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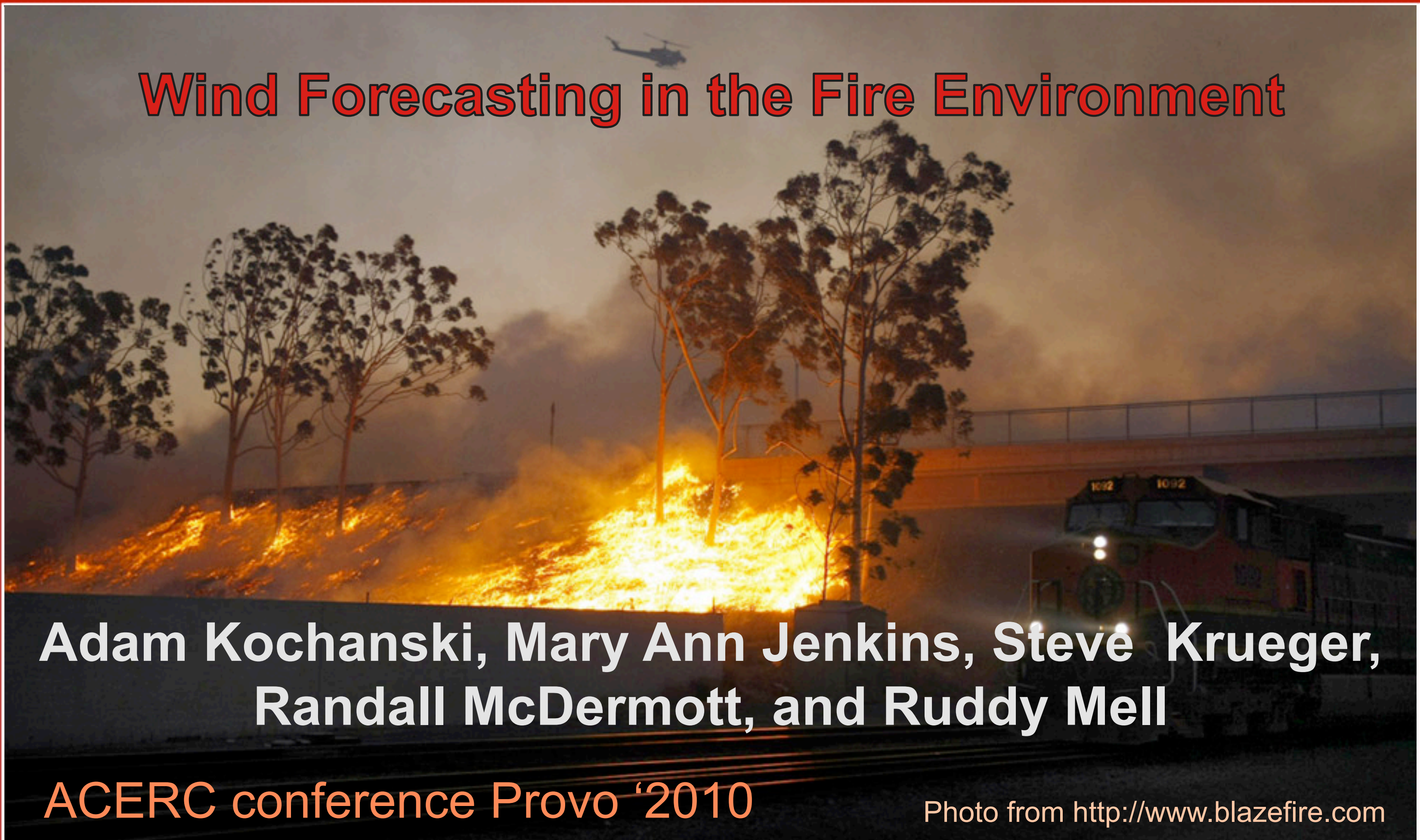
UNIVERSITY OF UTAH



Wind Forecasting in the Fire Environment

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ACERC conference Provo ‘2010

Photo from http://www.blazefire.com

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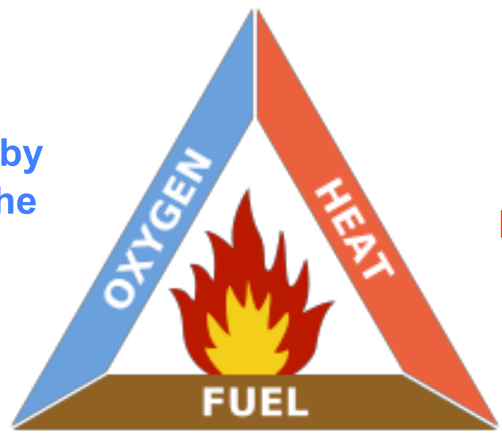
Importance of wind speed for fire spread prediction

- For a given fuel and ground inclination the wind wind speed is the most important factor affecting the fire spread rate
- Complex topography modifies flow, and generates eddies (turbulence)
- Generated turbulence:

Enhances oxygen transport from the atmosphere to the fuel by reducing the depth of the laminar boundary layer formed during the flow around fuel elements



Intensifies heat transfer from the hot air to the fuel (pre-heating)

Increases the rate of mass (moisture) transfer from the fuel to the atmosphere (drying out of fuels)

- **Therefore, correct prediction of the flow properties including wind speed, wind direction and turbulence intensity is required for realistic modeling of the fire spread**

Motivation – importance of the wind speed

- For a given fuel and ground inclination the wind wind speed is the most important factor affecting the fire spread rate

$$R = \mathbf{I_R}\, \xi (1 + \Phi_W + \Phi_S) / \rho_\eta \varepsilon Q_{ig}$$ *(Rothermel 1985)*

$$\mathbf{I_R \sim \mathit{U}^3}$$

R = rate of spread of the flaming front

U = wind speed

I_R = reaction intensity

ξ = propagating flux ratio

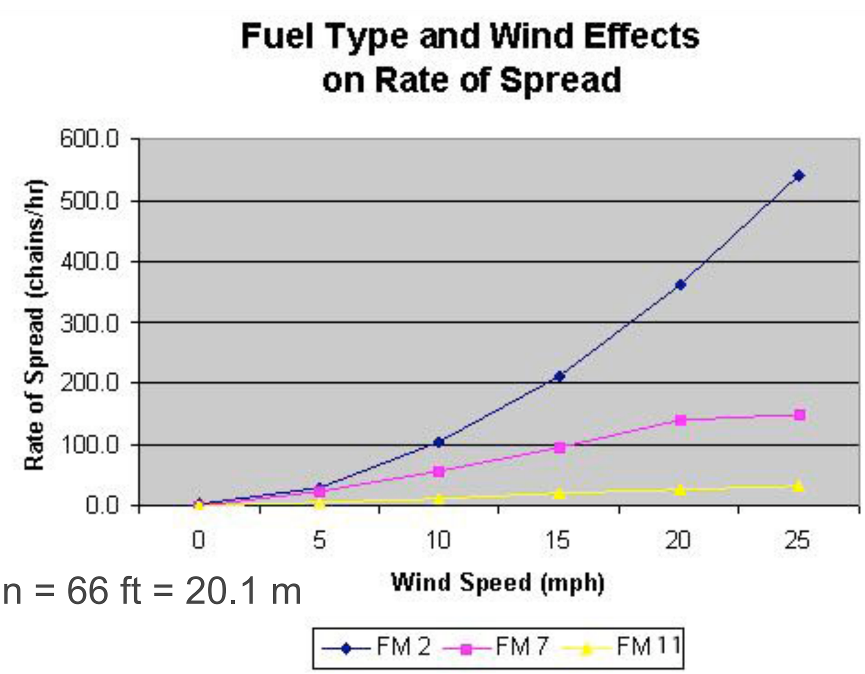
Φ_W = effect of wind on the heat transfer to adjacent fuels

