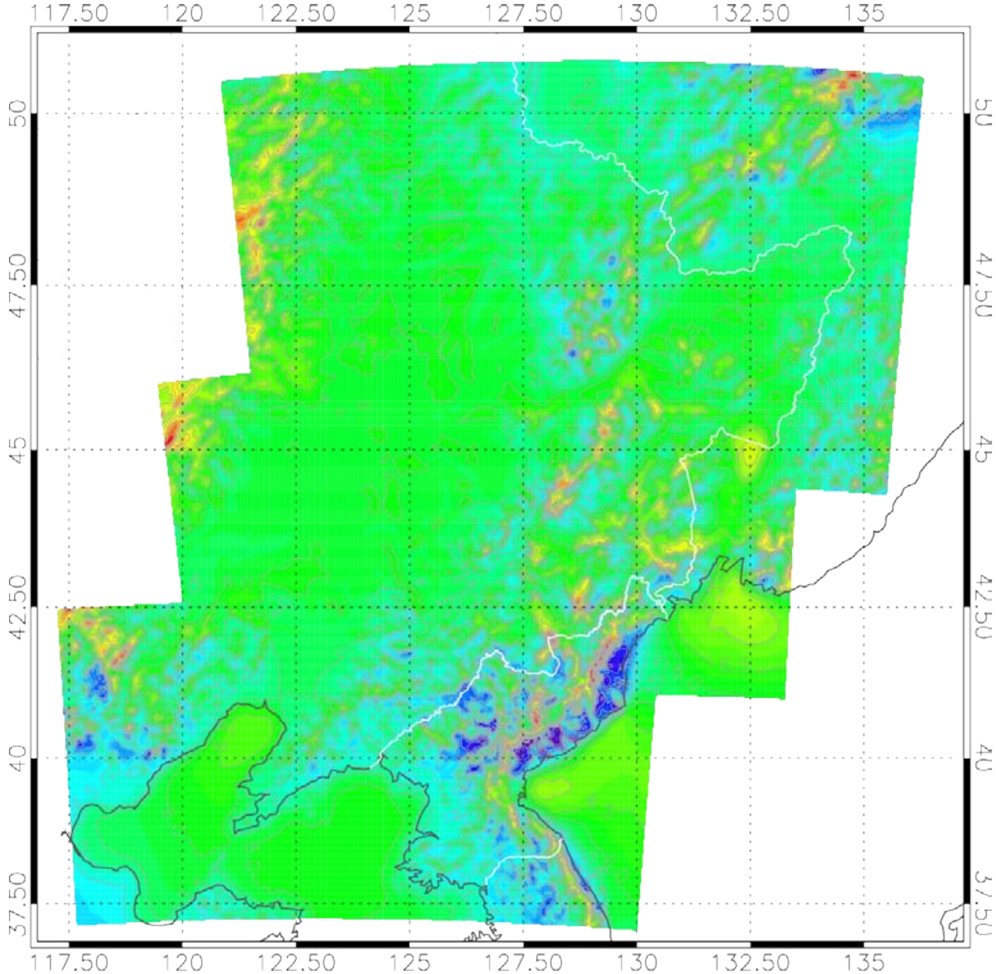






Each x represents a KAMM simulation

Wind resource maps (5 km resolution) wind speed at 100 m



mean simulated wind

- annual mean wind speed for 1978-2007
- wind class weighting from NCEP/NCAR 1978-2007

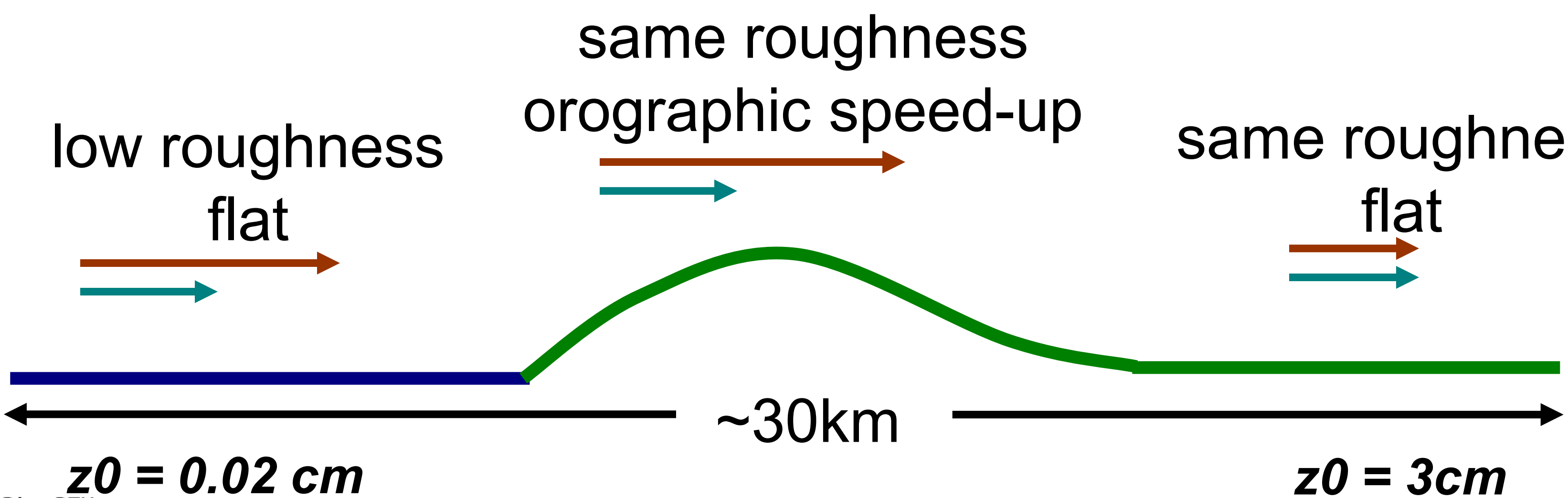
Generalizing wind climates
Post-processing

Example:

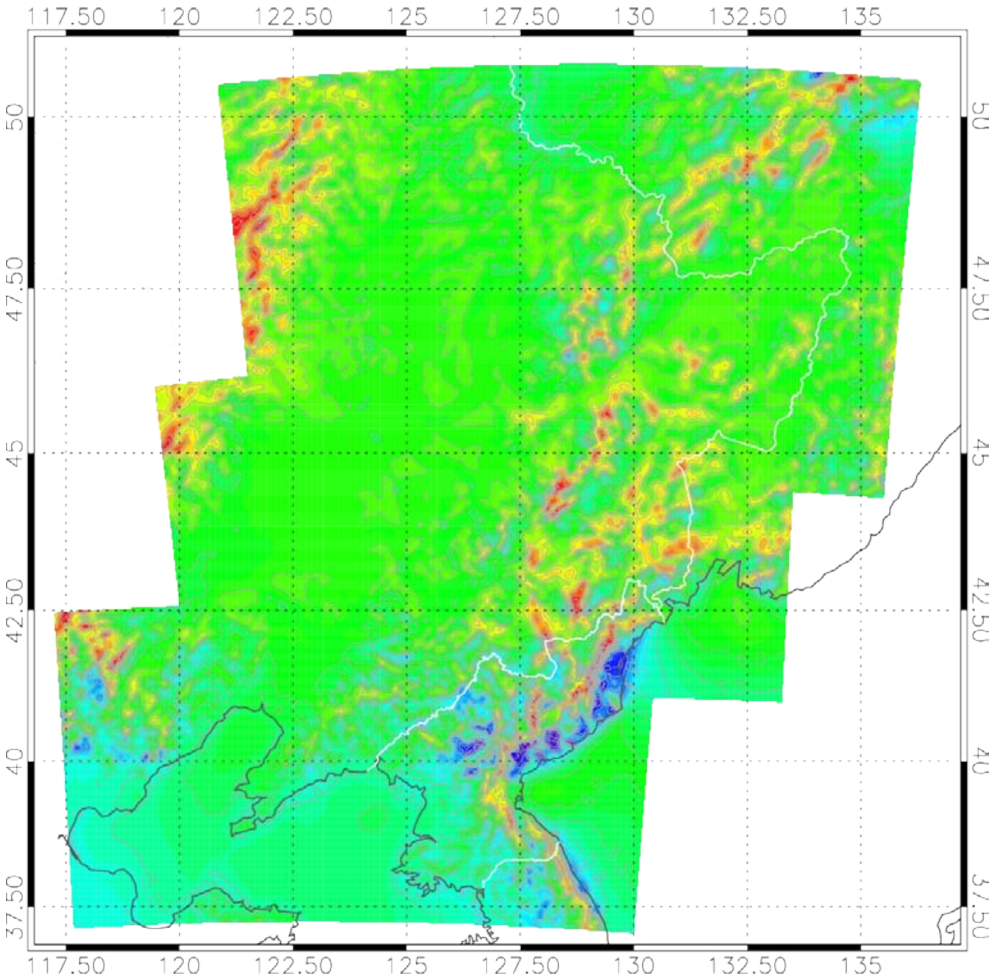
simulated wind

wind corrected to standard conditions

flat terrain *with* ***homogeneous roughness (z_0 = 3cm)***



Generalized wind maps (5 km resolution) wind speed at 100 m

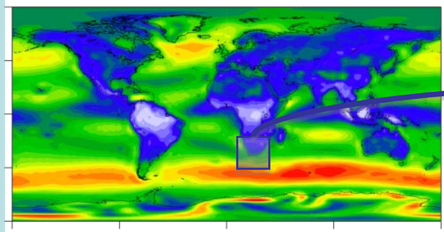


mean generalized wind

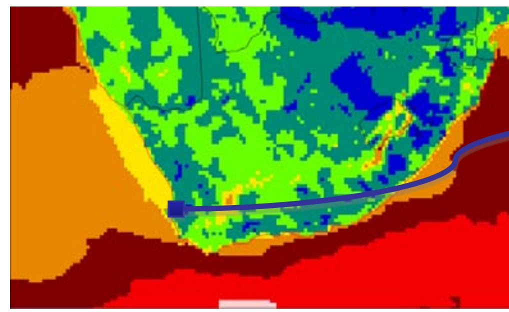
- annual mean wind speed for 1978-2007
- standardized surface conditions
- flat terrain, roughness 3cm everywhere
- wind class weighting from NCEP/NCAR 1978-2007

Numerical Wind Atlas - Downscaling steps

Global



Regional

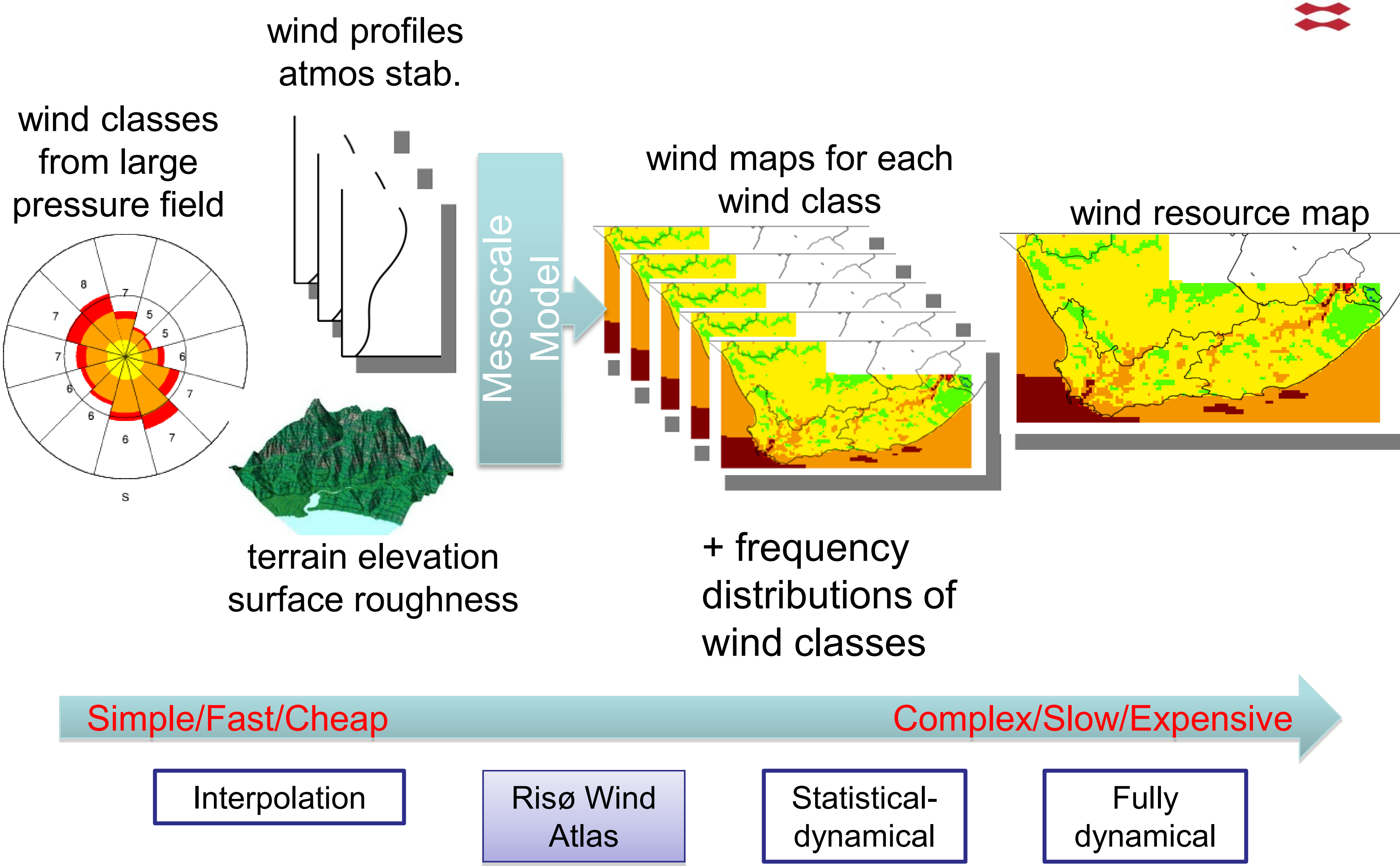


Local

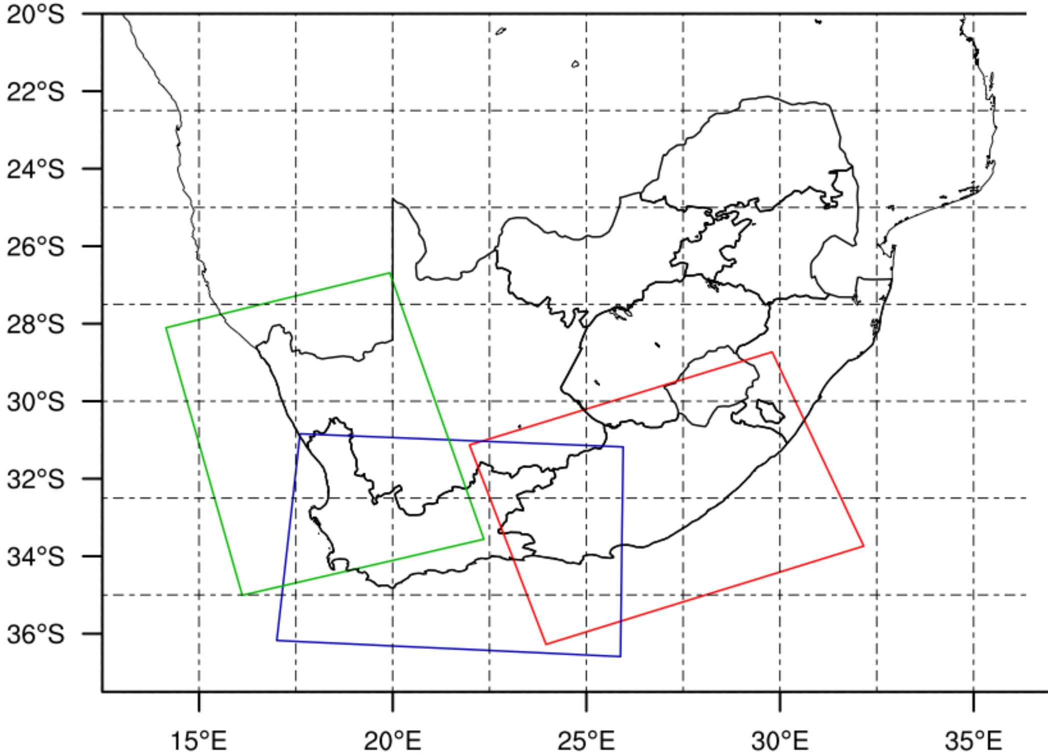
Mesoscale modeling
KAMM/WAsP
MM5, WRF, etc.

