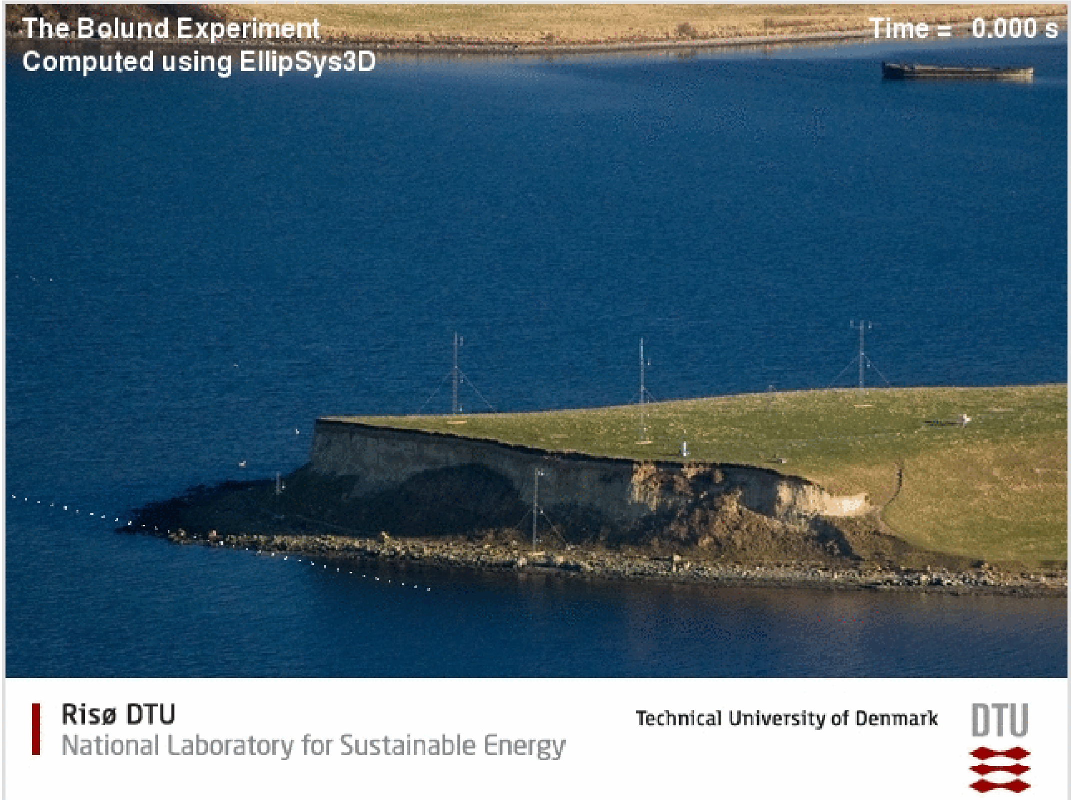
Flow modelling – hills, complex terrain and other issues



Risø DTU
National Laboratory for Sustainable Energy

Modelling approaches sorted after complexity

- Rules of thumbs
- Codes and standards
- Linear model, 1st order turbulence closure ← LINCOM/Wasp
- Reynolds-averaged Navier-Stokes (RANS) equations,
  often 2nd order or 2-equation turbulence closure by the k-ε scheme
  or k-◆ scheme (Risø models Ellipsys and SCADIS)
- Large-eddy simulation (LES)
- Direct numerical simulation (DNS)
- The real flow

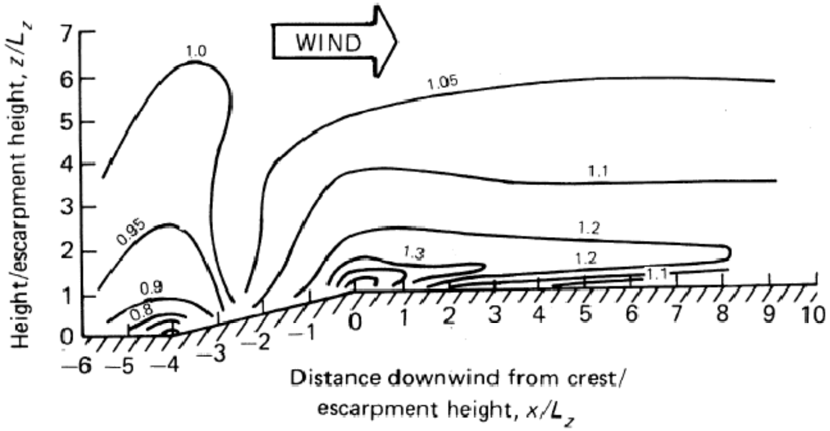
Differences among model types

ease of use, accuracy, detail, cpu time, computer memory, model-operator skills,

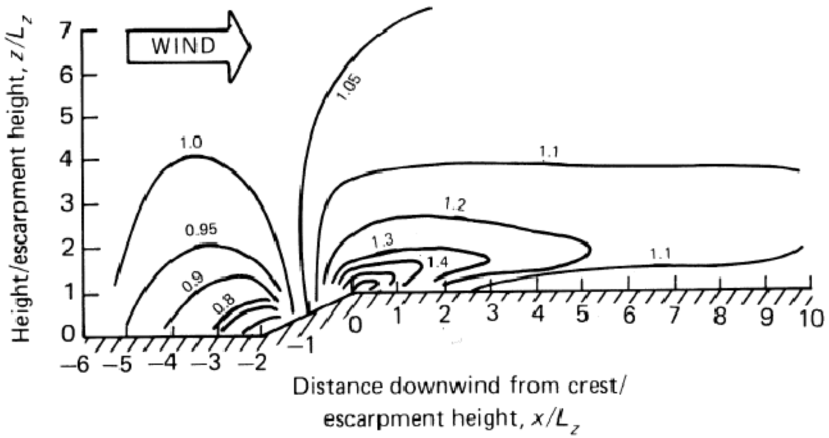
ease of interpretation

Flow over an escarpment (by N Cook ex from BS)

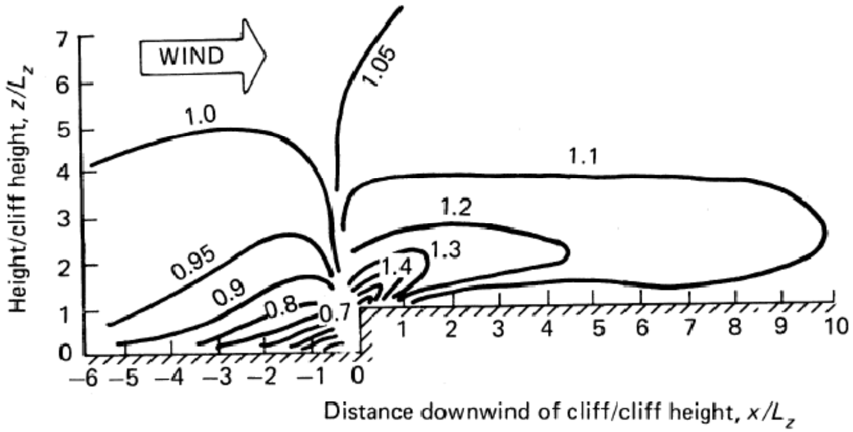
Moderate escarpment, slope ϕ = 0.25



Steep escarpment, slope ϕ = 0.5

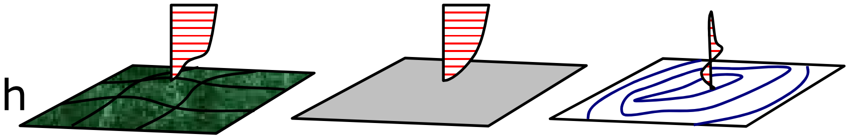


Cliff



LINearized COMputation

1. Splits wind field into
   - uniform mean field in balance with flat terrain and uniform z_0
   - perturbation field accounts for terrain and roughness variations