Φ_S = effect of slope on the heat transfer to adjacent fuels

ρ_η = fuel load

ε = effective heating number

Q_{ig} = heat of pre-ignition

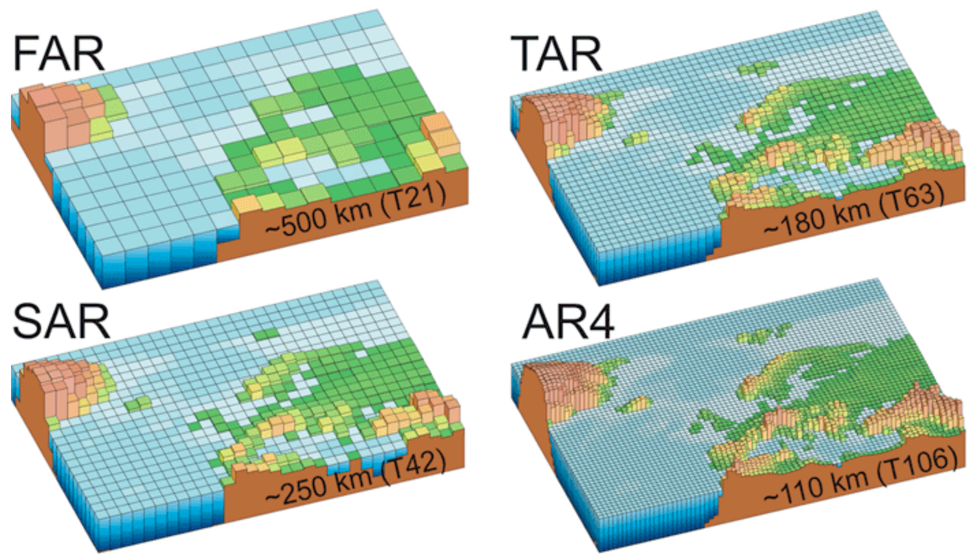


1 chain = 66 ft = 20.1 m

Graph from http://www.forestencyclopedia.net

Simulating the wind speed for fire models

- Combustion processes have characteristic scales of centimeters
- Most of current fire models work with resolution of meters
- Numerical Weather Prediction models, provide forecasts with the resolution of kilometers…



- Since the NWP models can not resolve local flow features crucial for the fire propagation, the very high resolution wind simulations must be performed first, in order to provide initial and boundary conditions for atmospheric components of coupled fire models.

Graph from http://www.windows.ucar.edu

Simulating the wind speed for fire models

- In order to get the high-resolution forecast for our area of interest we can perform a nested simulation, providing local meteorological conditions

150 km resolution

50 km resolution

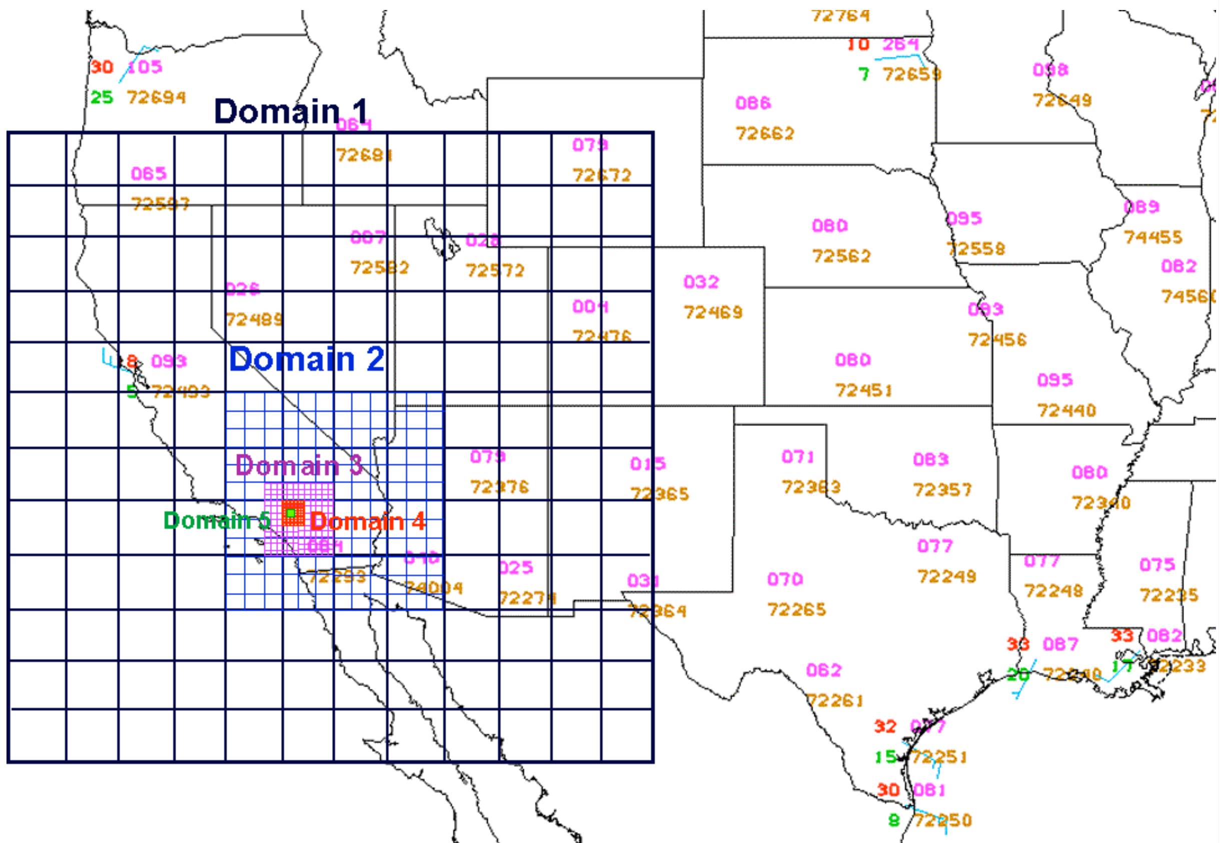
16 km resolution

5.5 km resolution

1.8 km resolution

…

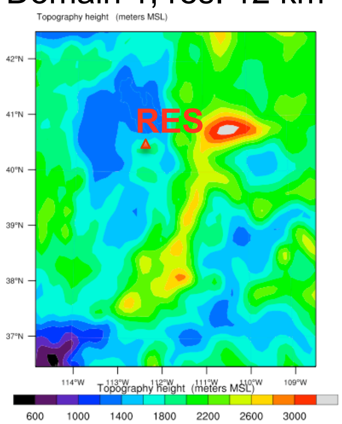
~20 m resolution



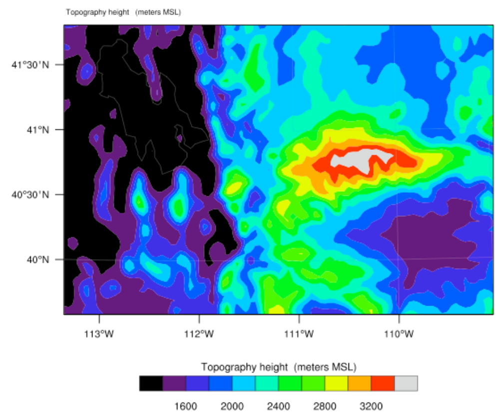
Practical example of the nested setup

- Practical implementation of the nested setup 12km/4km/1.3km/444m horizontal resolution