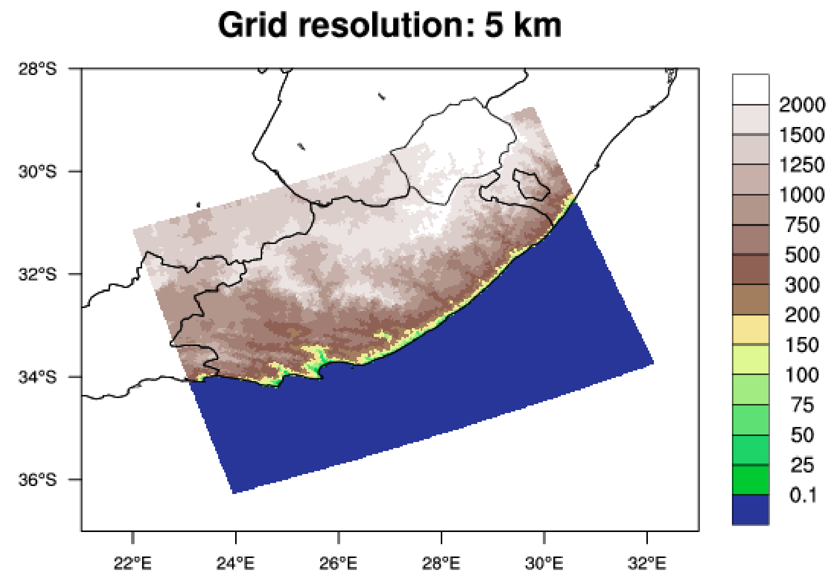
Microscale modeling
(WAsP, other linear/nonlinear models)

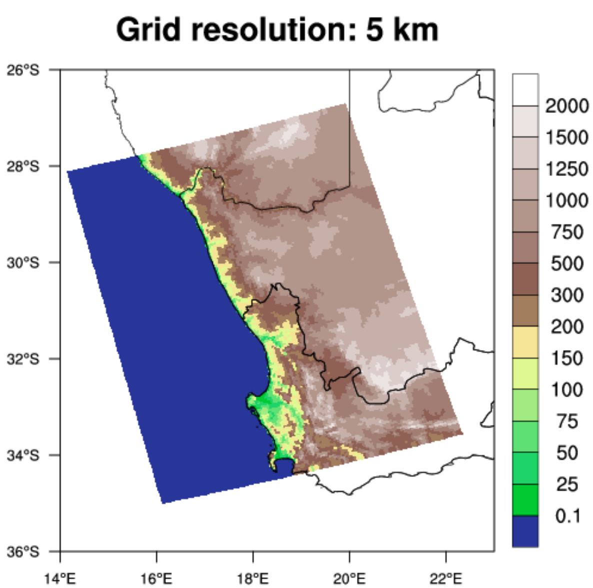
KAMM: Karlsruher non-hydrostatic mesoscale model
WAsP: Wind Atlas Analysis and Application (widely used wind resource tool)

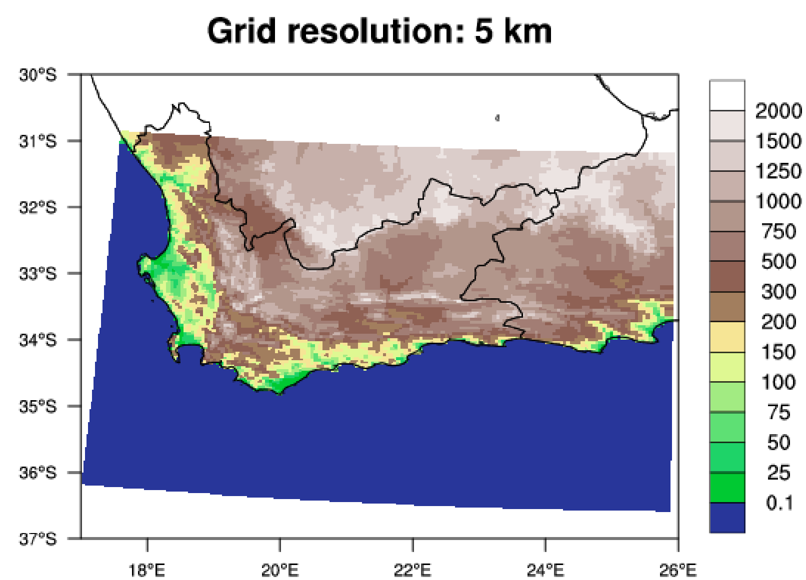

wind profiles
atmos stab.
wind classes
from large
pressure field
Mesoscale
Model
wind maps for each
wind class
wind resource map
terrain elevation
surface roughness
+ frequency
distributions of
wind classes
Simple/Fast/Cheap
Complex/Slow/Expensive
Interpolation
Risø Wind
Atlas
Statistical-
dynamical
Fully
dynamical

Original mesoscale model domains





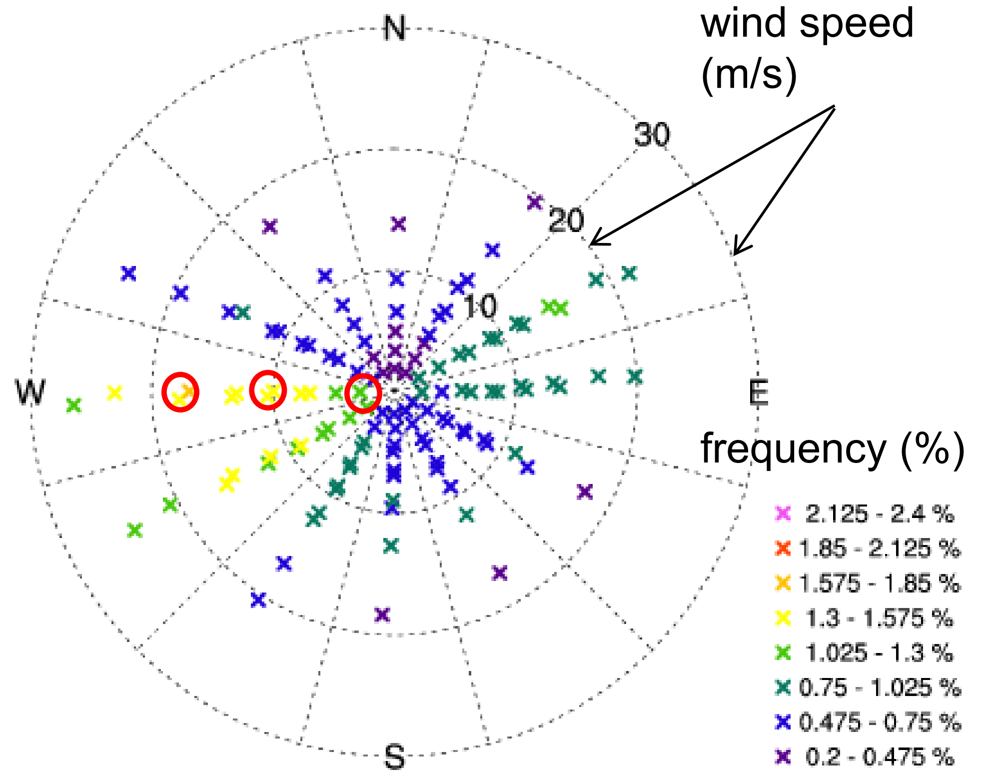




The Wind Atlas Method

- Determine the large-scale wind forcing of a region based on long-term, but spatially coarse, dataset.
- Classify the geostrophic wind (and stability) time-series into wind classes
- Use a mesoscale model (KAMM) to determine how topography modifies the large-scale wind defined by each wind class.

125 wind classes for Southern S. Africa – mean sea level geostrophic wind (NCEP/NCAR reanalysis)

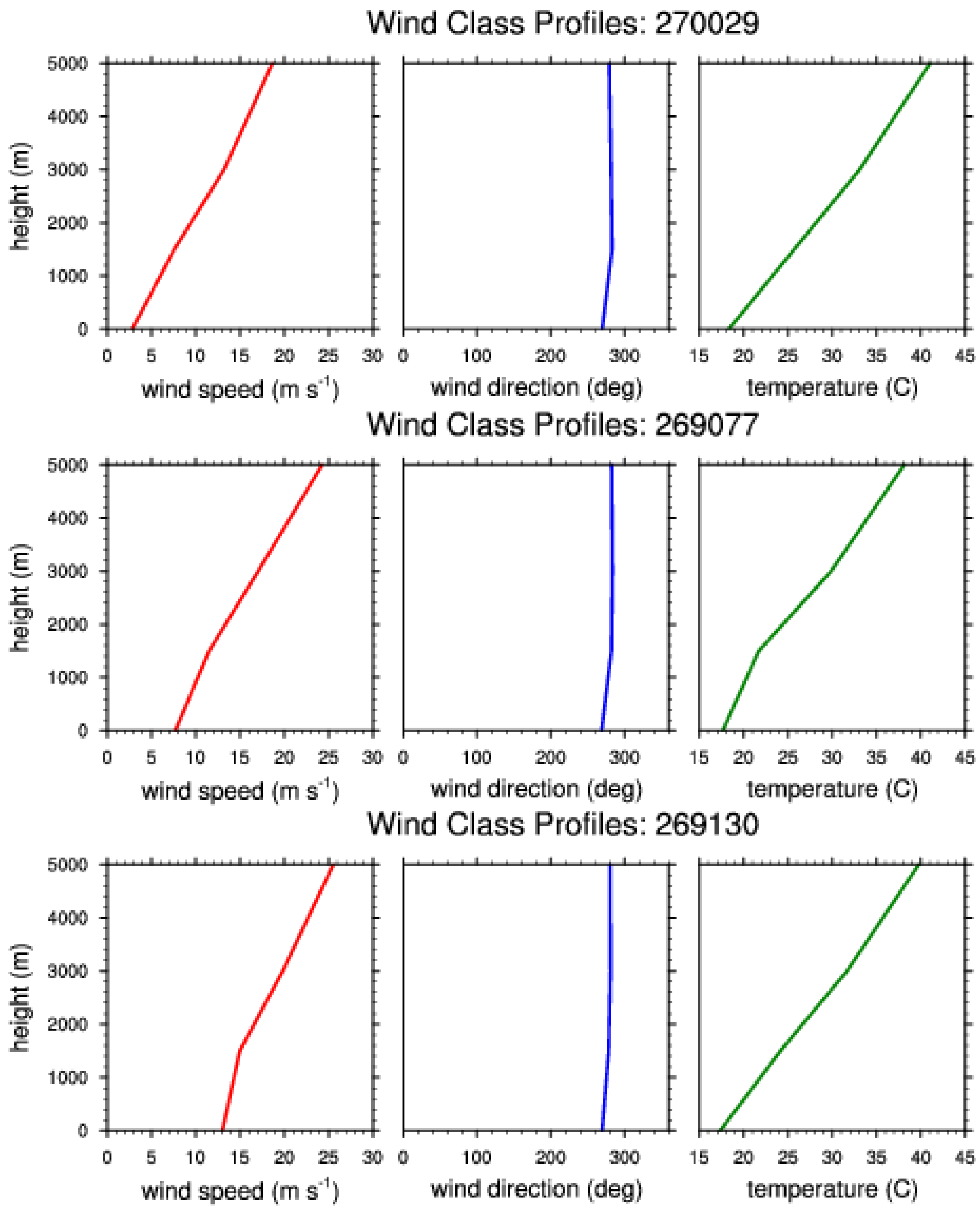


Example wind class profiles

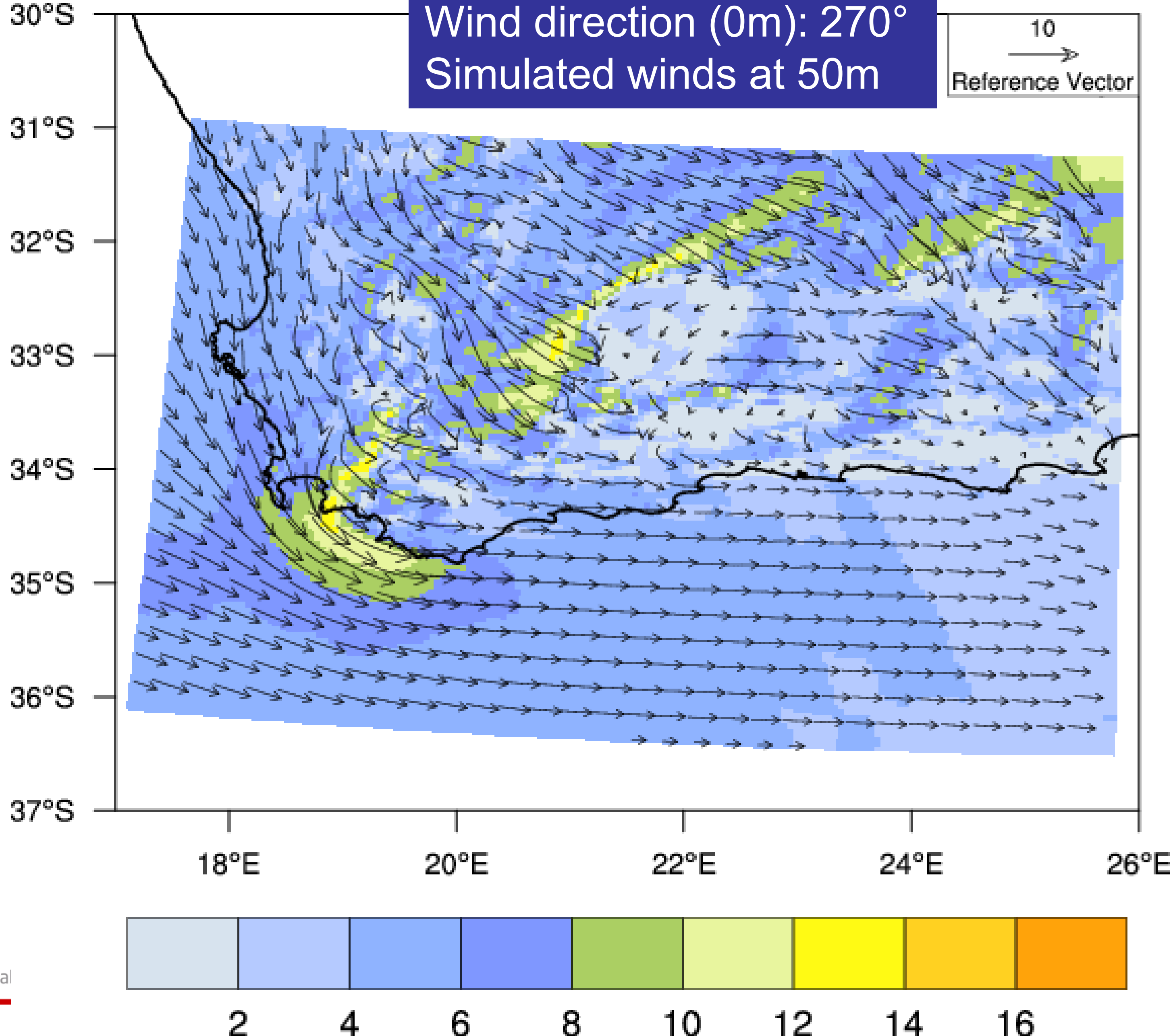
Wind Class: 095
Frequency: 1.17%
Wind speed 2.9 m/s
Wind direction: 270°