2. Derive RANS equations for velocity perturbations in terrain-following coordinates and disregard non-linear terms, i.e.

$$\left(U_j + u'_j\right)\frac{d\left(U_i + u'_i\right)}{dx_j} = U_j \frac{dU_i}{dx_j} + \boxed{U_j \frac{du'_i}{dx_j} + u'_j \frac{dU_i}{dx_j}} + O\left(u'^2\right)$$

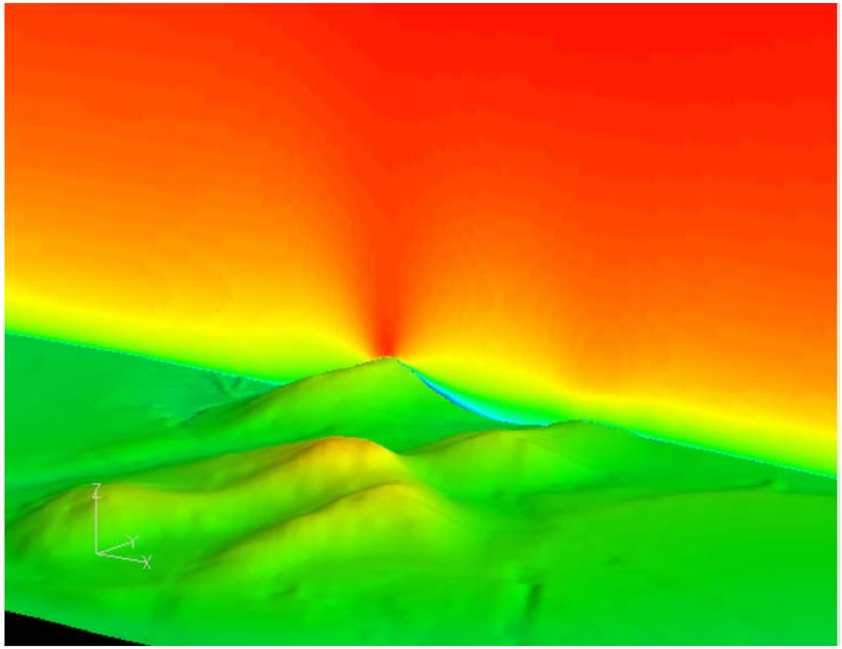
3. Fourier transform the RANS equations and solve them in Fourier space with appropriate boundary conditions
4. Find real-space perturbations by inverse FFT
5. Add perturbations to mean field

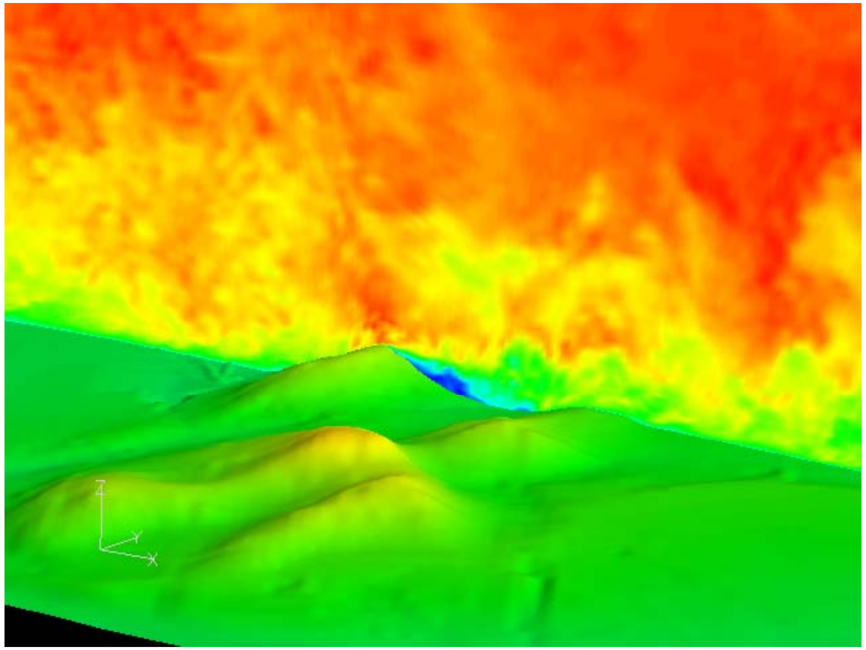
CFD calculations

Reynolds-averaged

Navier-Stoke equations (RANS)

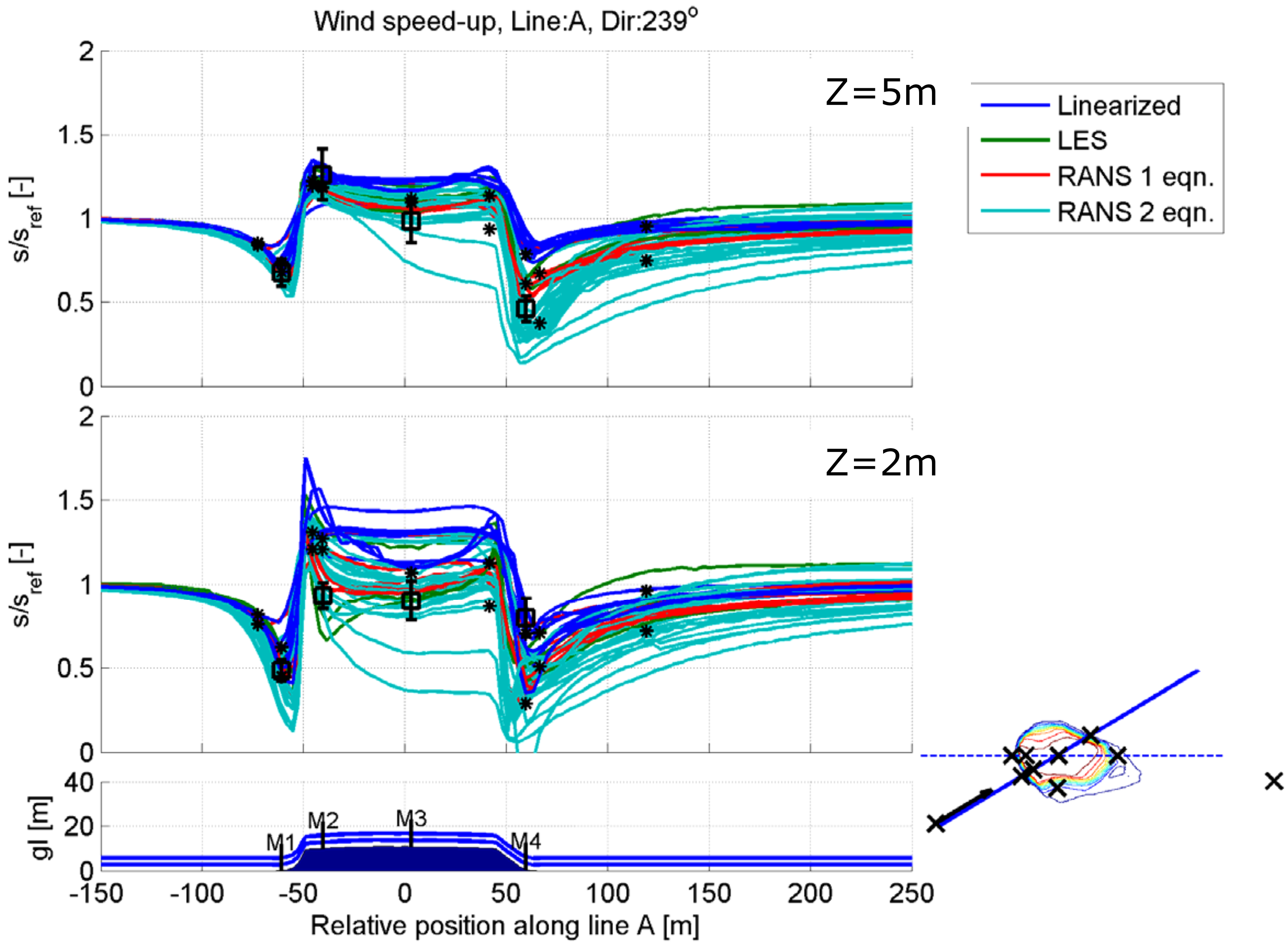
Large-Eddy Simulation (LES)