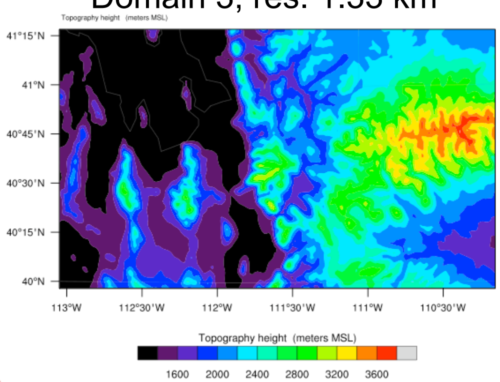
Domain 1, res. 12 km



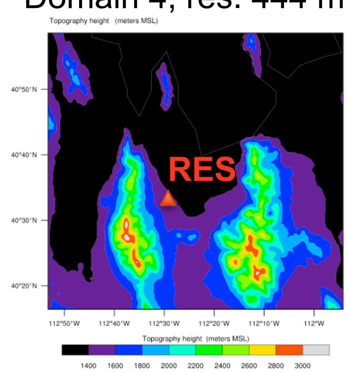
Domain 2, res. 4 km

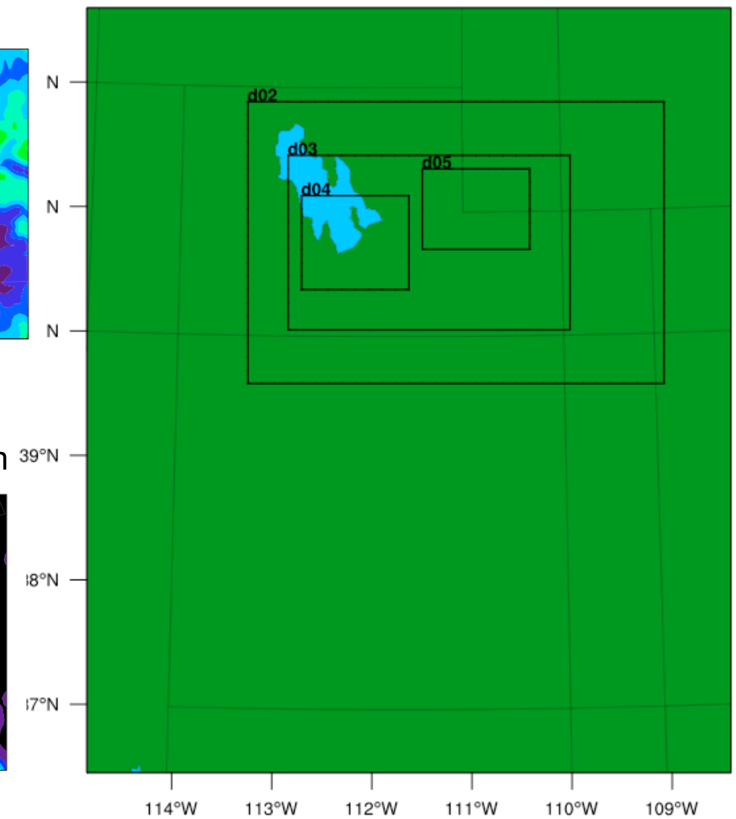


Domain 3, res. 1.33 km



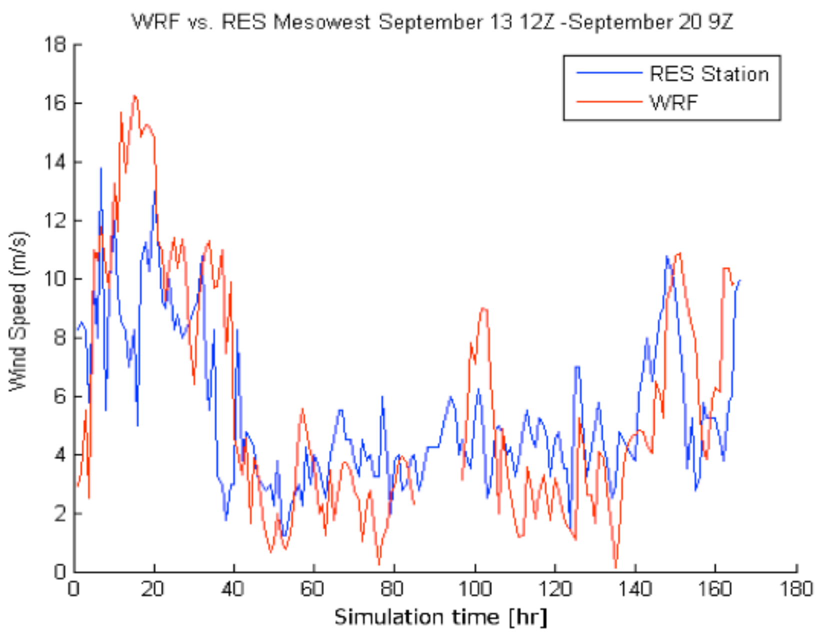
Domain 4, res. 444 m

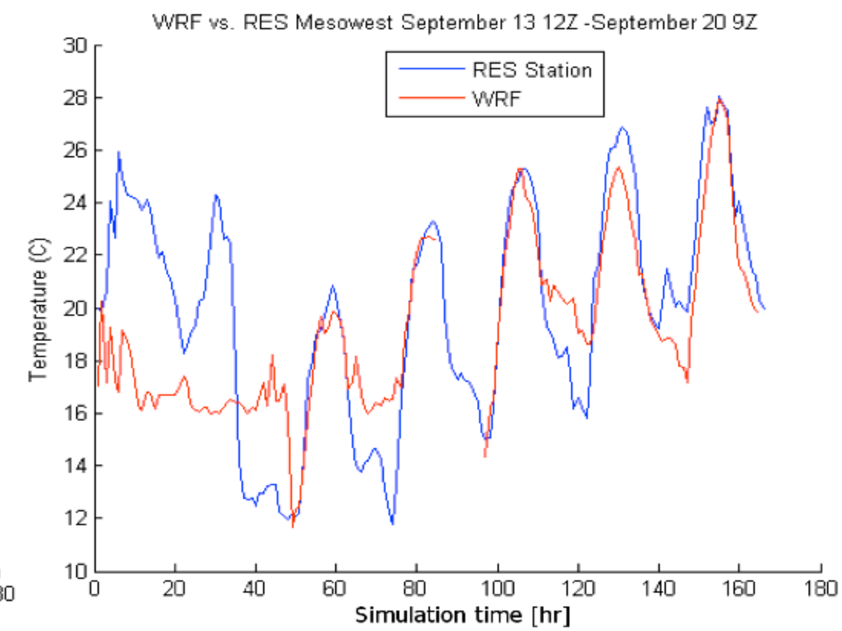




Evaluation of the high-resolution nested forecast

- Comparison of the simulated 10m wind speed and 2m air temperature with the surface observations from Grantsville Reservoir Station (RES)





R=0.67
RMSE=3.04 m/s

R=0.71
RMSE=3.09 °C

Graphs and statistics prepared by Morgan Farley-Chrust

Critical questions

- Let's assume that we have a perfect high resolution forecast from the numerical weather prediction model that we can use for initialization of a very high resolution Large Eddy Simulation (LES) model
- How good are the current wind forecasting models (components) used for fire modeling and prediction?
- Can we accurately resolve flows in a complex terrain?
- What are the limitations?