Wind Class: 098
Frequency: 1.33%
Wind speed 7.7 m/s
Wind direction: 269°

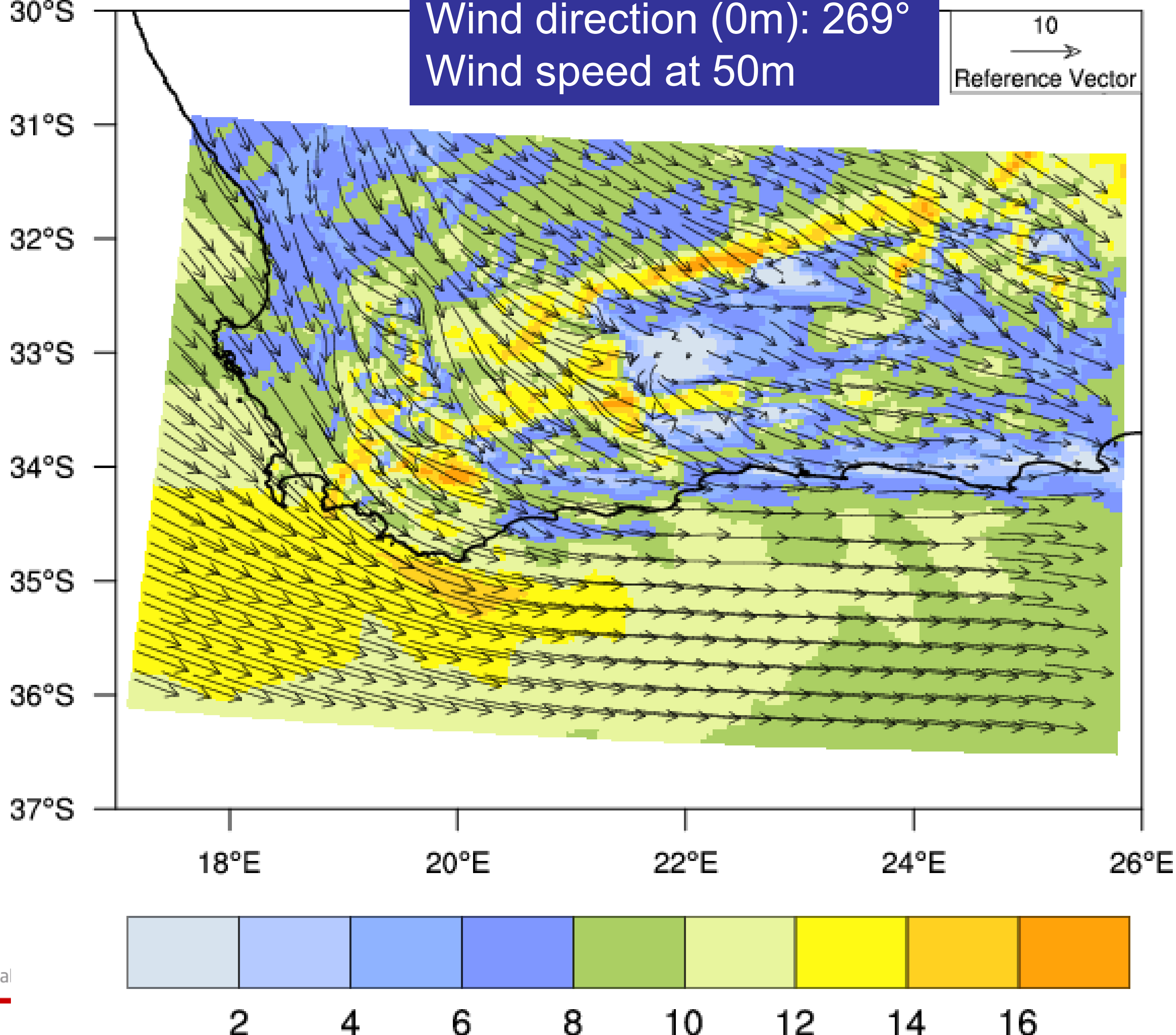
Wind Class: 101
Frequency: 1.51%
Wind speed 13.0 m/s
Wind direction: 269°



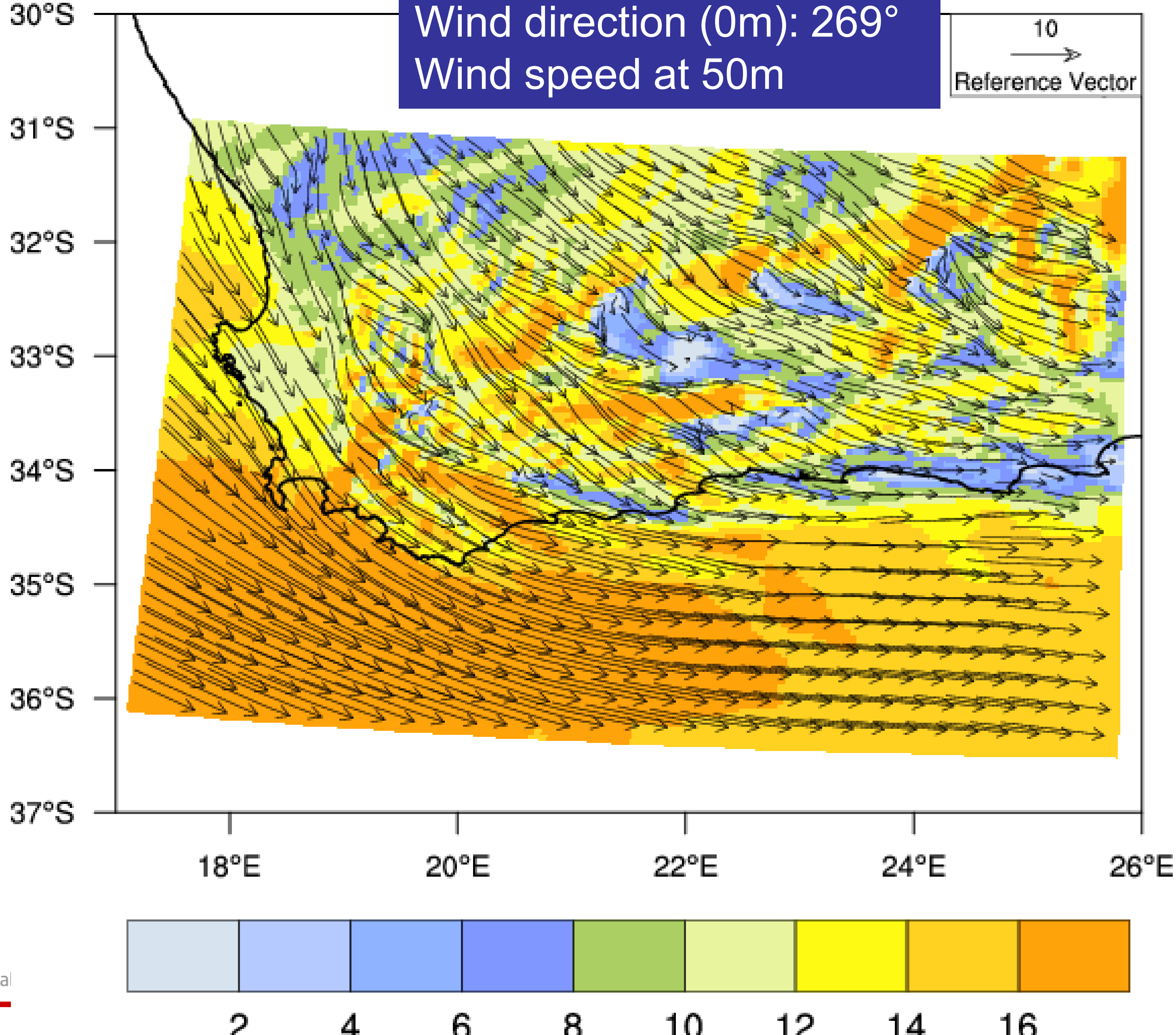
Wind Class Freq: 1.17%
Wind speed (0m): 2.9 m/s
Wind direction (0m): 270°
Simulated winds at 50m



Wind Class Freq: 1.33%
Wind speed (0m): 7.7 m/s
Wind direction (0m): 269°
Wind speed at 50m



Wind Class Freq: 1.51%
Wind speed (0m):13.0 m/s
Wind direction (0m): 269°
Wind speed at 50m



10
Reference Vector
30°S
31°S
32°S
33°S
34°S
35°S
36°S
37°S
18°E
20°E
22°E
24°E
26°E
2
4
6
8
10
12
14
16

Simulated wind climate

$$\overline{u}(x,y,z) = \frac{\sum f_i(x,y)\; u_i(x,y,z)}{\sum f_i(x,y)}$$

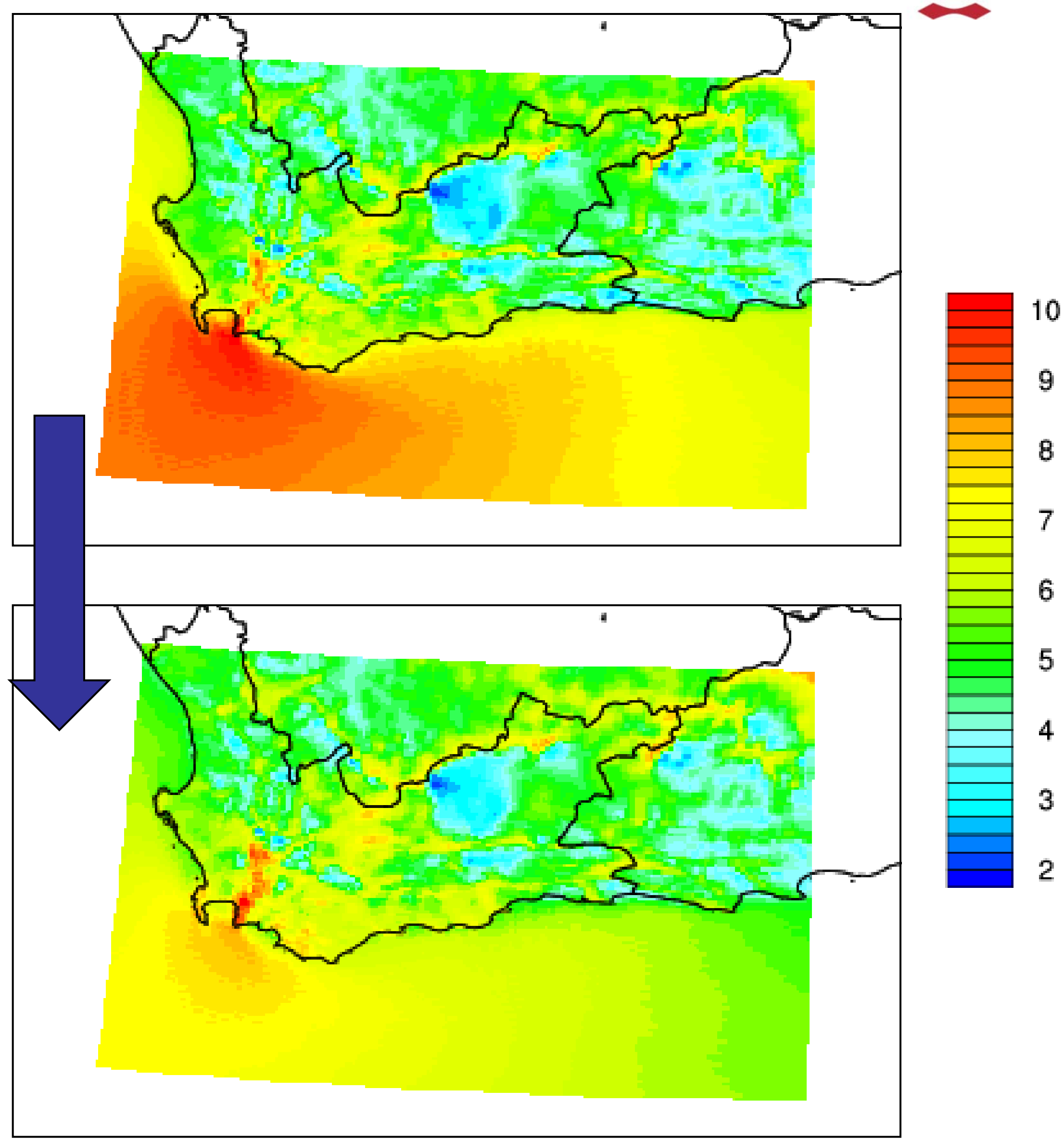
$u_i(x,y,z)$ = wind speed at *z* m a.g.l. for wind class *i*.

$f_i(x,y)$ = frequency of wind class *i*, a function of *x* and *y*.

$\overline{u}(x,y,z)$ = mean wind speed at *z* m a.g.l.