Calculations with EllipSys3D

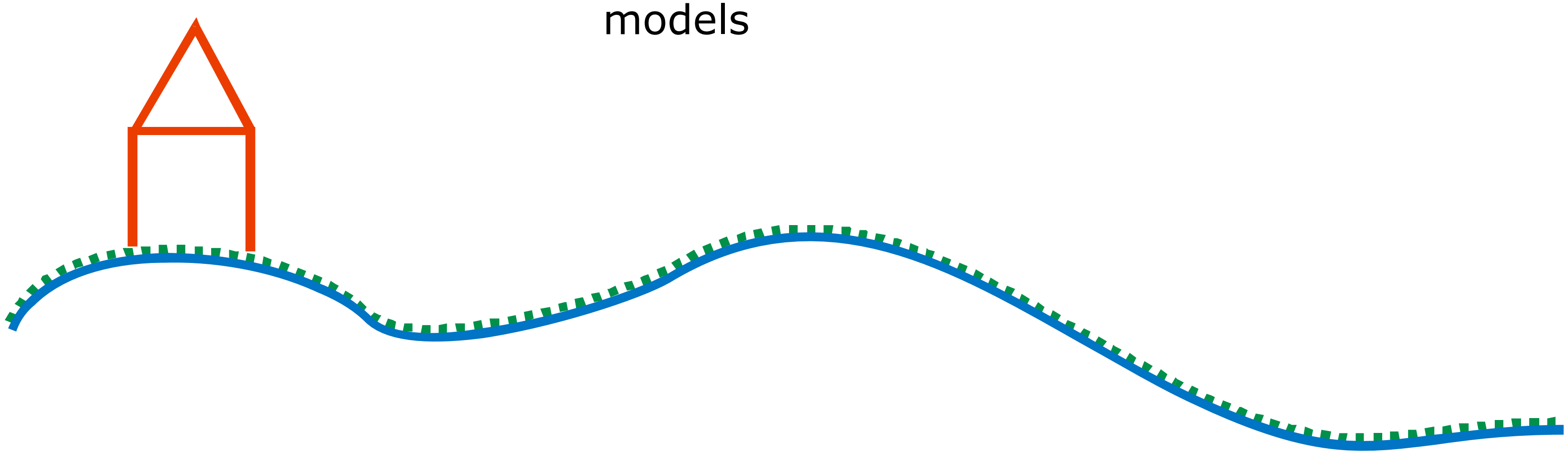
Blind test : Bolund



WAsP arithmetic (linear approach)

WAsP = ROU + ORO + OBST

Including empirical and parameterized models

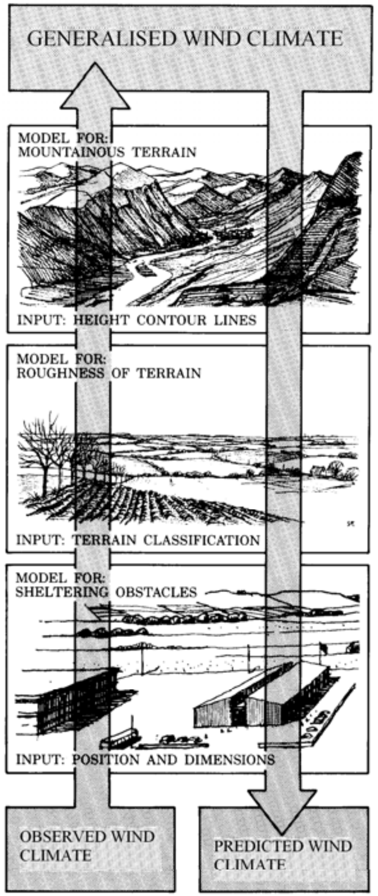


Land use and roughness length – neutral conditions

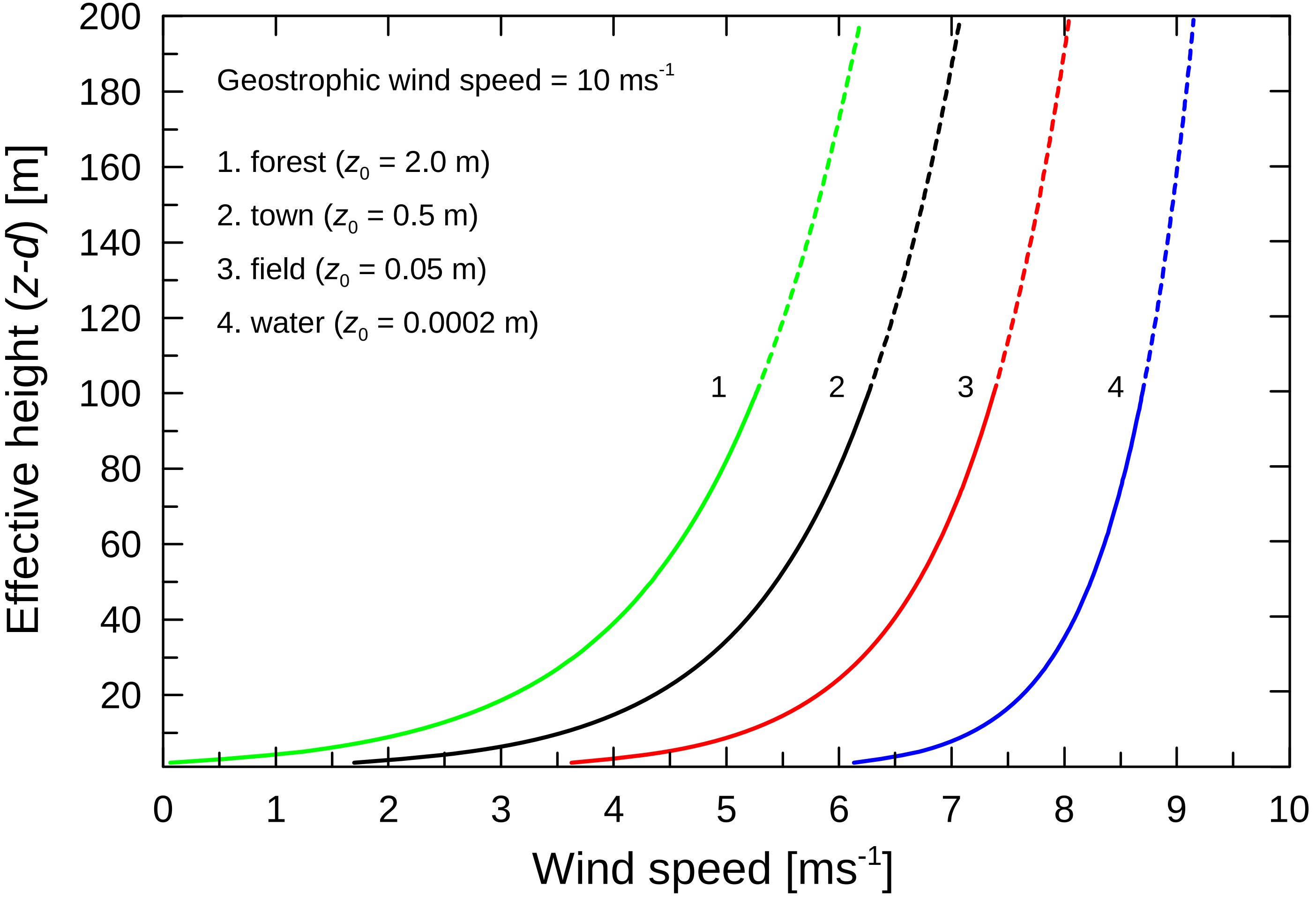
$$u(z) = \frac{u_*}{\kappa} \ln\left(\frac{z}{z_0}\right)$$