High-resolution simulation of the hill flow

Topography of the analyzed area (Askevein Hill, Scotland)

4960 m (N-S)
5300 m (E-W)
Max height 126 m

Simulation details - WRF and UU LES

WRF-LES:

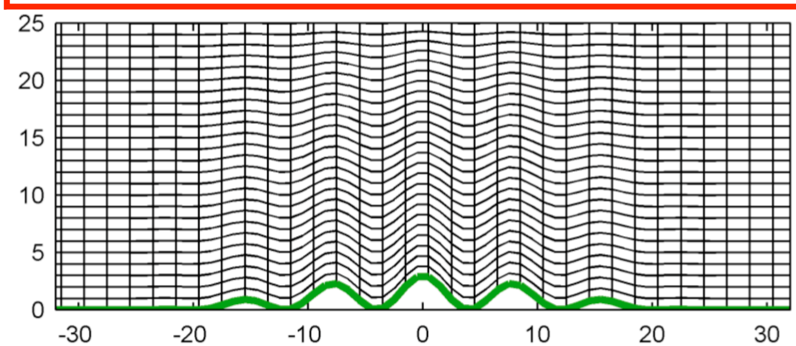
Analyzed domain:

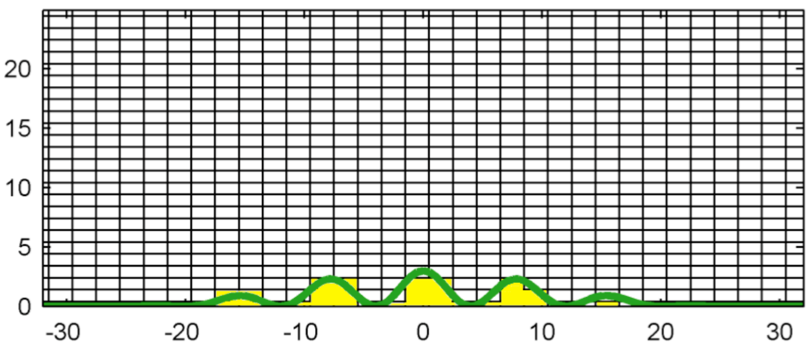
Grid: 256x256x200 (13,107,200 grid points)
Covered area: 5300 x 4960 x 600 m
Spatial resolution 20.7 x 19.3 x 3 m
Simulation length 1800s (30 min)
Time step 0.1 s, number of time steps 18,000
1.5 TKE sub-grid scale parameterization
Terrain-followingcoordinate system
Open boundary conditions
Wall clock simulation time on 8 CPU*: **206 h**
*restart files written each second

UU-LES:

Analyzed domain:

Grid: 256x256x200 (13,107,200 grid points)
Covered area: 5300 x 4960 x 600 m
Spatial resolution 20.7 x 19.3 x 3 m
Simulation length 1800s (30 min)
Time step 0.2 s, number of time steps 9,000
1.5 TKE sub-grid scale parameterization
Cartesian coordinate system
Cyclic boundary conditions
Wall clock simulation time on 8 CPU: **76h**





Graphs from Lundquist et al. 2008

Simulation details – WindNinja and FDS

FDS:

Analyzed domain:

Grid: 128x128x100 (1,638,400 grid points)

Covered area: 2650 x 2480 x 500 m

Spatial resolution 20 x 20 x 5 m

Simulation length 3600s (1 hr)

Smagorinsky (dynamical) sub-grid scale parameterization

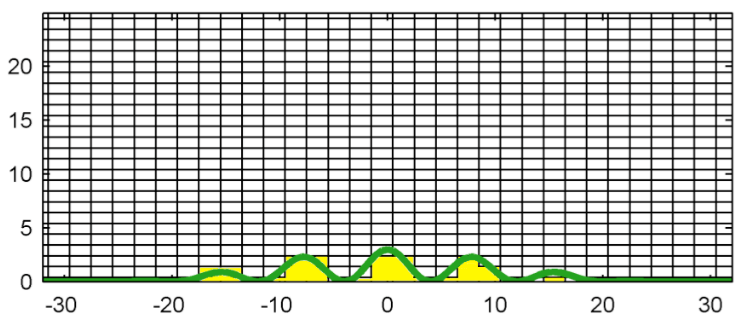
Cartesian coordinate system

Cyclic horizontal boundary conditions

No flux top boundary conditions

Wall clock simulation time on 8 CPU: **12h**

Expected 30 min simulation for WRF domain 48h



WindNinja 2.0.1 (mass-consistent model)

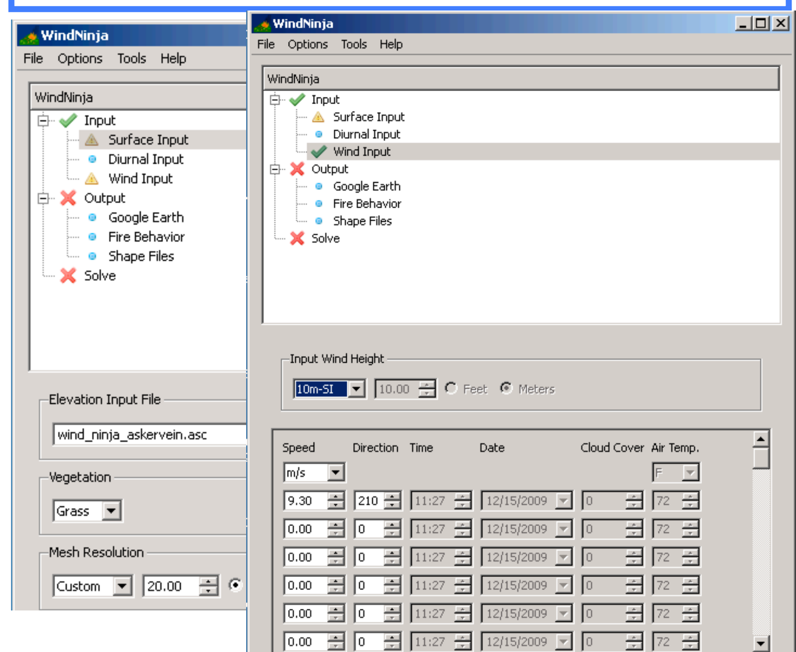
Analyzed domain:

Grid: 261x 261 2D (68,121 grid points)