Simulated wind climate
mean wind speed [m/s] at 50m

Generalized wind climate
mean corrected wind speed [m/s] at 50m flat terrain z0=3cm

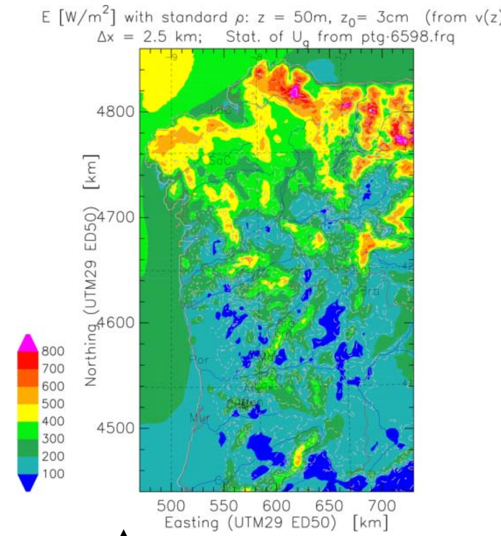


Validation against observations

Errors at 50m computed from all available observations

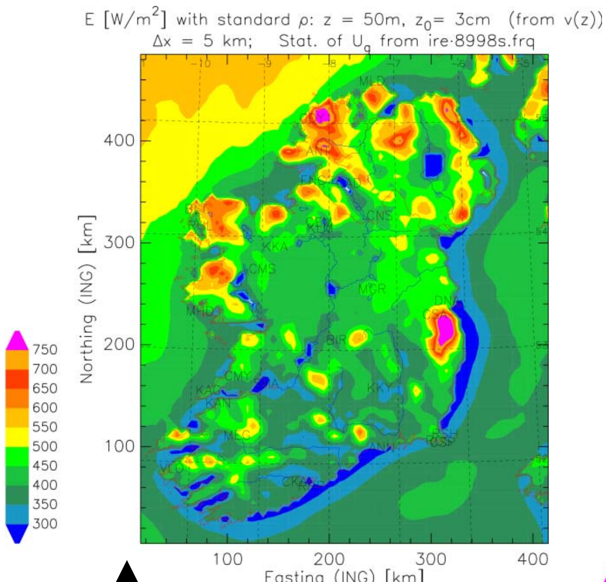
U = wind; P = power density

Portugal

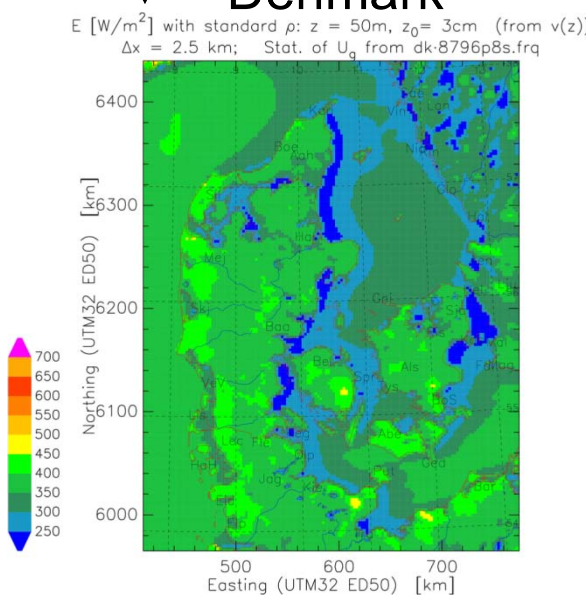


U rms 5%
P rms 16%
dx = 5km

Ireland



Denmark

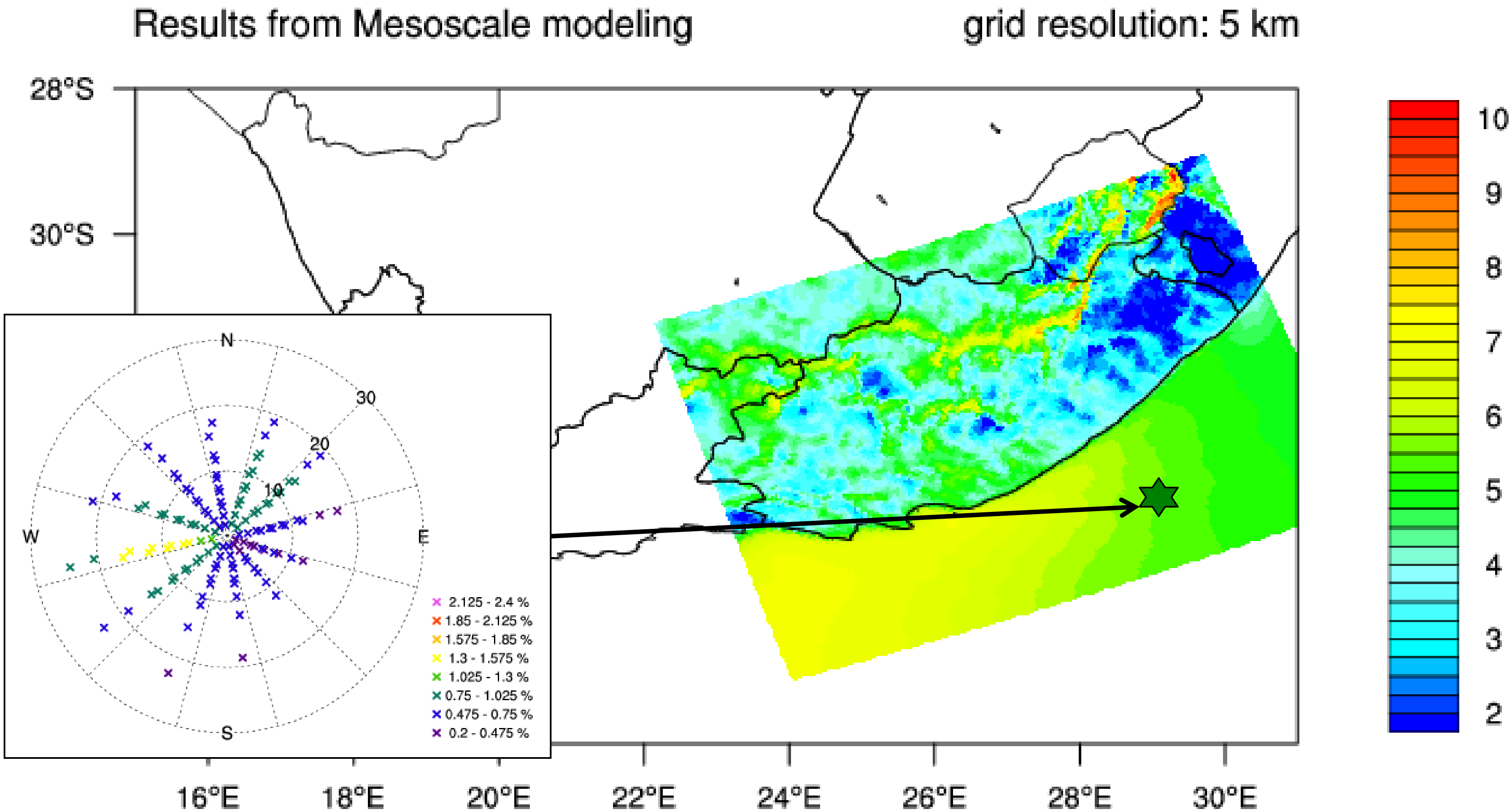


U rms 10%
P rms 34%
dx = 2.5km

U rms 7%
P rms 17%
dx = 5km

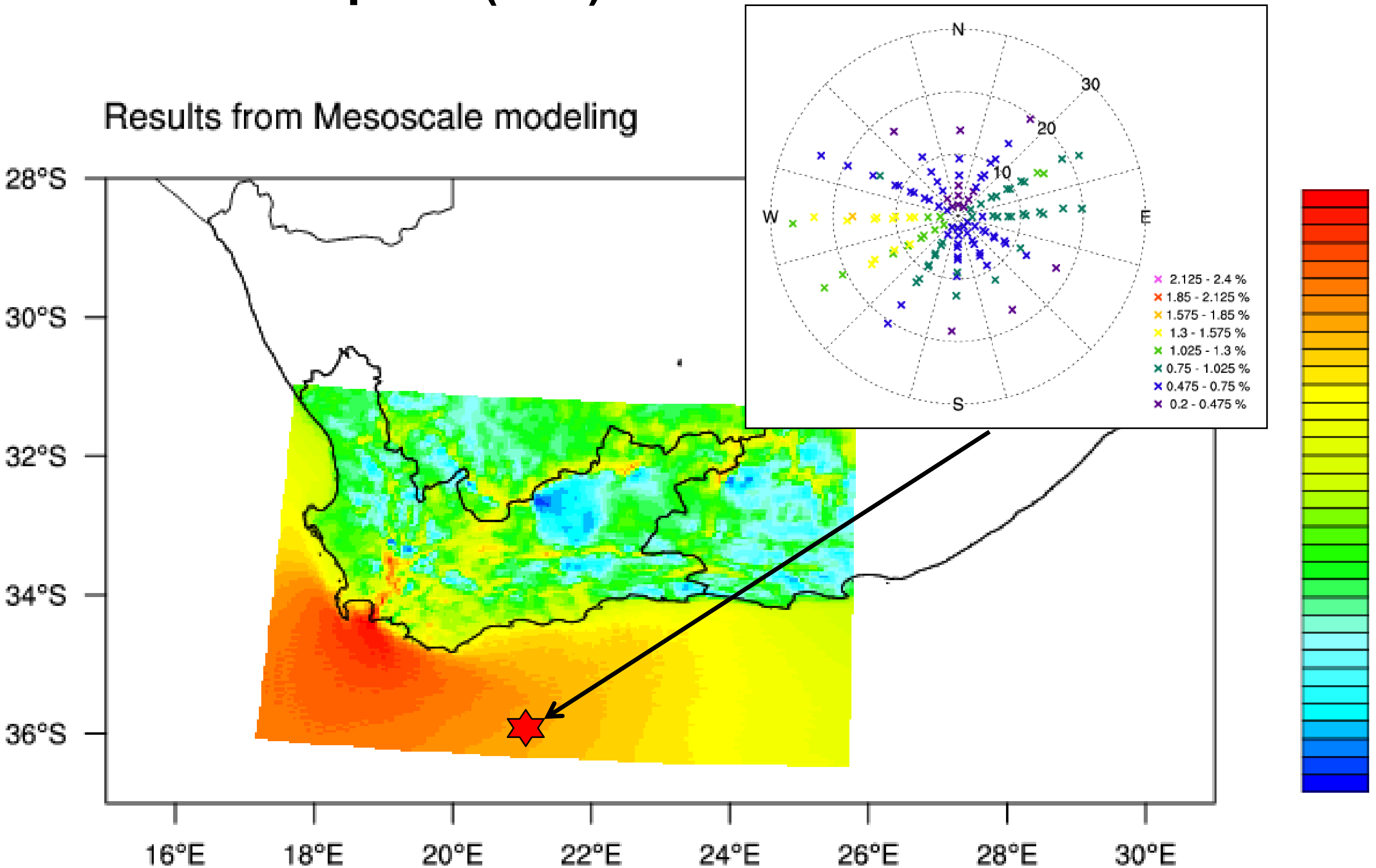
Frank, H. P., O. Rathmann, N. G. Mortensen, L. Landberg: The Numerical Wind Atlas – The KAMM/WAsP Method. (2001)