$$G = \frac{u_*}{\kappa} \sqrt{\left[\ln\left(\frac{u_*}{f z_0}\right) - A\right]^2 + B^2}$$

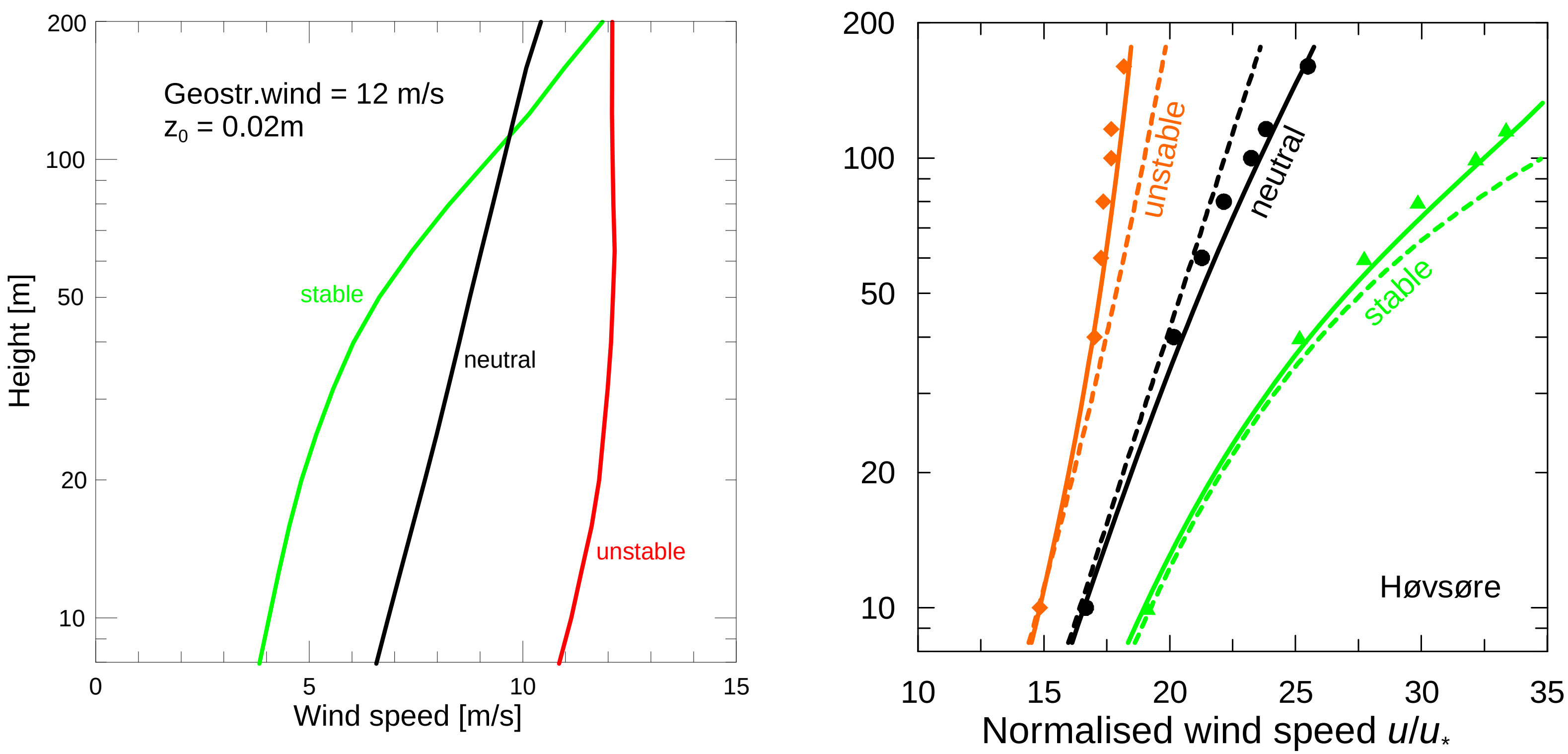
$$A = 1.8; \quad B = 4.5$$



Logarithmic wind profiles

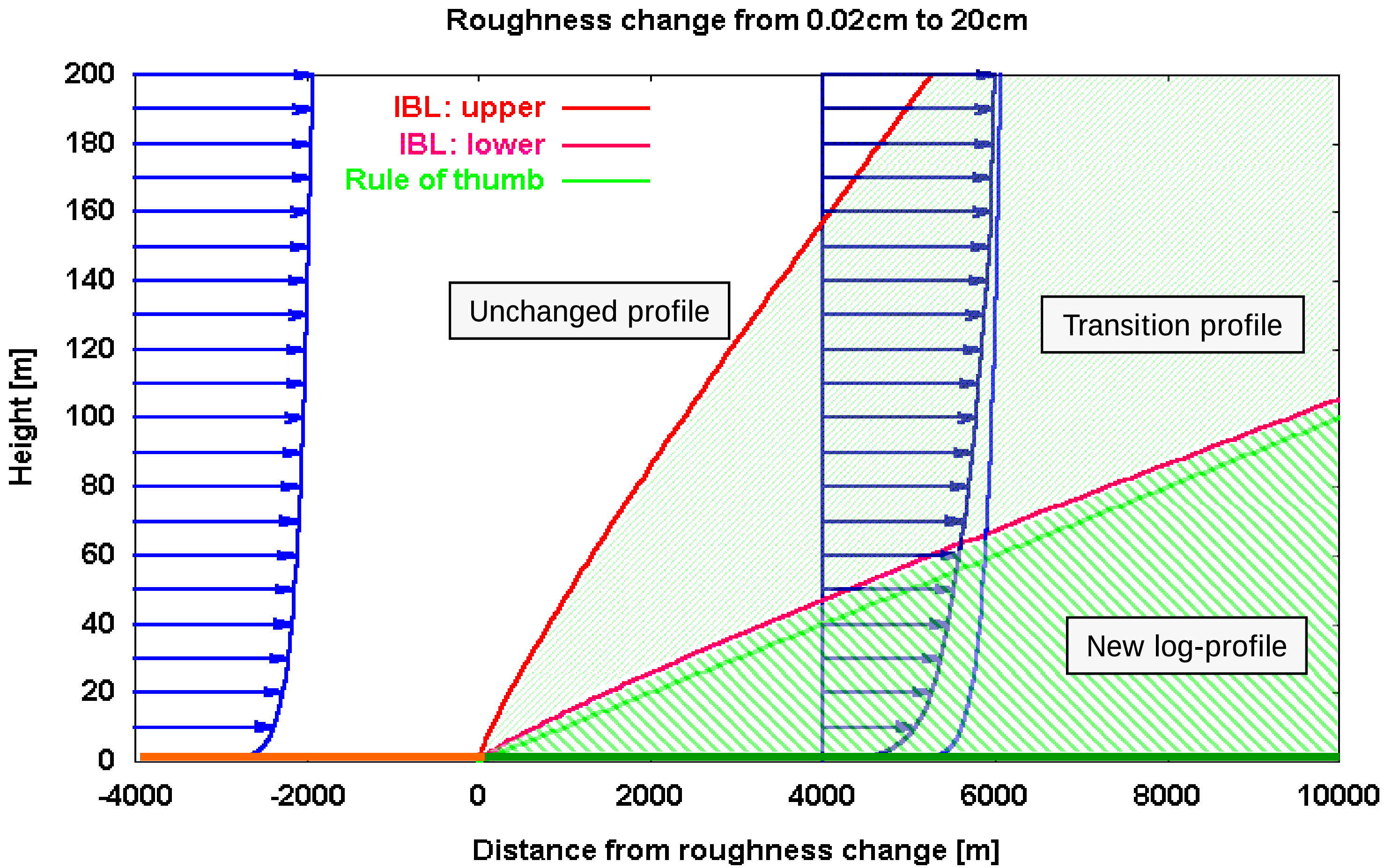


Surface layer wind profiles



- Variation of mean wind speed with height above ground level for three different stability conditions: unstable (L = -71 m), neutral ($L \rightarrow \infty$) and stable (L = 108 m) according to N.O.Jensen (priv.comm.) and Gryning et al. (2007).

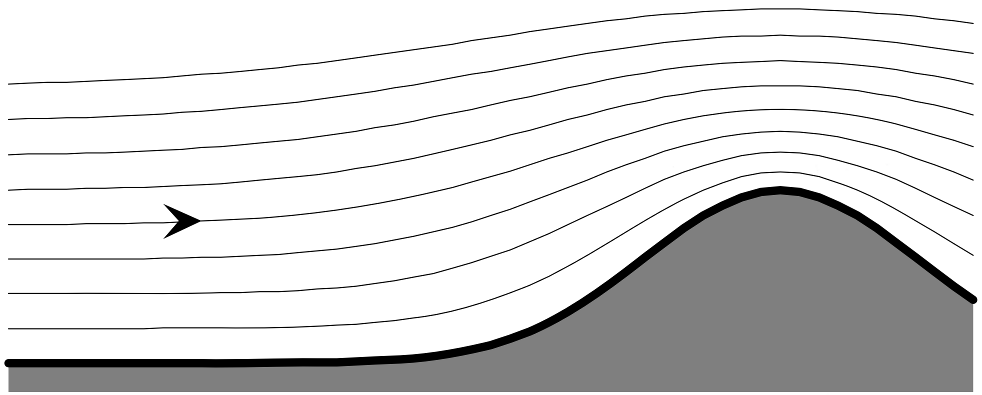
Internal Boundary Layer (IBL)

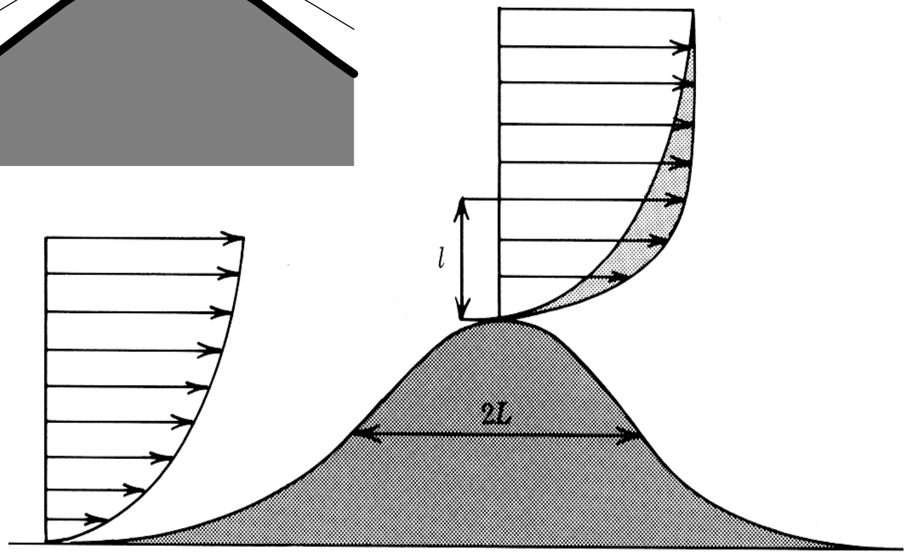


Rule of thumb 1:100

Effect of orography

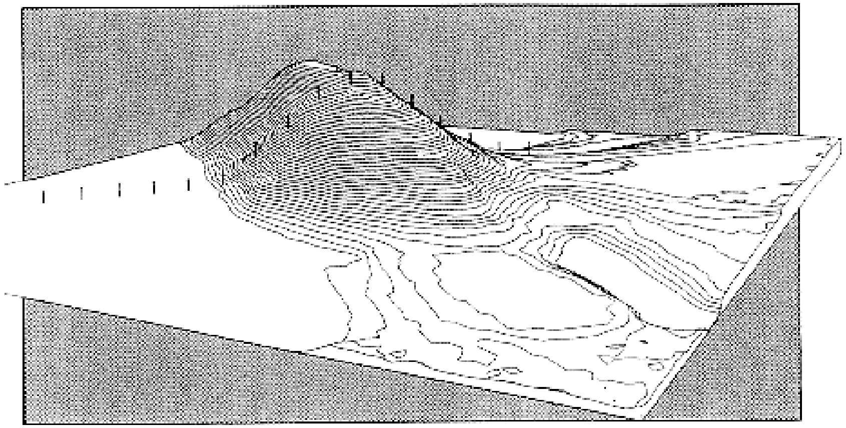
Streamlines over a hill





Streamlines are compressed => the wind speeds up!