Covered area: 5220 x 5220

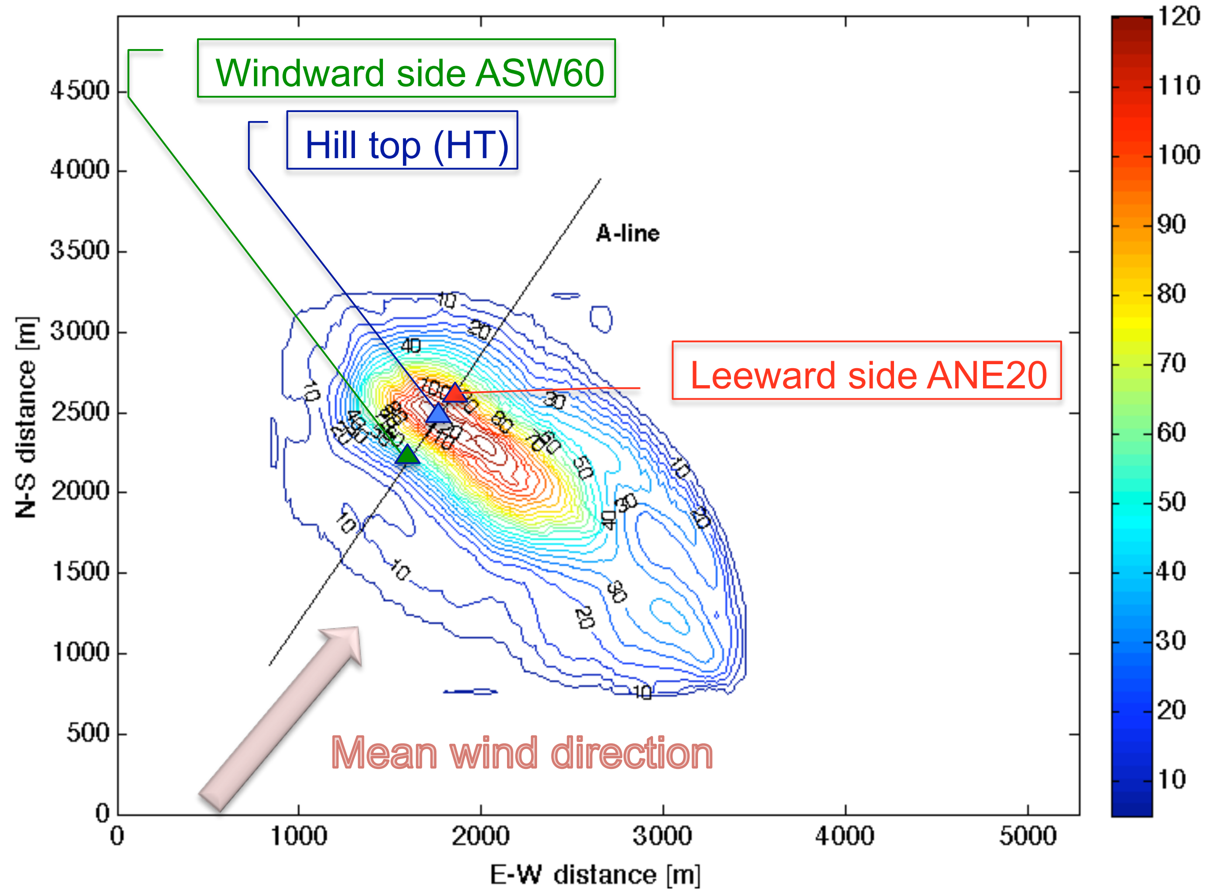
Spatial resolution: 20 m

Simulation time: **< 1 minute**



Simulation details

Topography of the analyzed area (Askevein Hill, Scotland)
4960 m (N-S)
5300 m (E-W)
Max height 126 m



WRF and UU LES initialization

Both the WRF and UU LES were initialized using the measurement data collected during the Askervein '83 experiment (Taylor and Tunissen 1983) on the third of October 1983:

- Kite wind profiles up to 600 m
- Rawisond data (temperature humidity)
- Tower wind profile data (up to 30 m)

The FDS was initialized using:

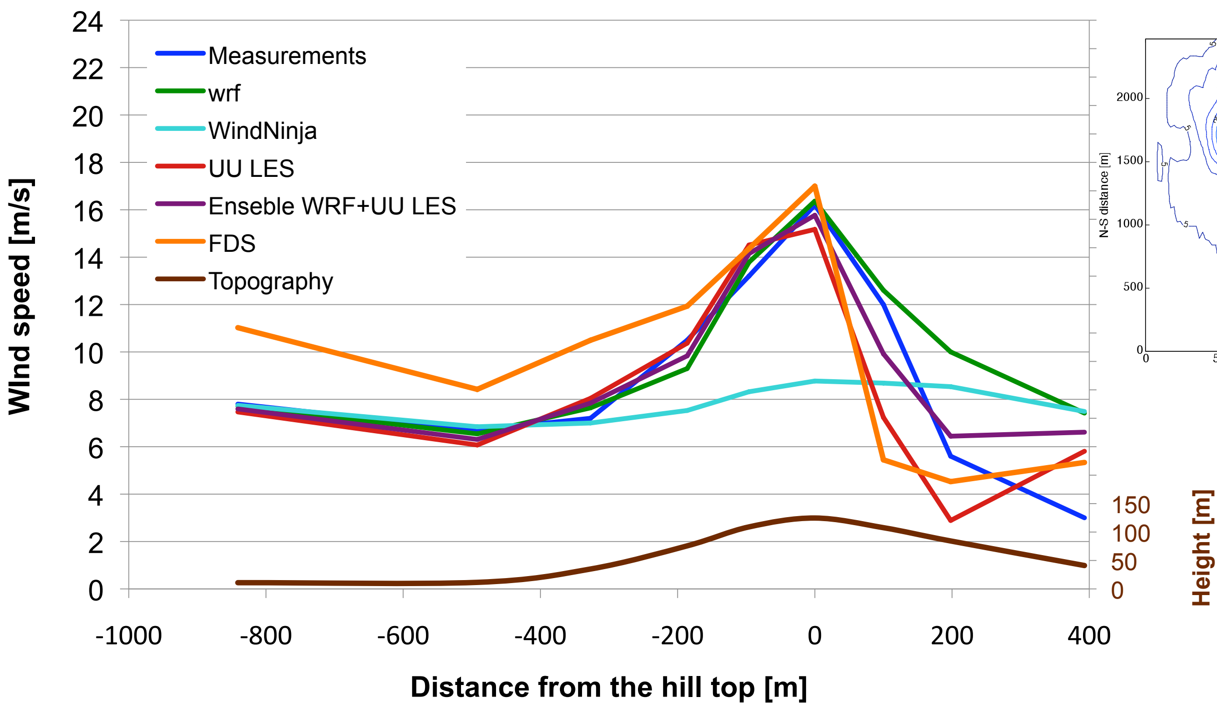
- Tower wind profile data (up to 30 m)
- Kite wind profiles up to 600 m
- Constant lapse rate -0.01^{o}C/m, and constant RH=95%

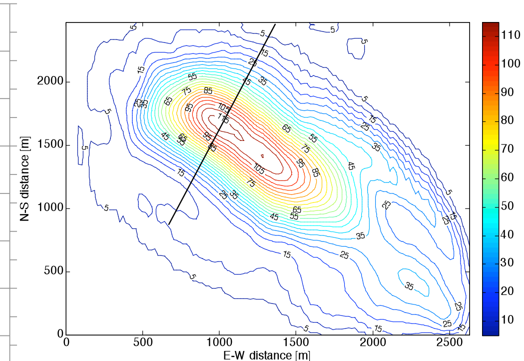
WindNinjawas initialized using:

- The wind speed at the reference station (10 m AGL)

Models validation (cross-hill)

- Comparison between the wind speed simulated by the WRF-LES, WindNinja, UU LES, FDS and measured during Askervein '83 experiment along the short hill axis 'A'.