Preliminary calculations for South Africa
Mean wind speed (m/s) at 50 m



unverified output, do not use these numbers

Preliminary calculations for South Africa
Mean wind speed (m/s) at 50 m



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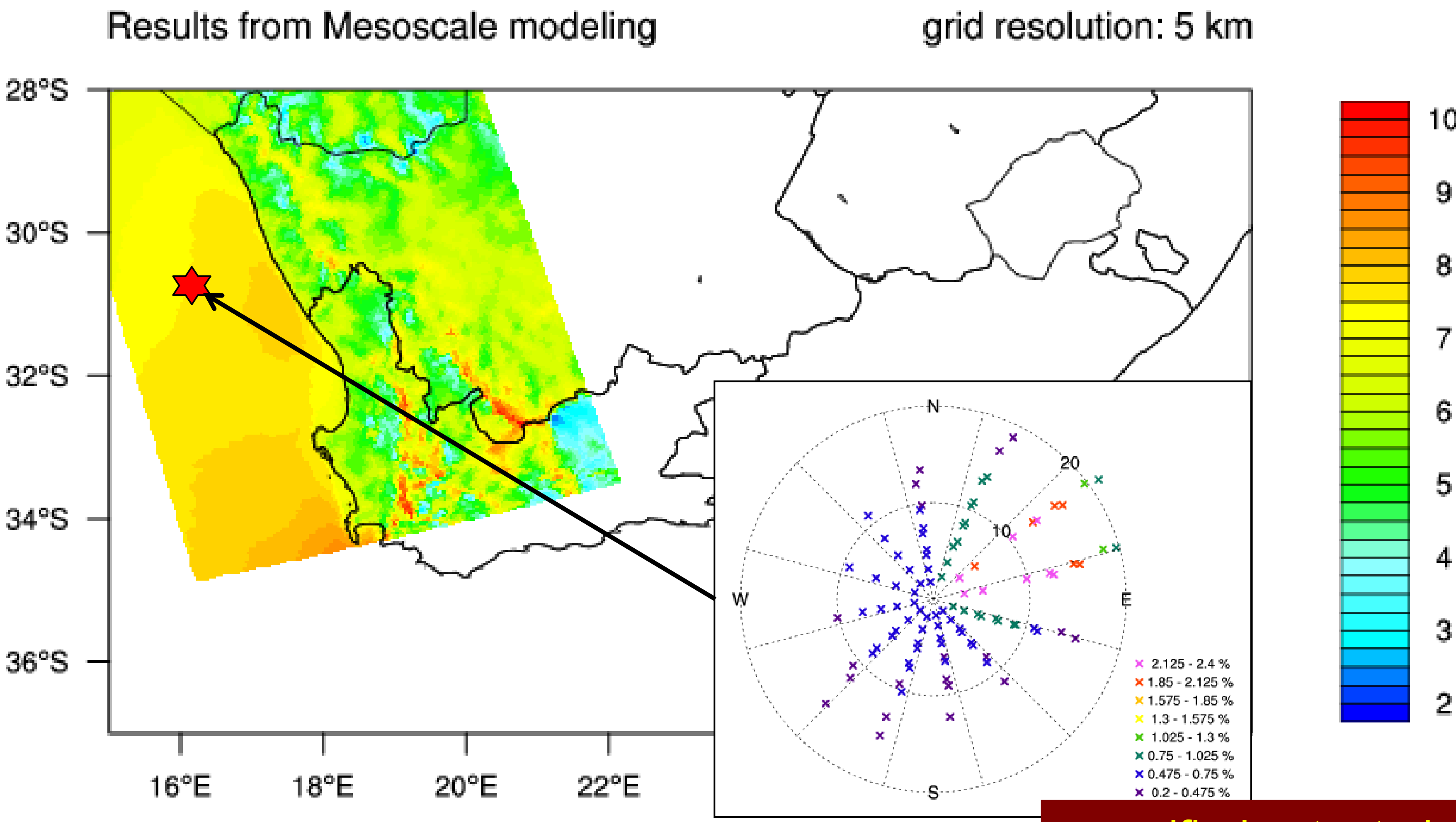
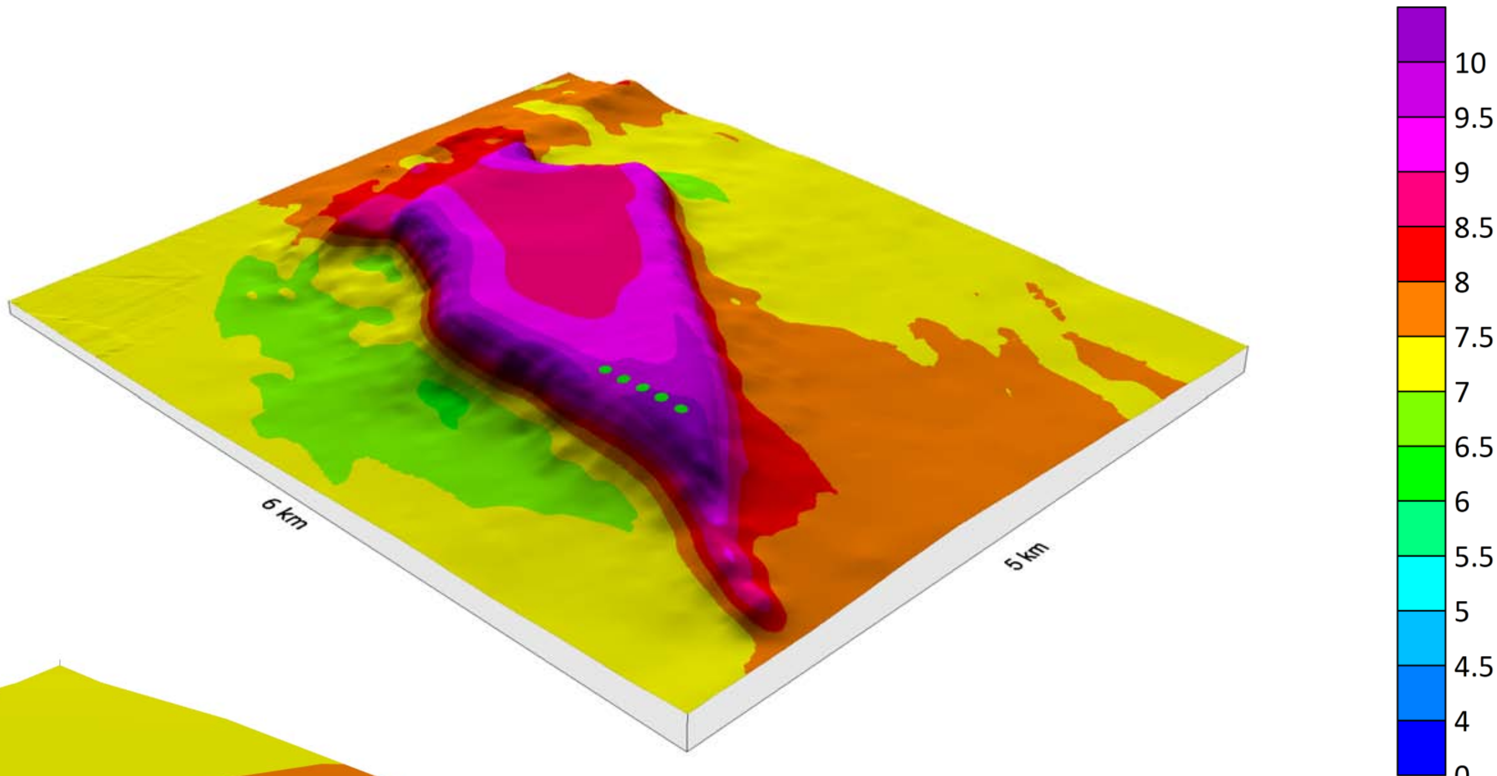
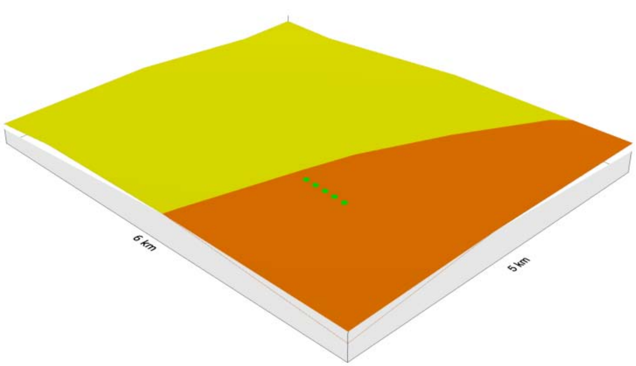
Preliminary calculations for South Africa
Mean wind speed (m/s) at 50 m



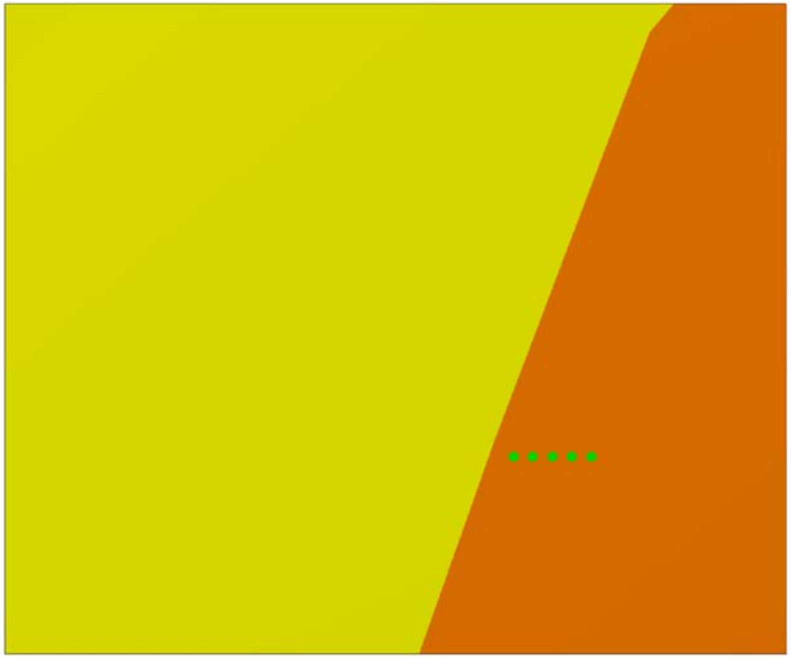
unverified output, do not use these numbers

Resolution is key in applications

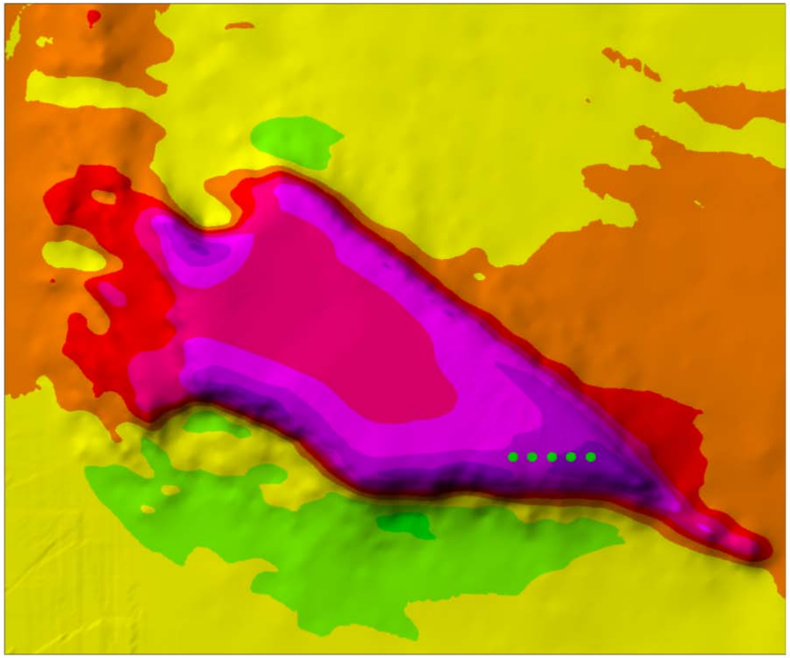




Mesoscale vs. Microscale – effect of model resolution



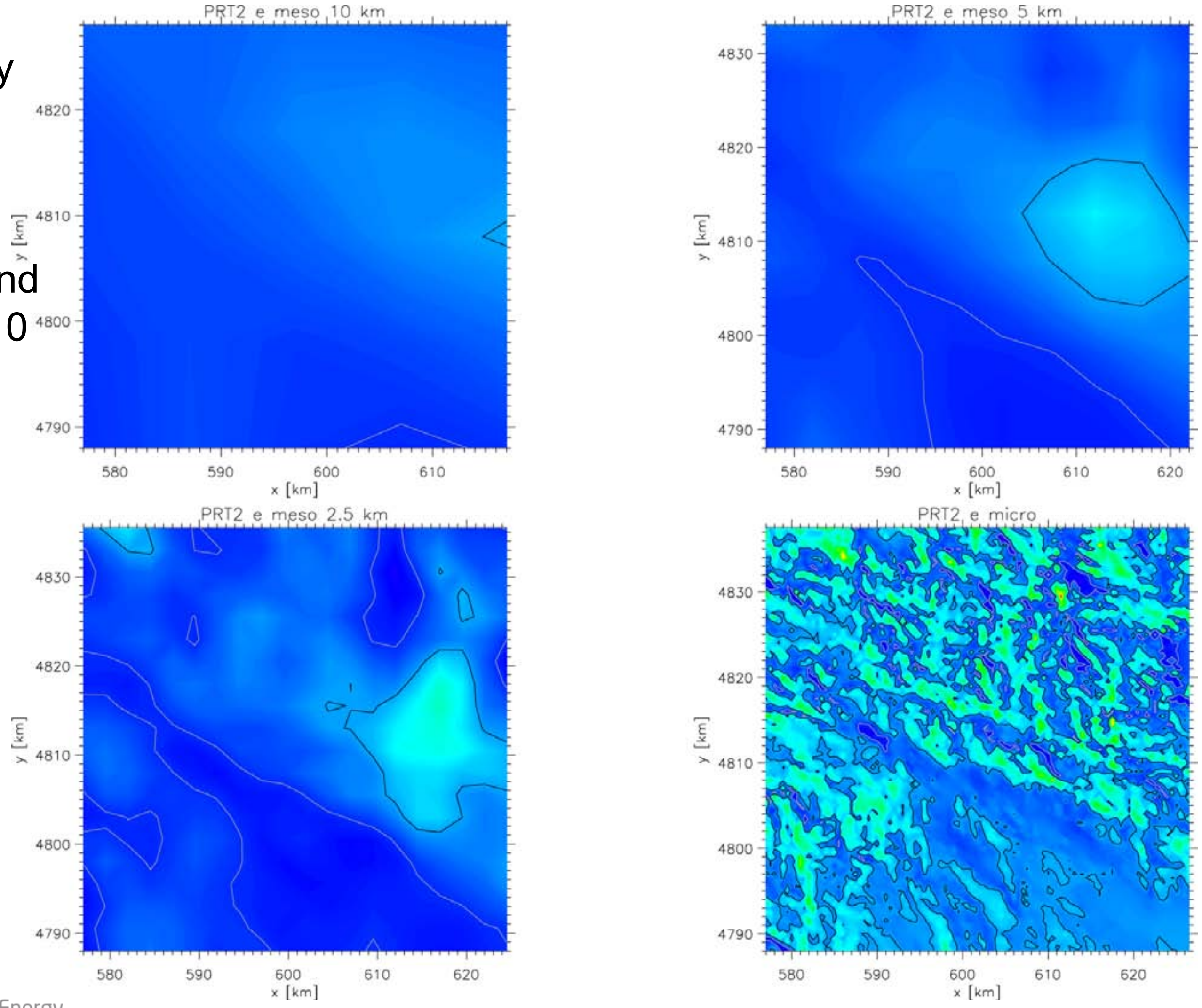
- KAMM wind resource map only
- Grid cell size 5120 m
- Wind farm of five 2 MW turbines
- Estimated AEP = 39 GWh



- KAMM/WAsP wind resource map
- Grid cell size 20 m
- Wind farm of five 2 MW turbines
- Estimated AEP = 55 GWh

Comparing area wind power density

- wind power density [W/m**2] at 50 m a.g.l.
- contours at 0.95 and 0.05 full range of 10 km results