Askervein Hill field experiment

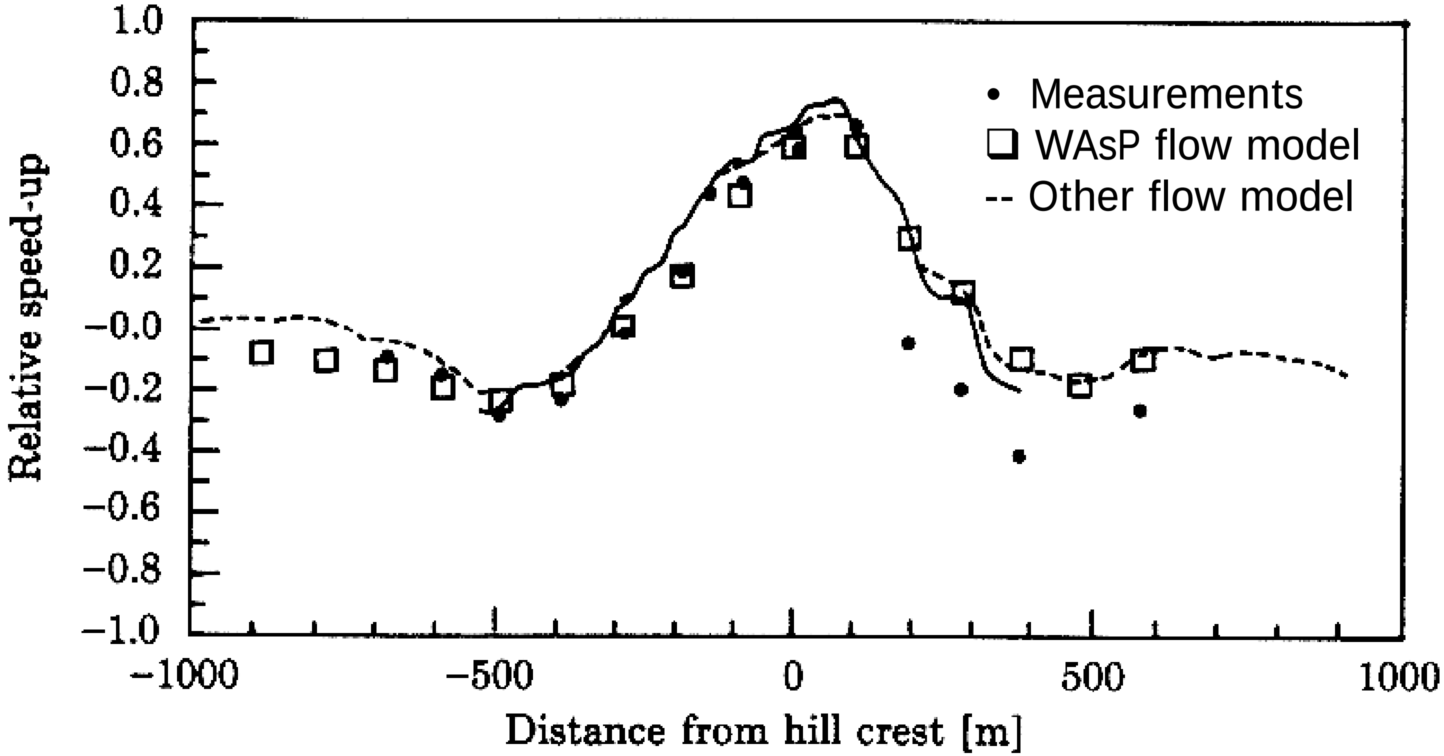


Height of hill: 123 m
(vertical scale
exaggerated)

- Mother of all flow-over-hill studies: The Askervein Hill field experiment on the island of South Uist, Outer Hebrides, Scotland.
- Wind measured on masts along a line across the hill and on top of hill
  - mast interval: 100 m

- Salmon J.R. et al.(1987): ”The Askervein Hill project: Mean Wind ..”, Bound.-Layer Meteorol. **43**, 247-271. Taylor P.A. et al. (1987): ”The Askervein Hill project: Overview ..”, *Bound.-Layer Meteorol*. **39**, 15-39 (1987)

Askervein wind speed variation



- Orography effects on horizontal wind speed profile (transect)

Flow model output at single site

'Hilltop' Turbine site (3.379 GWh)

Settings | Wind | Power | Site effects | User corrections

Sector		Roughness			Obst.	Orography			
#	a [°]	ch	ref. [m]	sp [%]	sp [%]	sp [%]	tu [°]	RIX	dRIX
1	0	0	0.03	0.00	0.00	5.71	-2.1	0.0	0.0
2	30	0	0.028	0.00	0.00	5.12	1.6	0.0	0.0
3	60	3	0.011	-2.00	0.00	10.30	3.4	0.0	0.0
4	90	2	0.025	-0.31	0.00	16.89	1.9	0.0	0.0
5	120	0	0.03	0.00	0.00	17.61	-1.5	0.0	0.0
6	150	0	0.03	0.00	0.00	12.08	-3.5	0.0	0.0
7	180	0	0.03	0.00	0.00	5.71	-2.1	0.0	0.0
8	210	0	0.03	0.00	0.00	5.15	1.6	0.0	0.0
9	240	0	0.03	0.00	0.00	11.03	3.6	0.0	0.0
10	270	0	0.03	0.00	0.00	17.11	1.9	0.0	0.0
11	300	0	0.03	0.00	0.00	17.61	-1.5	0.0	0.0
12	330	0	0.03	0.00	0.00	12.08	-3.5	0.0	0.0
All								0.0	0.0

Orography corrections:
Speed-up and Turning

Limitations of the WAsP and WENG flow model

1. Prevailing conditions near-neutral (except for the background profile)
2. Mesoscale effects not taken into account
3. Orography gentle (mostly attached flow)

Even outside these limits WAsP <u>may</u> do surprisingly well!

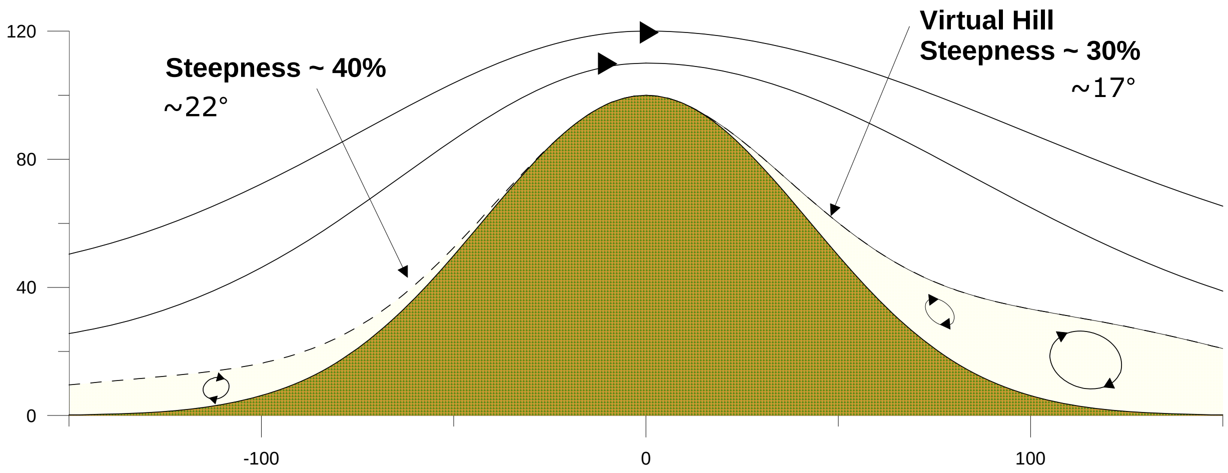
1 Stability effects: vertical wind profile

- Example from Hurghada in Egypt (sub-tropical desert)
- Significant daily changes in atmospheric stability

	Measurement height (**bold** values measured)			
	10 m		25 m	
z	<U>	<Power>	<U>	<Power>
[m]	[m/s]	[W/m2]	[m/s]	[W/m2]
10	**6.0**	**233**	6.1	230
25	7.0	339	**7.1**	**336**
50	7.8	545	7.9	543
100	8.9	675	9.1	684

- On average, the vertical profile of mean wind speed over the desert surface seems to be predicted quite well!