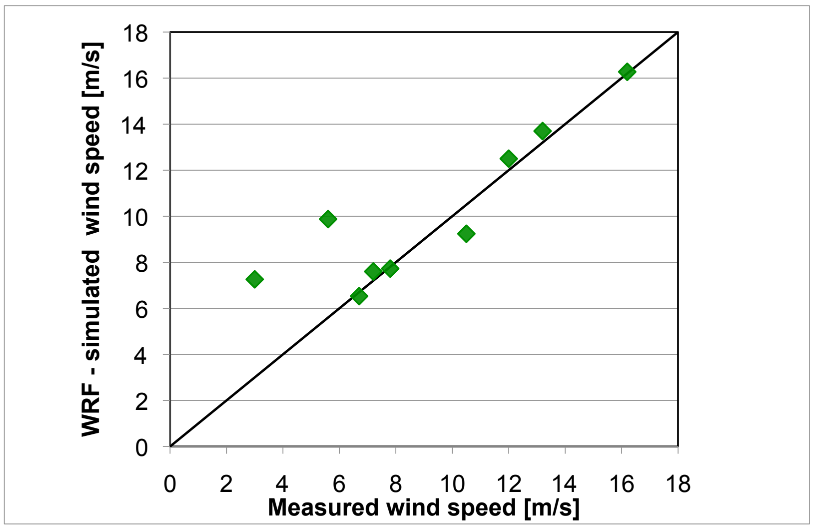




Models validation (WRF and UU LES)

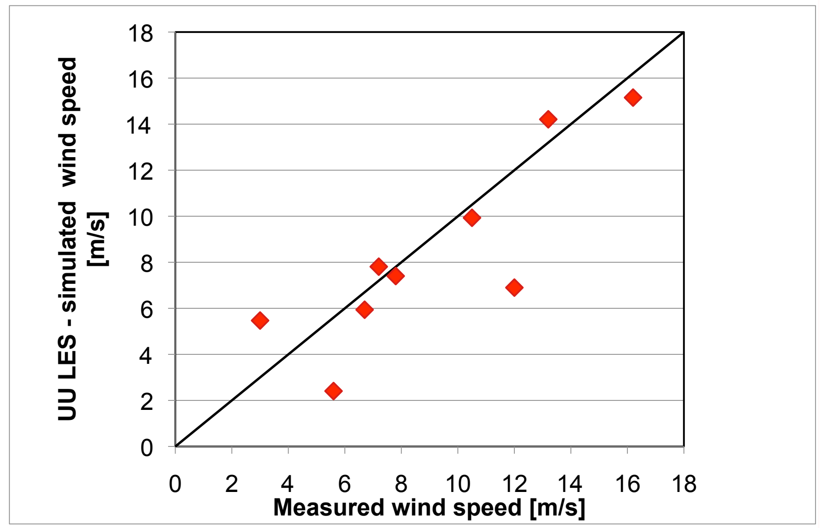
- Scatter plots of measured and simulated wind speeds across the hill (along ‘A’ axis), for the WRF-LES and UU LES.

WRF-LES



Correlation coefficient: R=0.88
Mean Absolute Error: MAE=1.34 m/s

UU LES

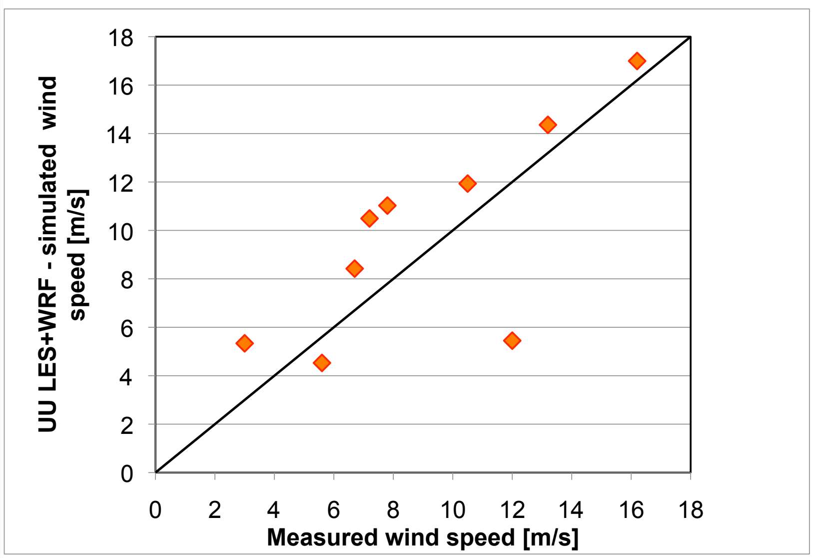


Correlation coefficient: R=0.85
Mean Absolute Error: MAE=1.62 m/s

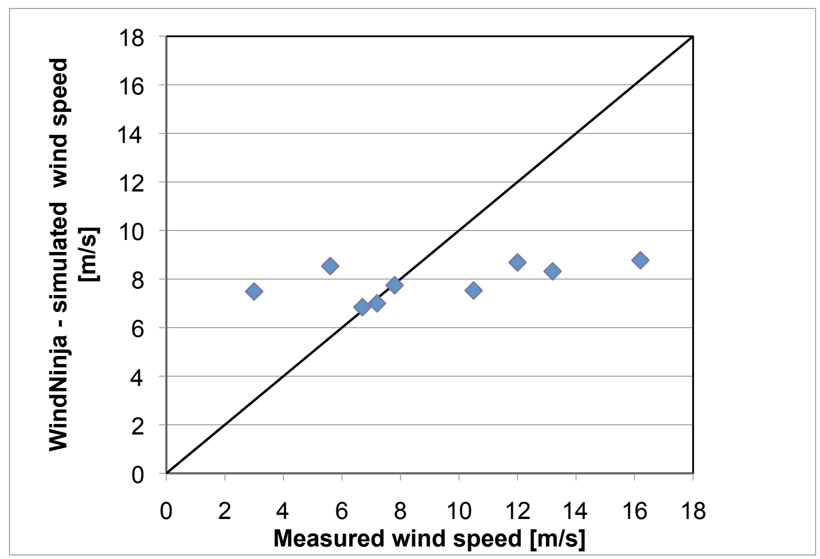
Models validation (FDS and WindNinja)

- Scatter plots of measured and simulated wind speeds across the hill (along ‘A’ axis), for the WindNinja and the FDS