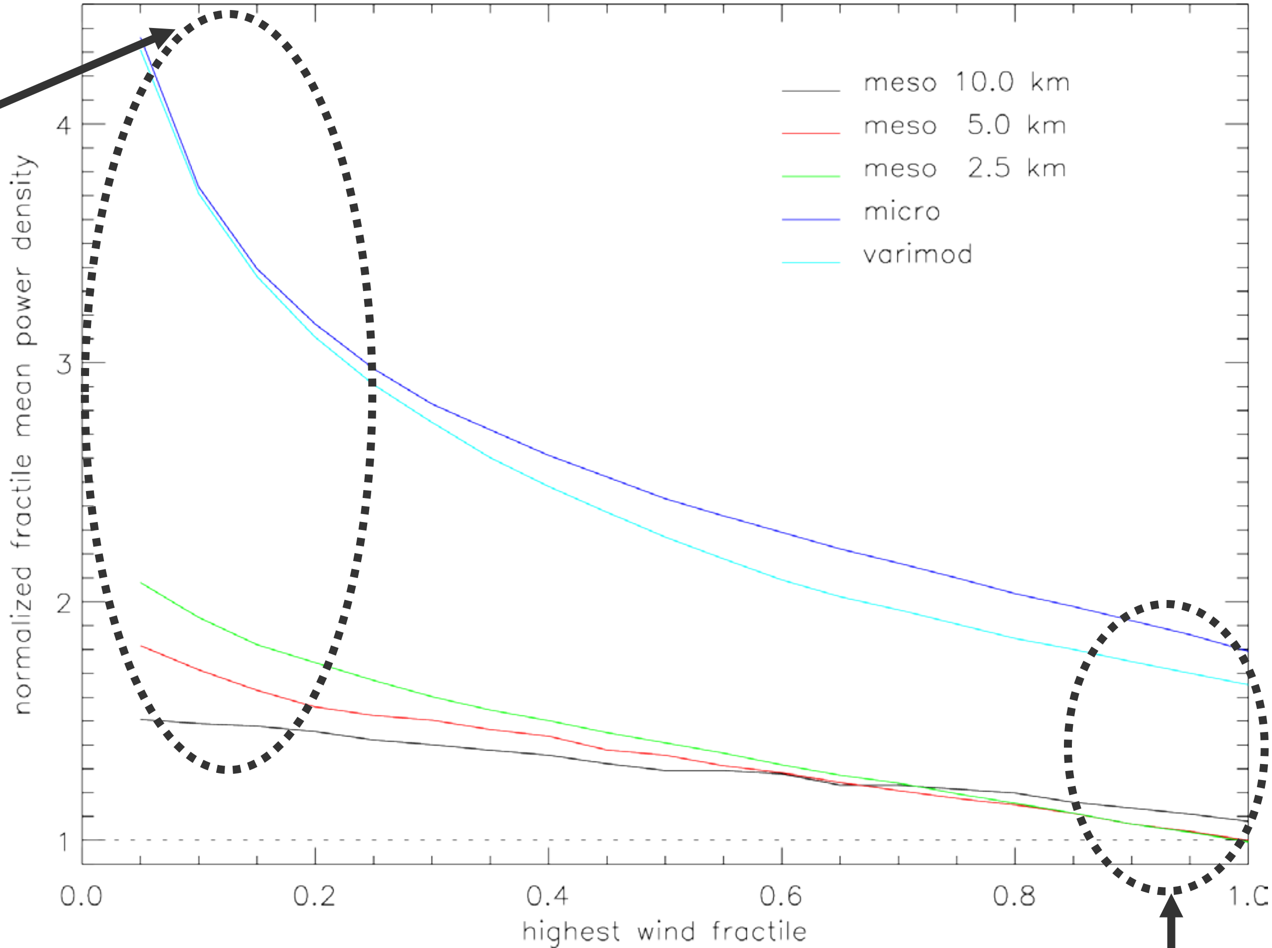


Power density fractile plot

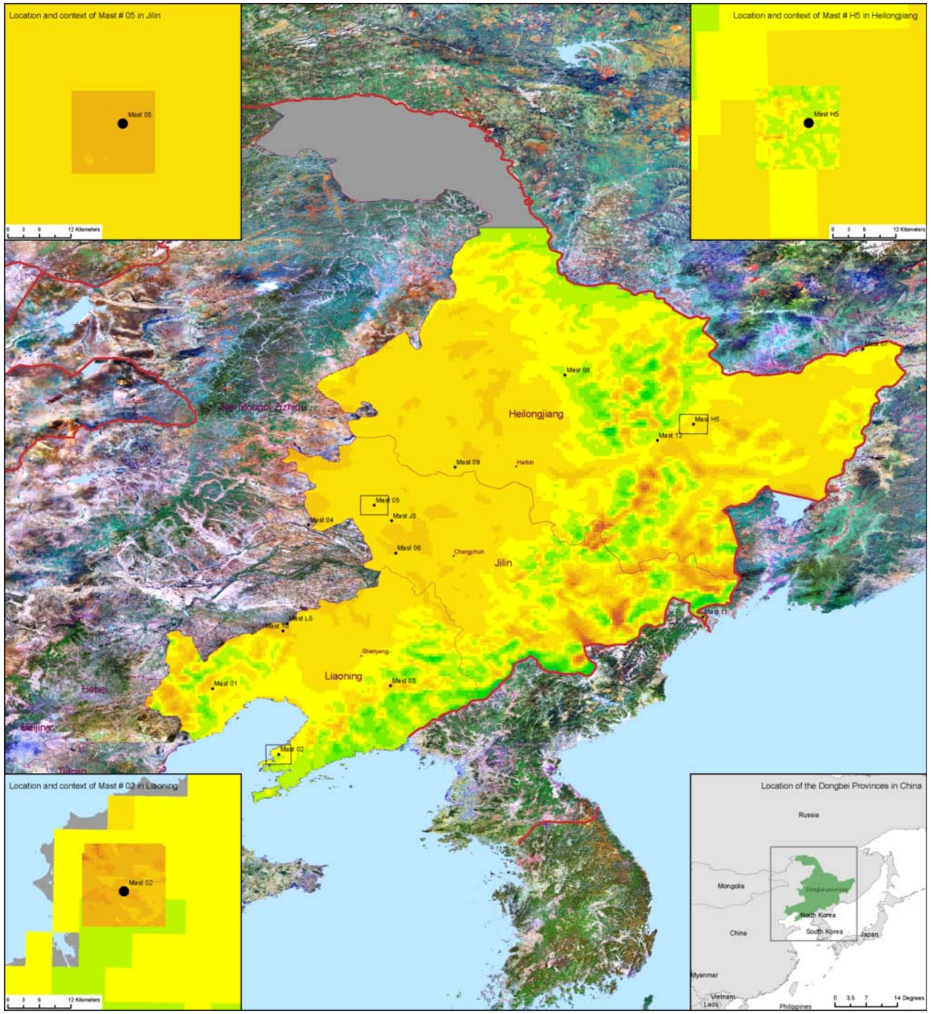
Wind power density at 50 m a.g.l.

Very large (~100%) enhancement for the microscale modelling for windy fractile

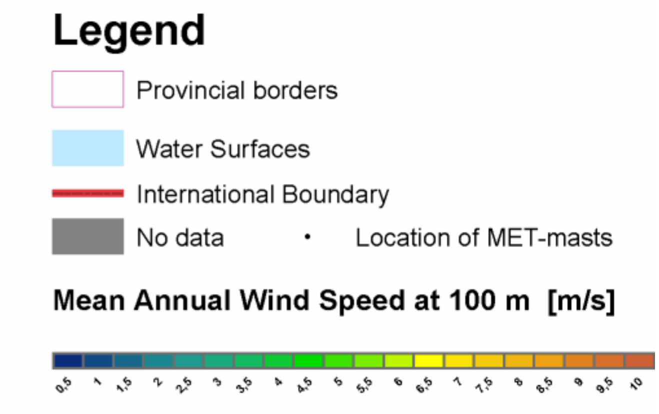
Big differences in whole area mean, related to the variance of the wind speed within the test area

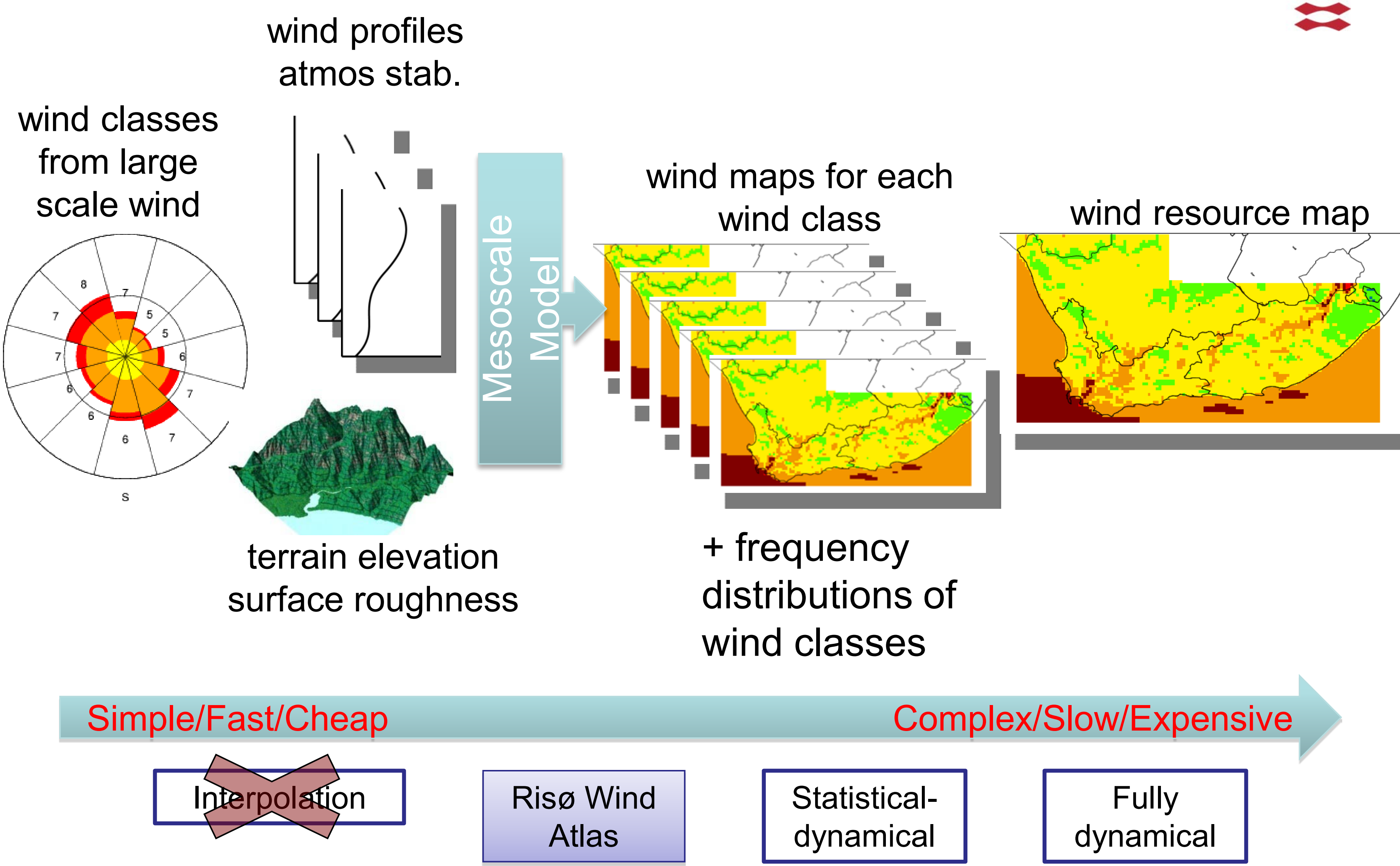


Wind Atlas for NE China (Dongbei)



- Some text about the atlas



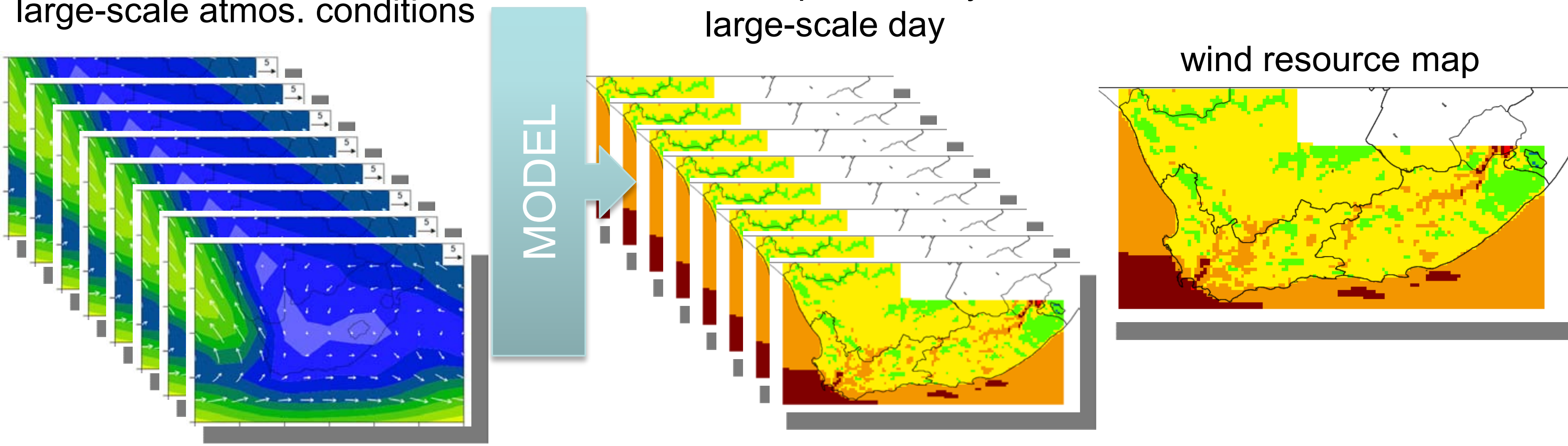

wind profiles
atmos stab.
wind classes
from large
scale wind
Mesoscale
Model
wind maps for each
wind class
wind resource map
terrain elevation
surface roughness
+ frequency
distributions of
wind classes
Simple/Fast/Cheap
Complex/Slow/Expensive
Interpolation
Risø Wind
Atlas
Statistical-
dynamical
Fully
dynamical

Dynamical downscaling

entire collection of
large-scale atmos. conditions

wind maps for every
large-scale day

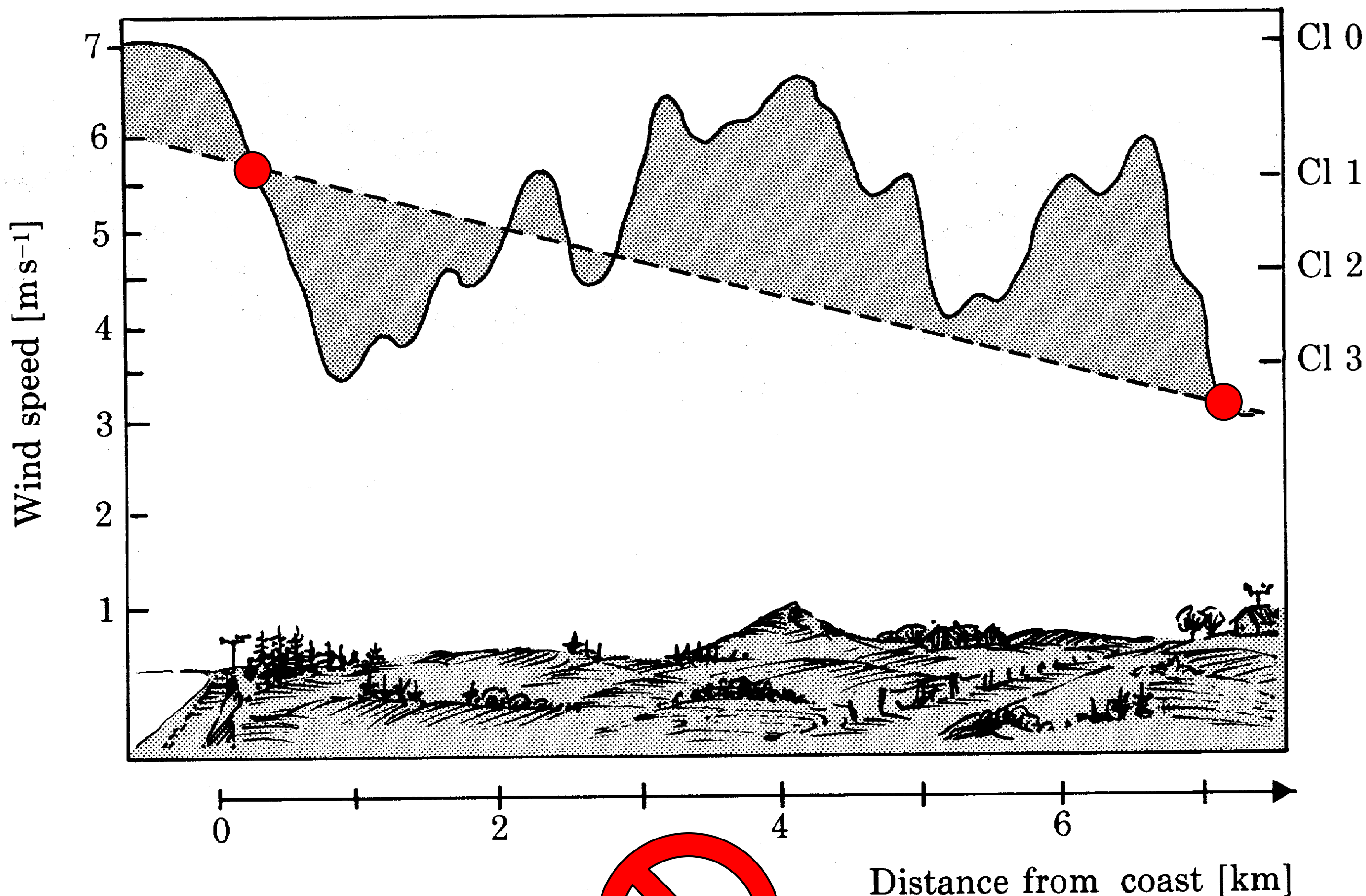
wind resource map

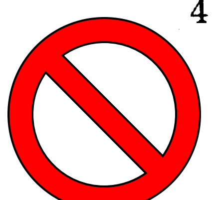


Simple/Fast/Cheap → Complex/Slow/Expensive

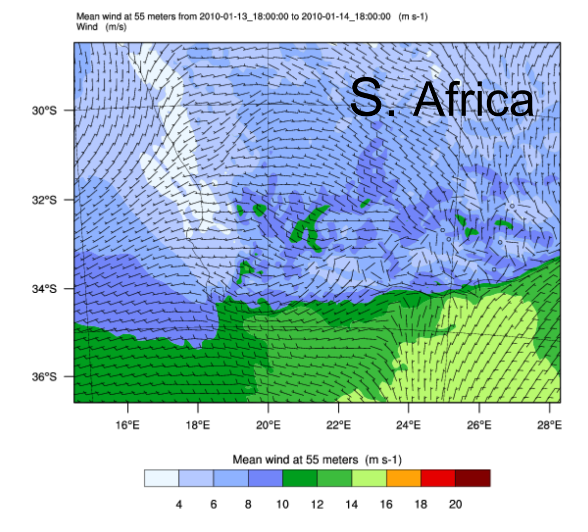
~~Interpolation~~ | Risø Wind Atlas | Statistical-dynamical | Fully dynamical