3 Effect of a steep hill



- Flow separation on steep but smooth hill

- The flow behaves – to some extent – as if moving over a virtual hill with less steep slopes => **actual speed-up is smaller than calculated by WAsP**

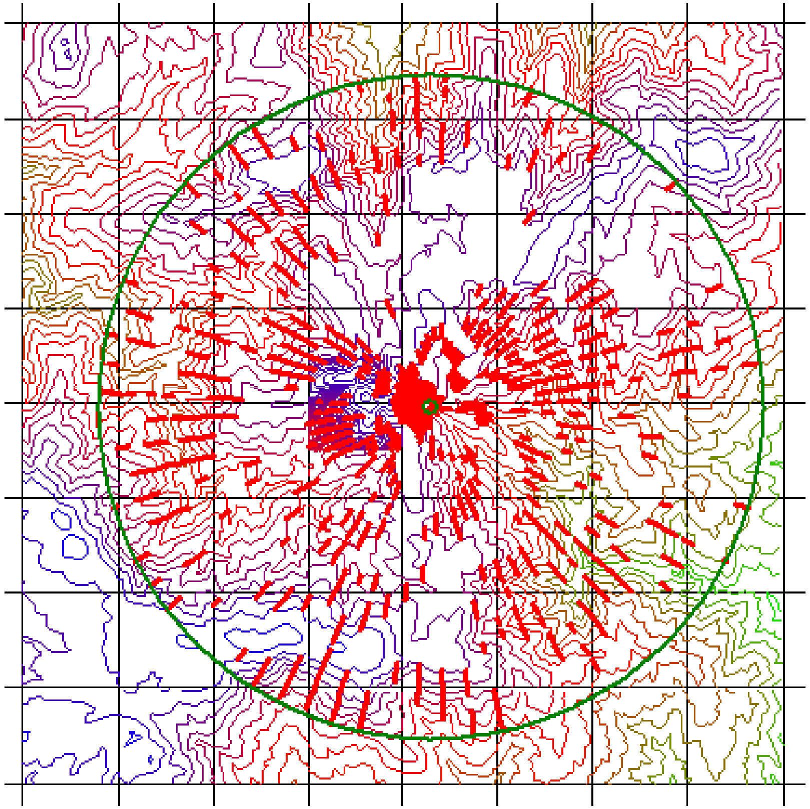
- Reference: N. Wood (1995). "The onset of flow separation in neutral, turbulent flow over hills", *Boundary-Layer Meteorology* **76**, 137-164.

Complex terrain measure: RIX

- **RIX** = **R**uggedness **I**nde**X**
  - fraction (in %) of 'steep' terrain within, say, 3.5 km of the site of interest
  - where 'steep' means a terrain slope of, say, > 0.3 to 0.4 (approximate limit of attached flow)

- The index is evaluated by WAsP for all sites:
  - Met. station
  - Reference site
  - Turbine sites (single or in farm)
  - Resource grid nodes

Complex terrain measure: RIX



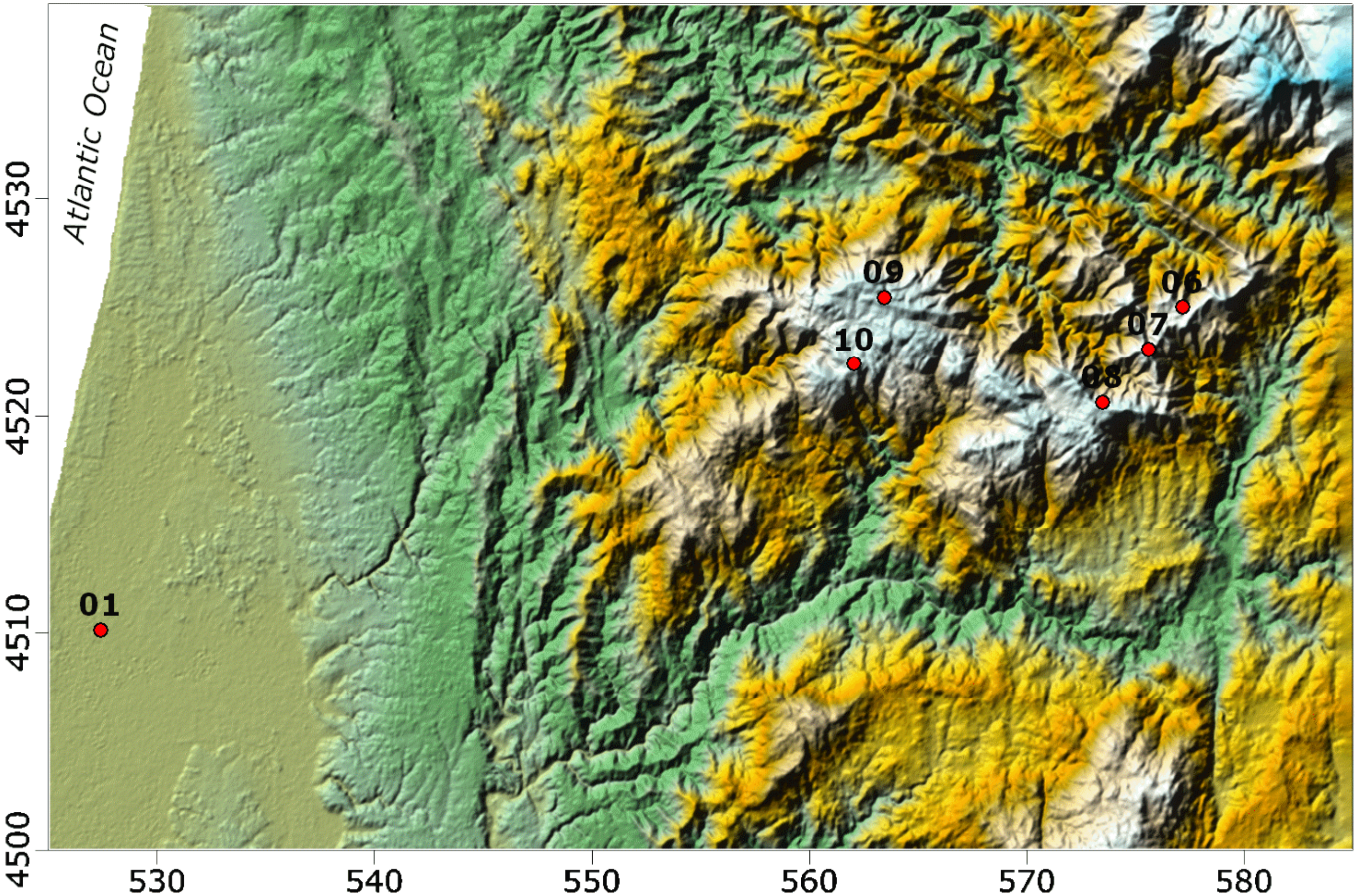
Default values for RIX calculation:

- calculation radius 3.5 km
- radii for every 5 degrees
- threshold slope 0.3

- Steep terrain is indicated by thick red lines in the map.