FDS



WindNinja



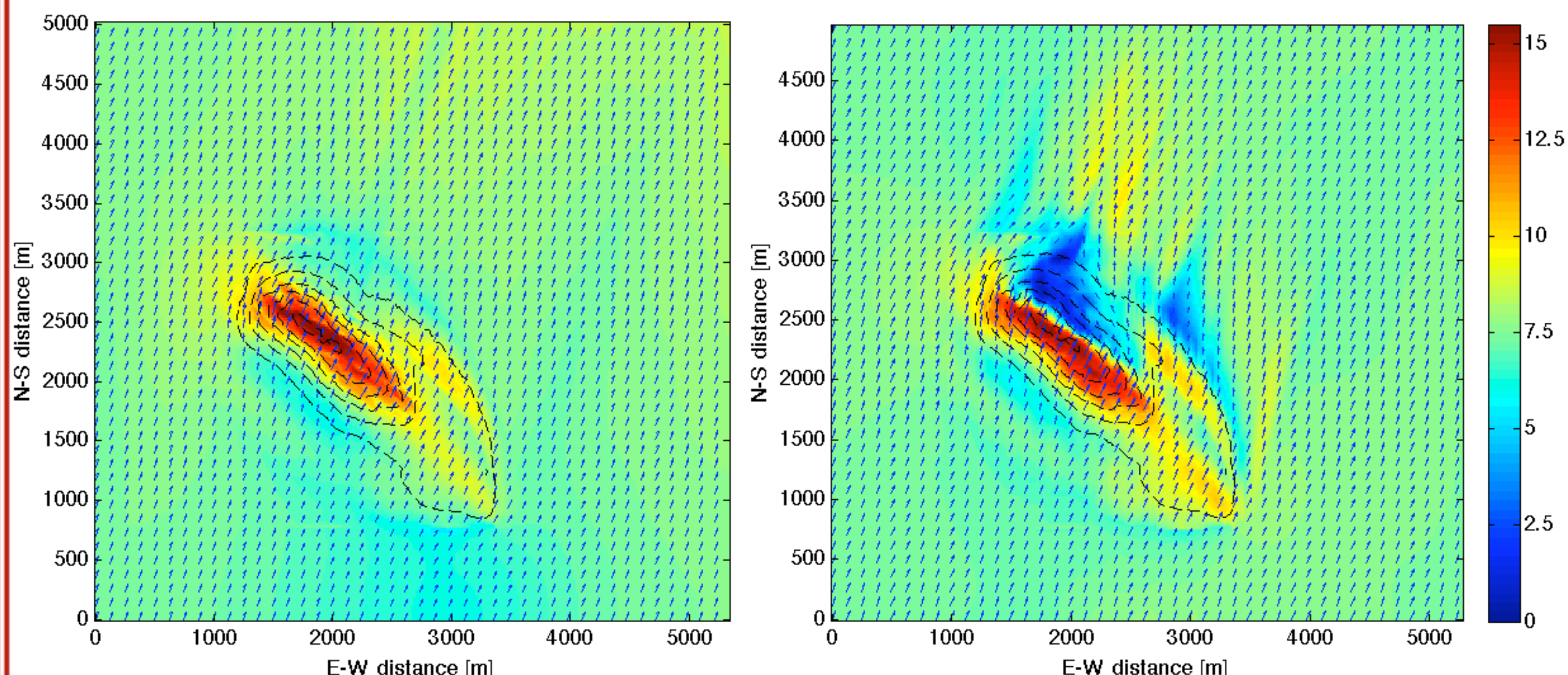
Correlation coefficient: R=0.74
Mean Absolute Error: MAE=2.07 m/s

Correlation coefficient: R=0.60
Mean Absolute Error: MAE=2.93 m/s

Simulated mean surface flow for WRF-LES and UU-LES

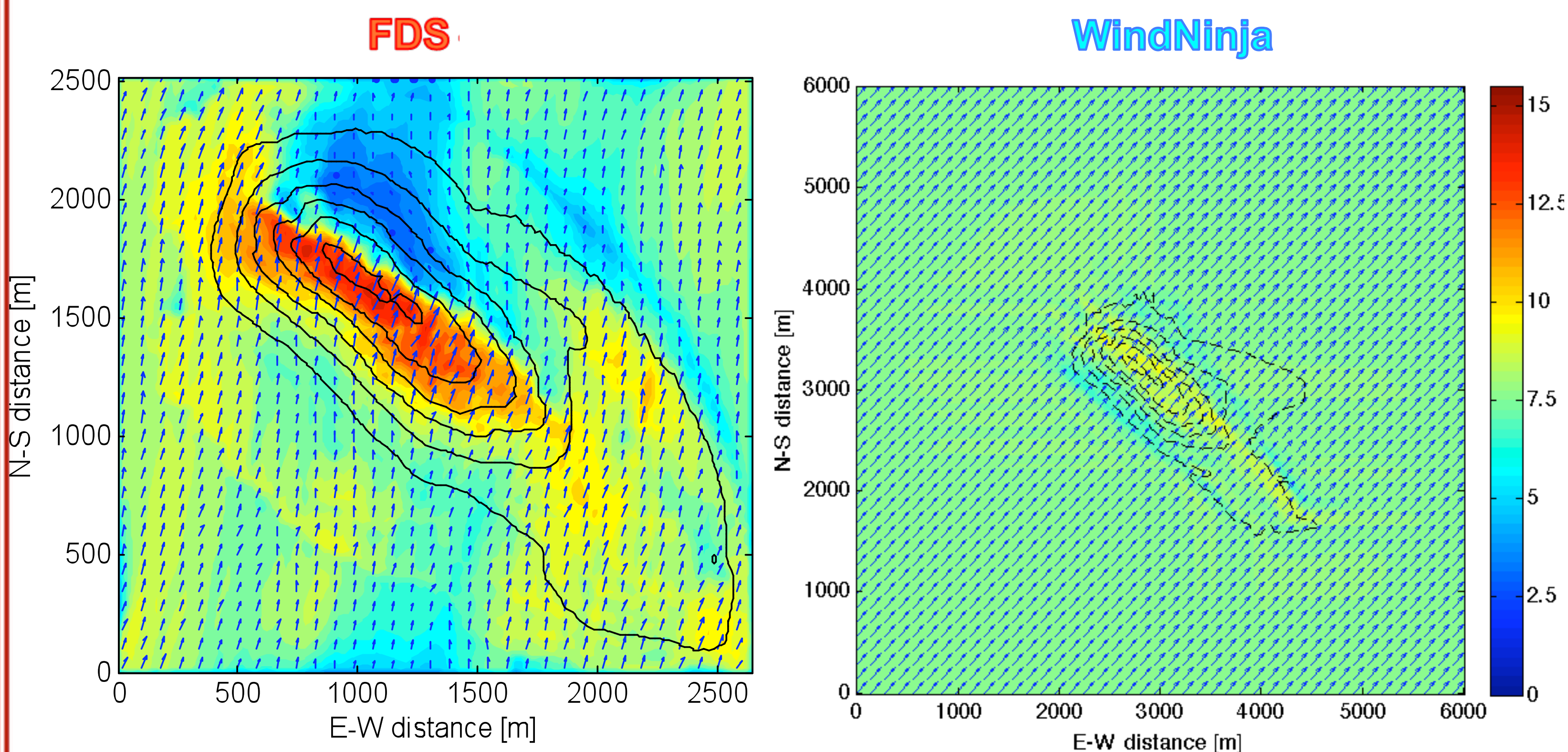
- Mean wind vectors at 10 m above the ground level with color coded wind speed [m/s], and topography contour for WRF-LES and UU LES

WRF-LES **UU LES**



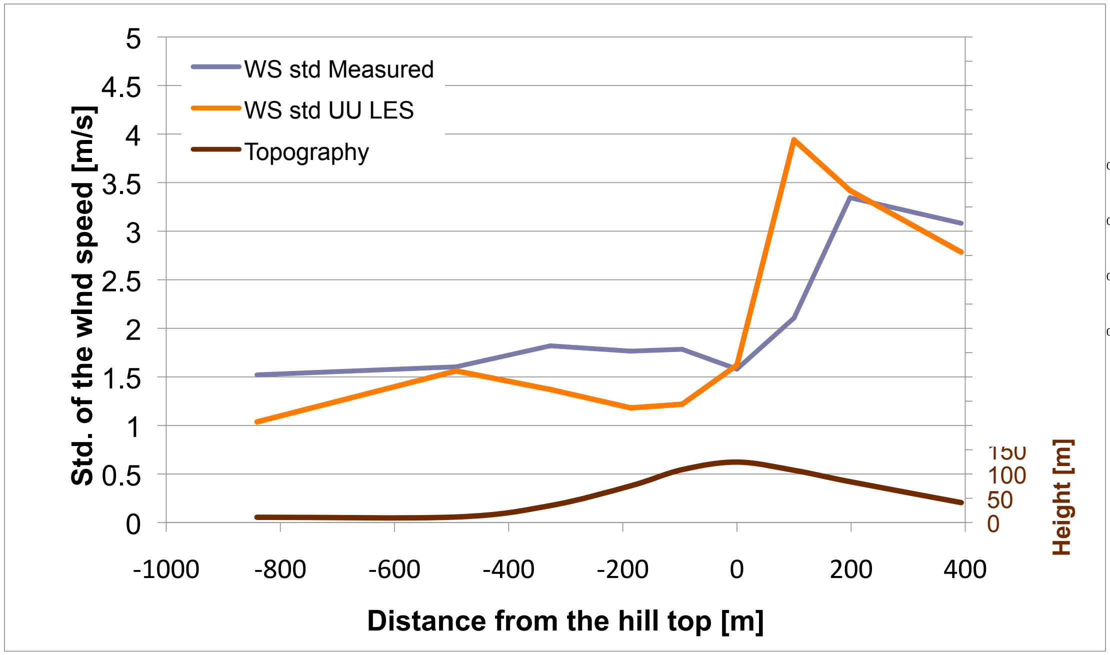
Simulated mean surface flow for the FDS and WindNinja