Linear interpolation

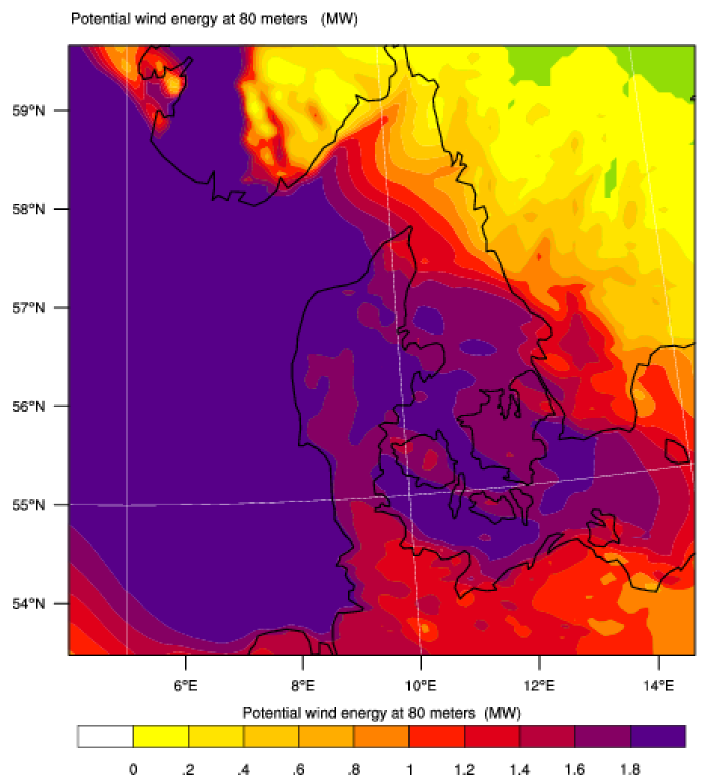


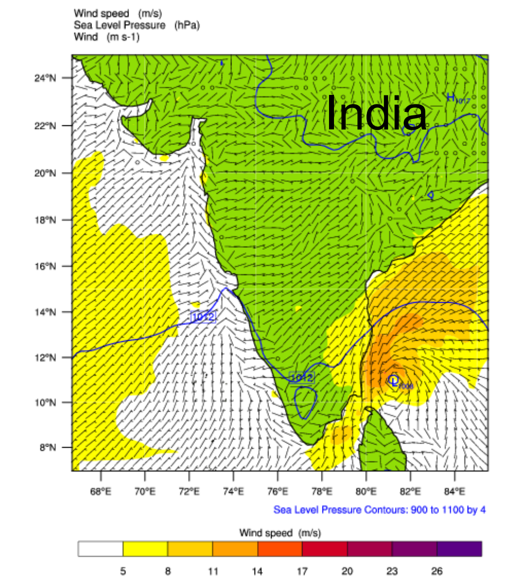


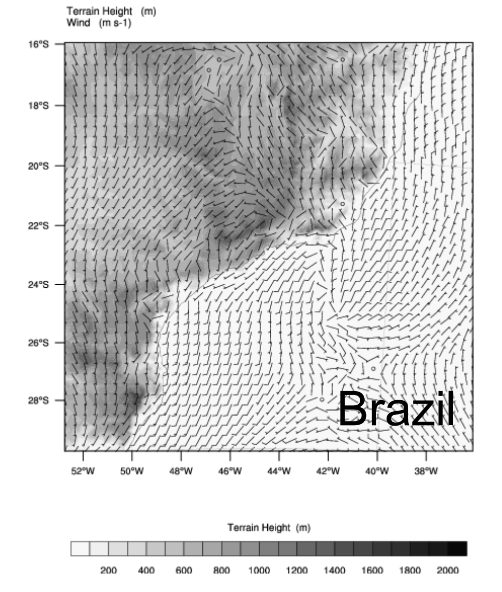
Developed a real-time wind (weather) forecast system for Denmark. System operational since March 2009 running twice daily