- This graphic can be made by the Map Editor.

Example of highly complex terrain



6 met. stations in Northern Portugal (RIX = 0 to 33%)

Cross predictions in complex terrain

- Met. stations in (too) complex terrain in Northern Portugal:large positive and negative prediction errors.

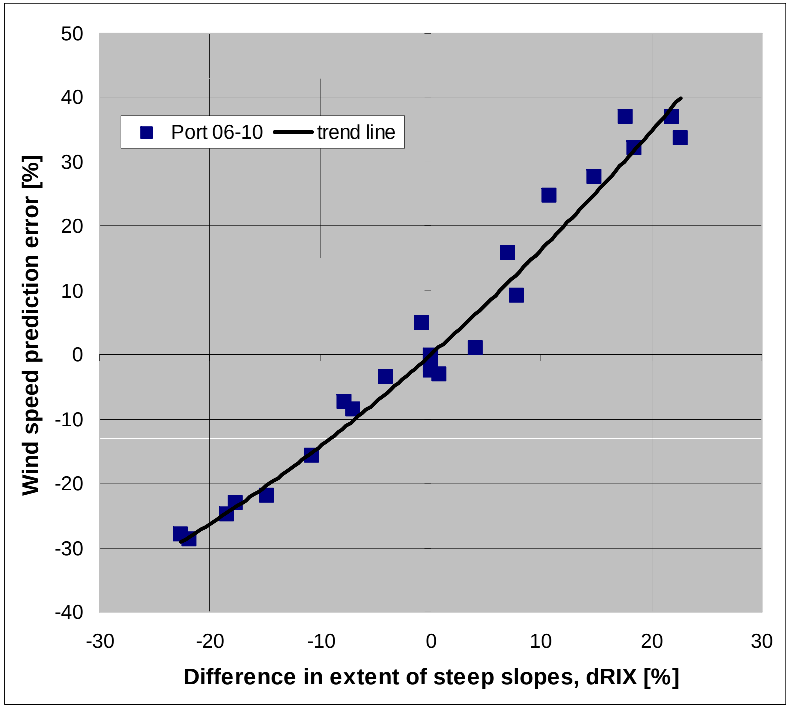
Reference sites

Predicted sites

Site		01	06	07	08	09	10	Obs.
01	*U* [m/s]	4.2	3.4	3.3	4.1	4.4	4.5	**4.3**
06	*U* [m/s]	5.6	4.6	4.4	5.7	6.1	6.3	**4.6**
07	*U* [m/s]	6.5	5.5	5.3	6.9	7.2	7.4	**5.4**
08	*U* [m/s]	6.9	5.2	4.8	6.2	6.8	7.2	**6.2**
09	*U* [m/s]	5.8	4.6	4.4	5.7	6.1	6.4	**6.1**
10	*U* [m/s]	5.6	4.4	4.1	5.2	5.5	5.6	**5.7**
	0-10%			10-25%			25-40%	

Predicted wind speeds and color-coded prediction errors (absolute value).

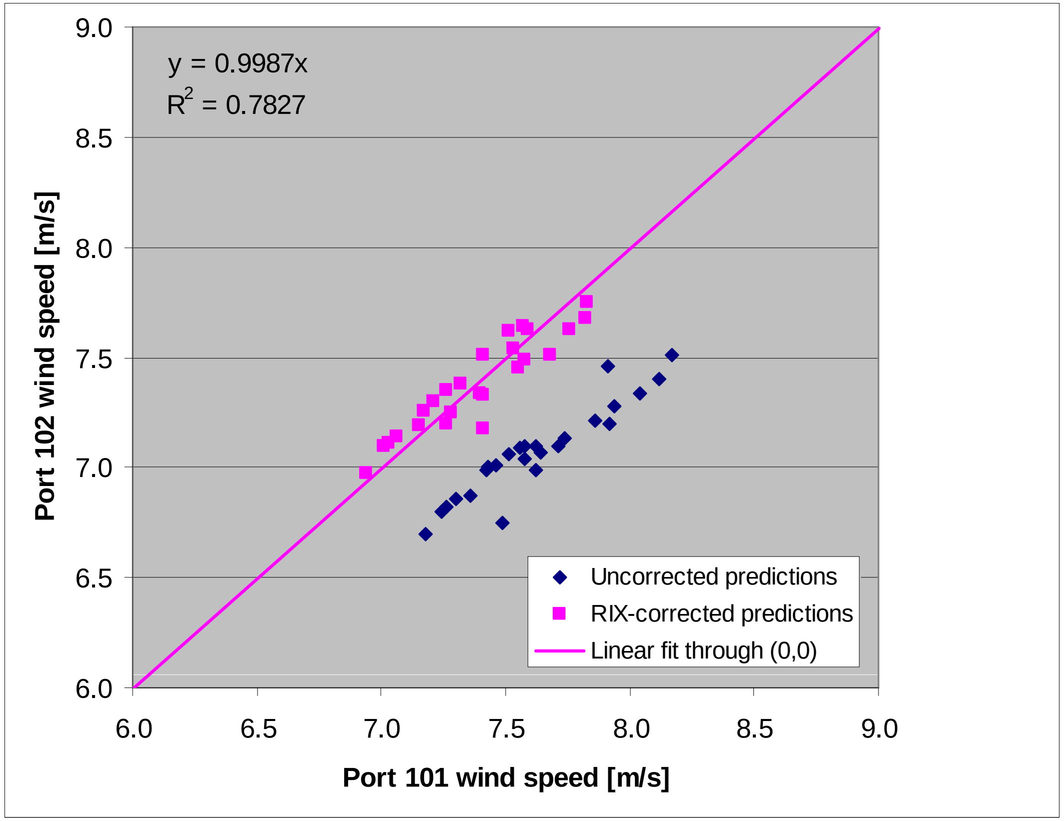
Prediction error vs. difference in RIX



- The key parameter is ΔRIX!
- ΔRIX = RIX(WTG site) – RIX(met.site)
- ΔRIX is a performance indicator for WAsP calculations in (too) complex terrain.

- N.G. Mortensen and E.L. Petersen (1997). "Influence of topographical input data on the accuracy of wind flow modeling in complex terrain". 1997 European Wind Energy Conference, Dublin, Ireland.

Predictions from two masts in very complex terrain



The ‘similarity principle’

The predictor (met. station) and the predicted (turbine) sites should be as similar as possible with respect to:

- Topographical setting
  - ruggedness index (RIX)
  - elevation and exposure
  - distance to significant roughness changes (coastline)
  - background roughness lengths

- Climatic conditions
  - regional wind climate (synoptic and mesoscale)
  - general forcing effects
  - atmospheric stability