Forecast potential wind energy at 80 meters

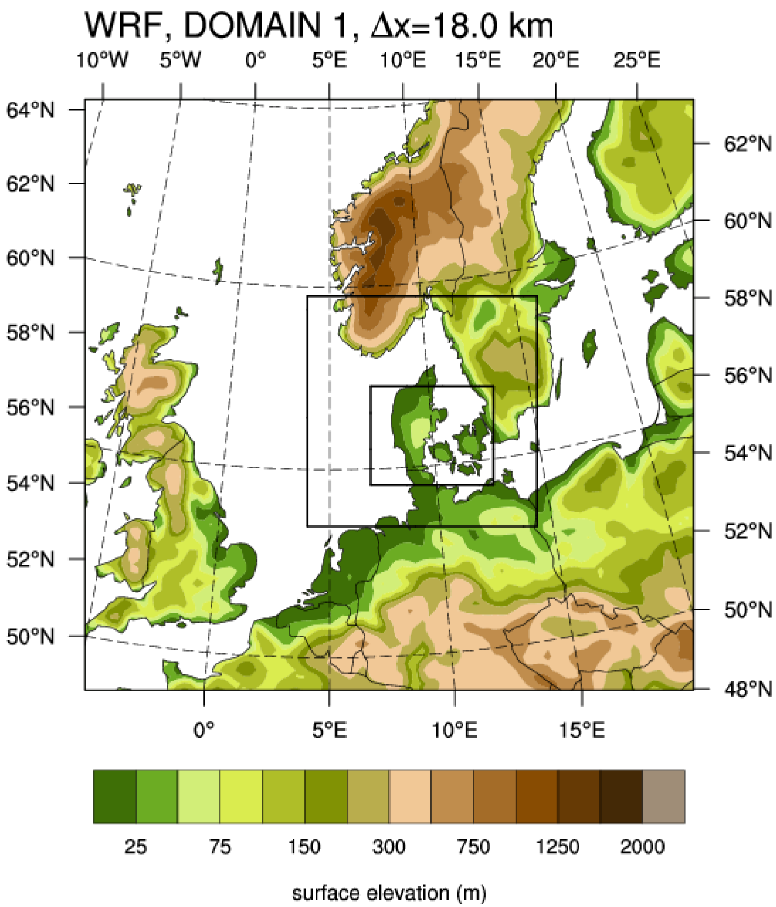




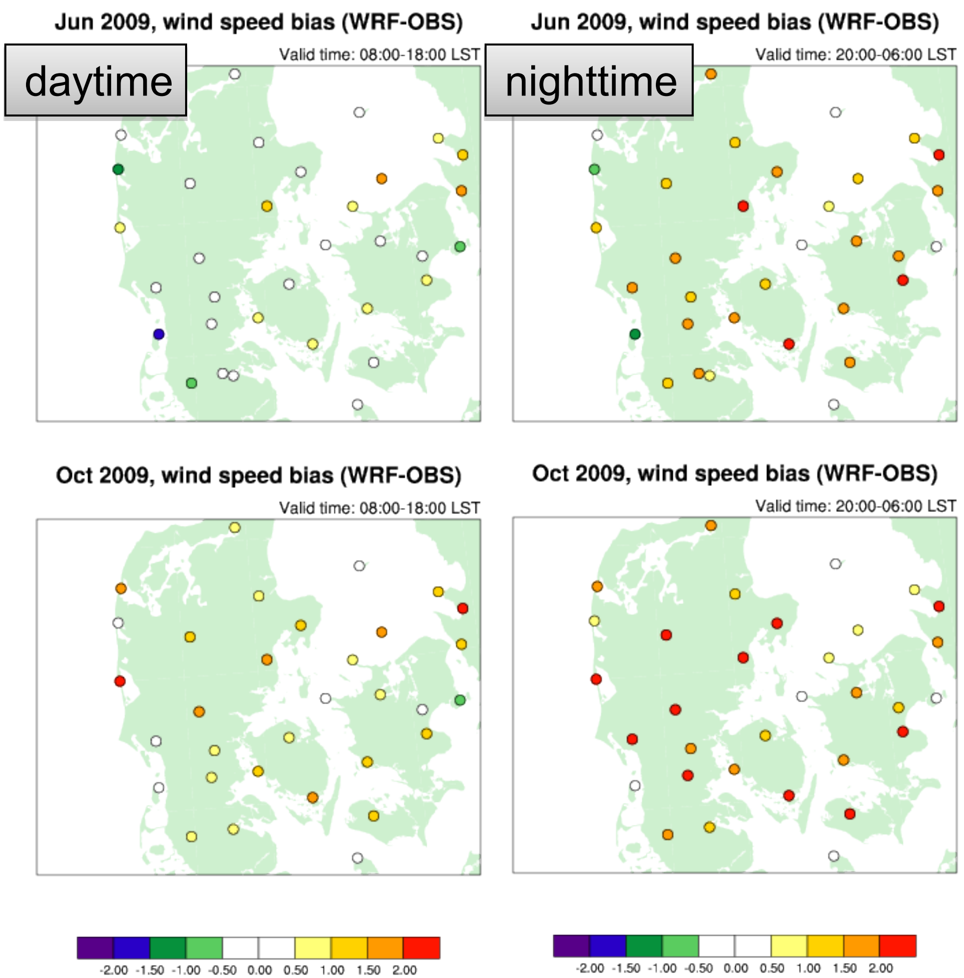


Similar systems for South Africa, Brazil, and India

Verification of WRF real-time wind forecast system over Denmark

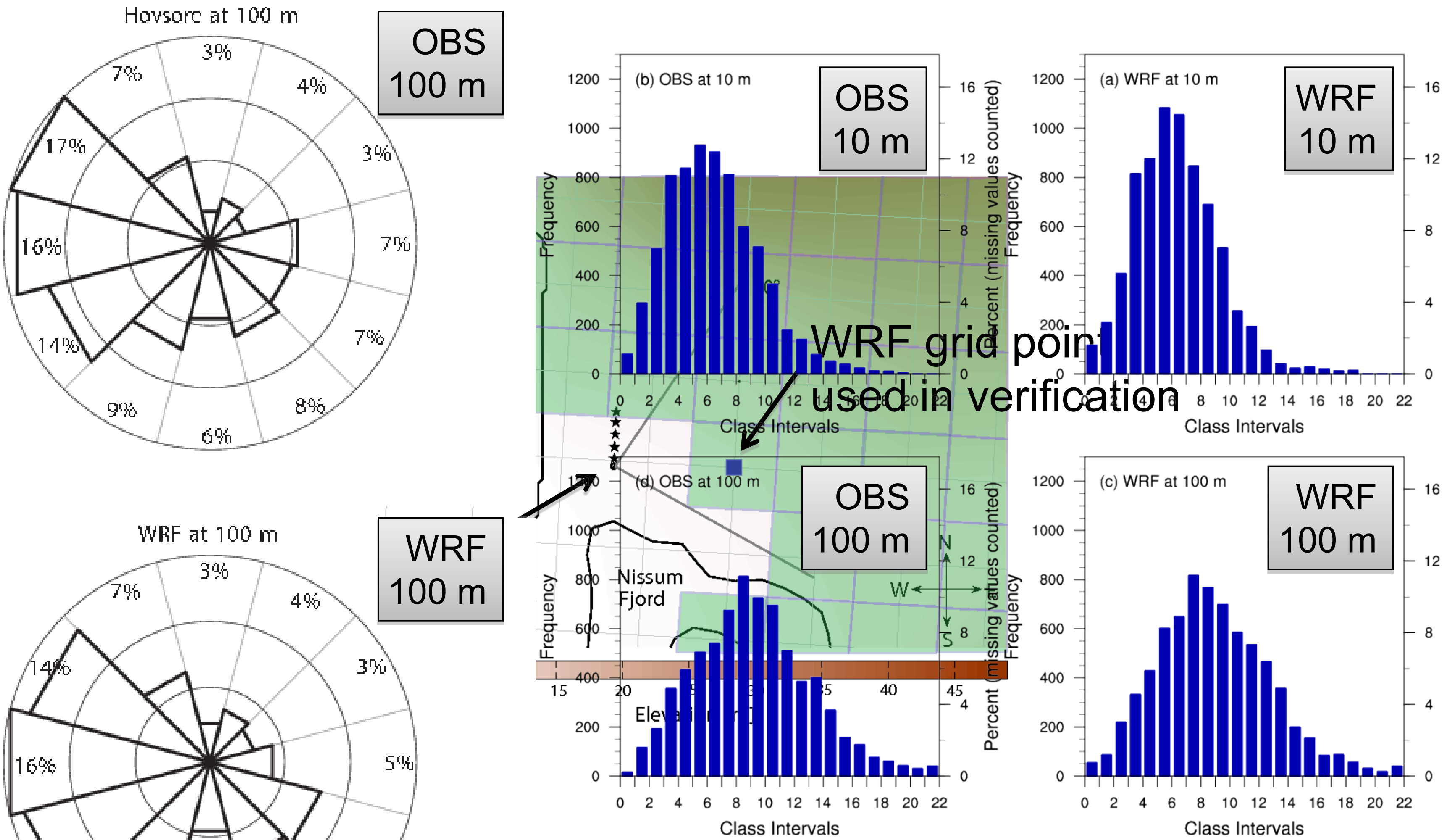


WRF topography and configuration
Δx = 18, 6 and 2km



10-meter wind speed mean error (WRF-OBS) for the months of June and October 2009

Verification at Høvsøre test site, 116 m mast

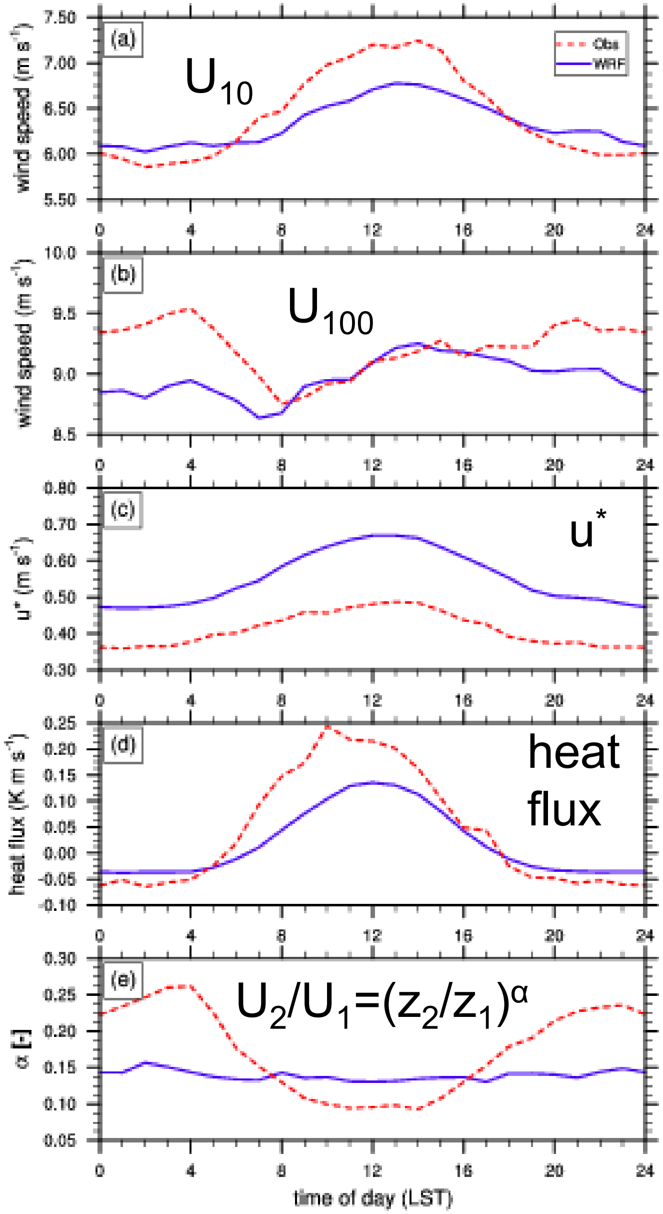


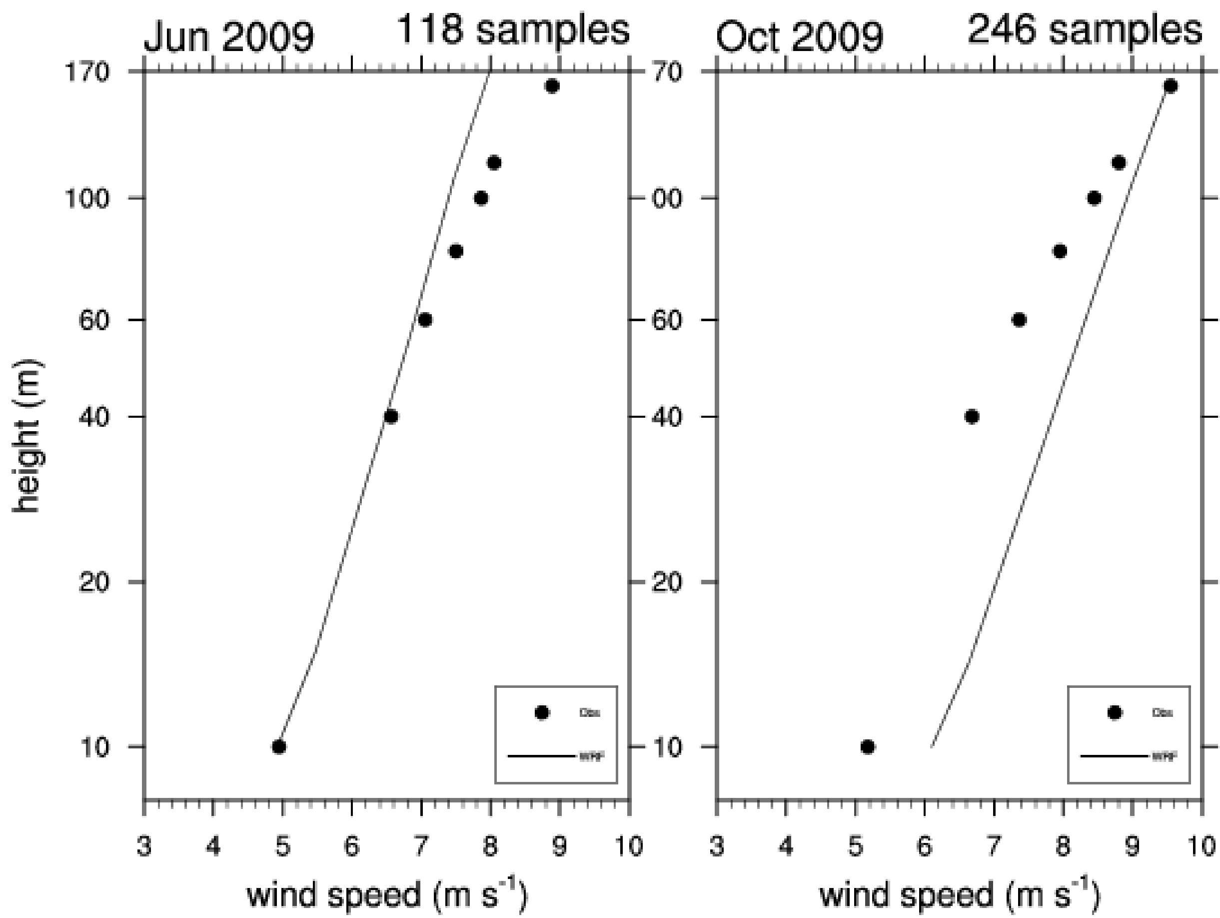
Wind speed distributions at 10 and 100 meters

Computed from all 4-27 hour forecasts (1200 UTC run)
May – October 2009

Verification at Høvsøre test site

Averaged diurnal cycle of various quantities



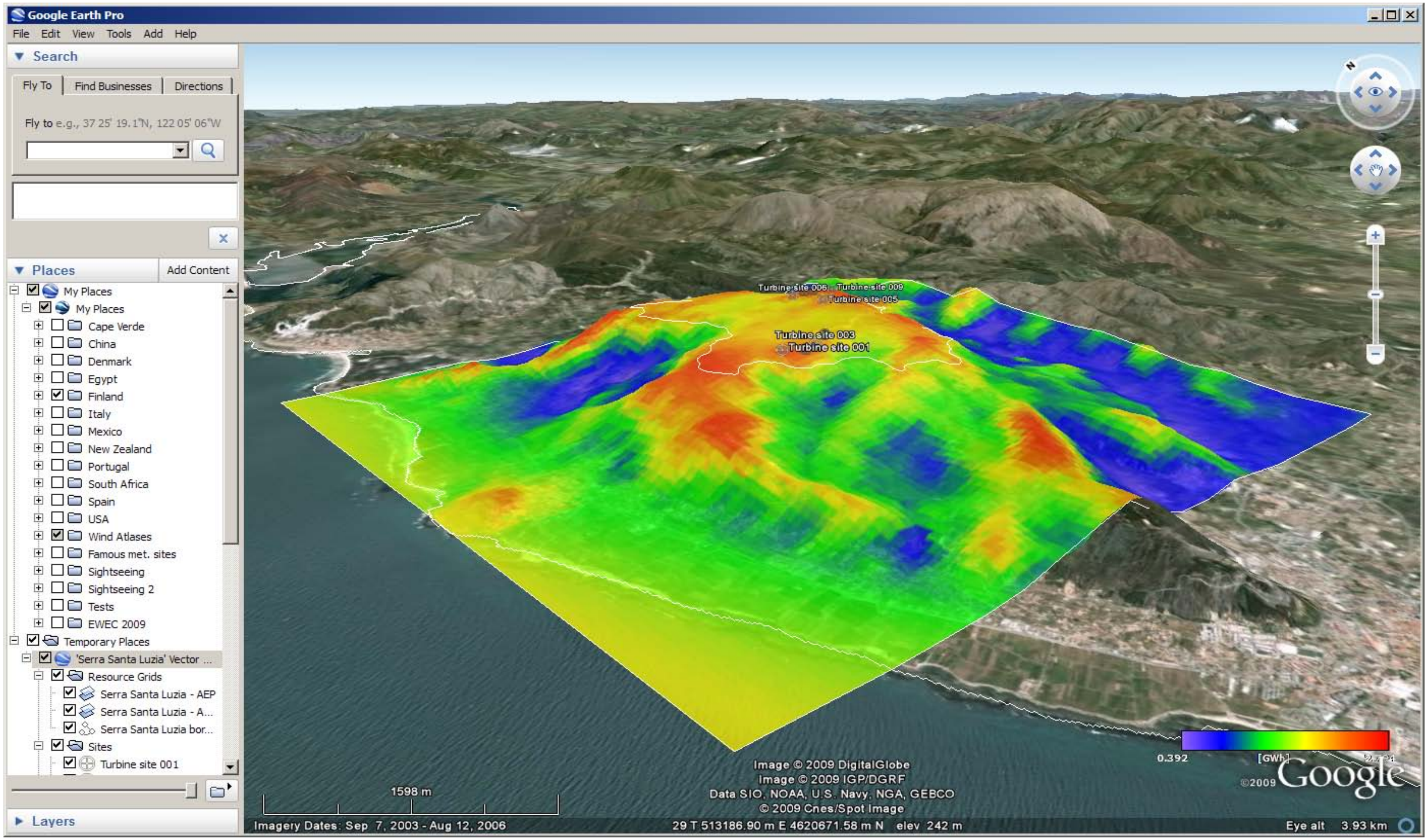


Comparison of profiles from the flat and homogeneous sector (minimize site effects) at Høvsøre

Conclusions

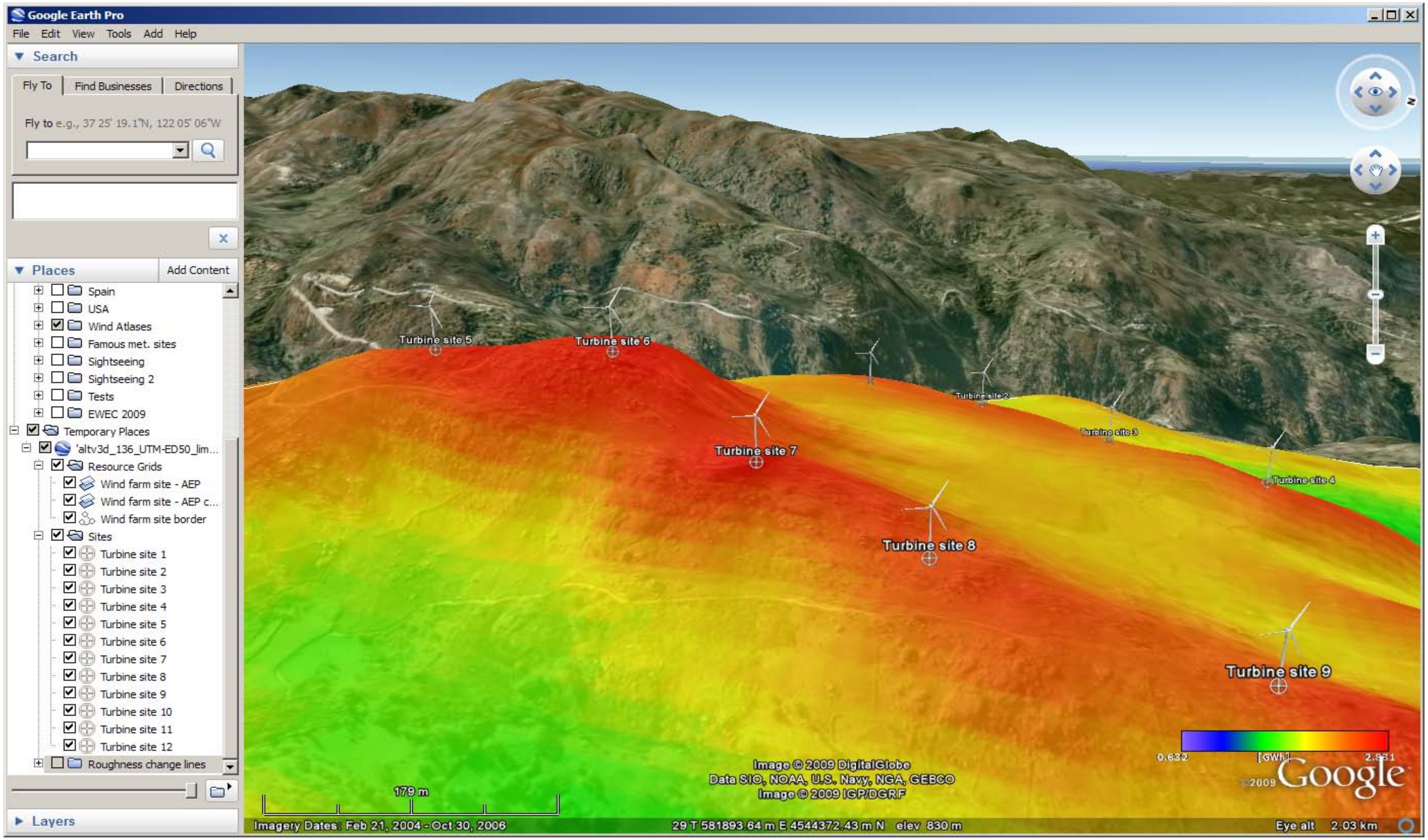
- The method used to generate mesoscale wind atlas is presented.
- Preliminary, unverified modeling results for South Africa are presented.
- The importance of downscaling mesoscale results to the microscale is emphasized.
- The dynamical downscaling method is introduced
- Validation results of mesoscale weather forecasts for Denmark illustrate the difficulties in modeling the vertical wind profile.

The goal…



Thanks to Niels Mortensen

End of story



Thanks to Niels Mortensen

After the end off story
Site assessment in IEC 61400-1

$V_{50} < V_{REF}$

Class	V_{ref}
I	50 m/s
II	42.5 m/s
III	37.5 m/s
IV*	30 m/s
S	Designer specifies

Checklist

- Extreme winds
- Shear of vertical wind profile
- Flow inclination
- Background turbulence
- Wake turbulence
- Wind-speed distribution