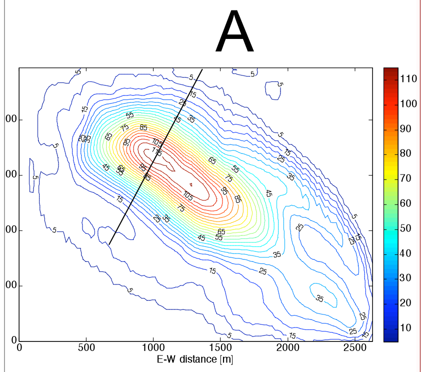
- Mean wind vectors at 10 m above the ground level with color-coded wind speed [m/s]



Wind speed fluctuations across the hill

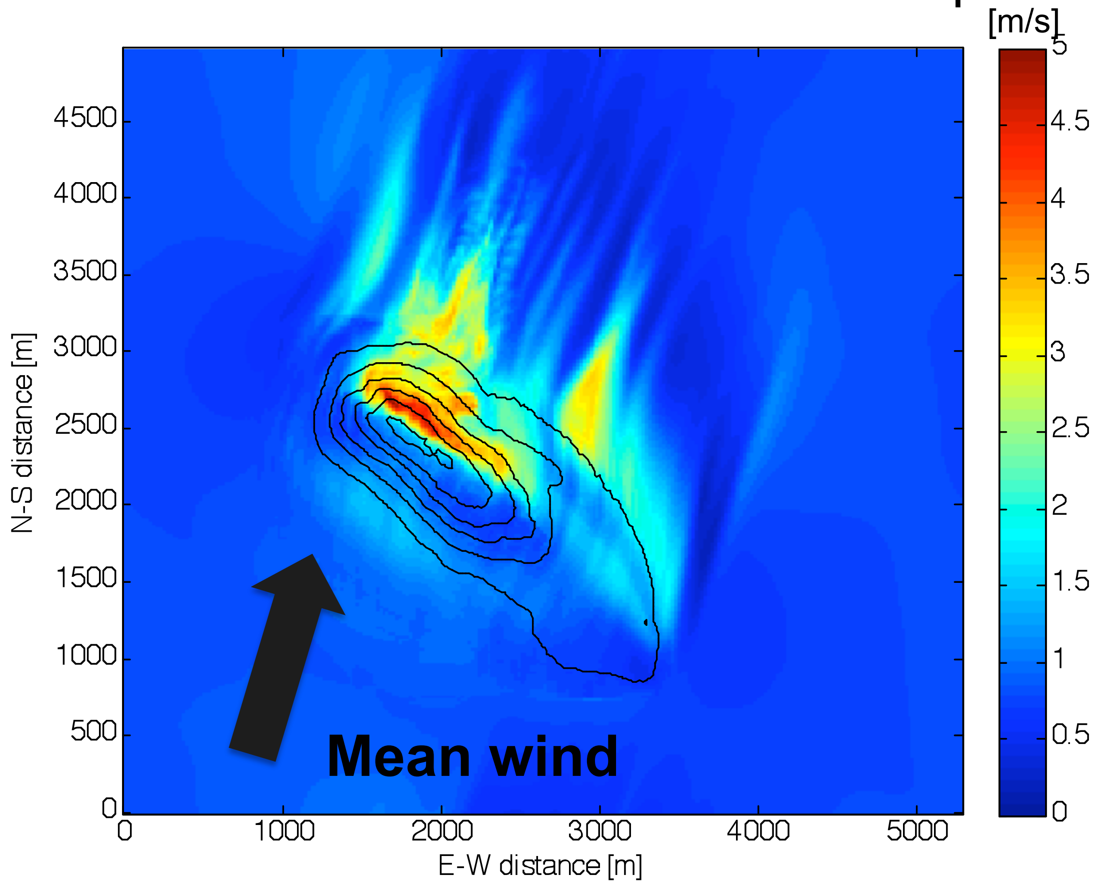
- Standard deviation of the LES-simulated wind speed for measurement points located on the short hill axis ‘A’.





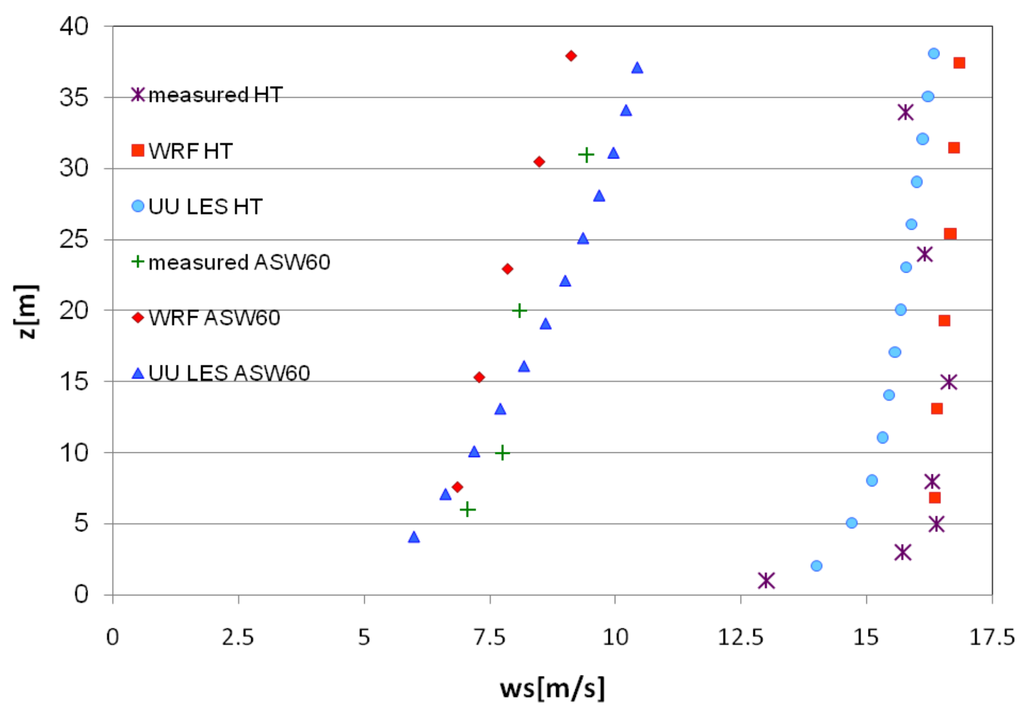
Simulated wind speed variability

Standard deviation of the LES-simulated wind speed at 10 m AGL



Analysis of the vertical wind profiles

- Simulated vs. observed wind profiles for the tower located 60 m ahead of the hill top (ASW60) and the hill top (HT)

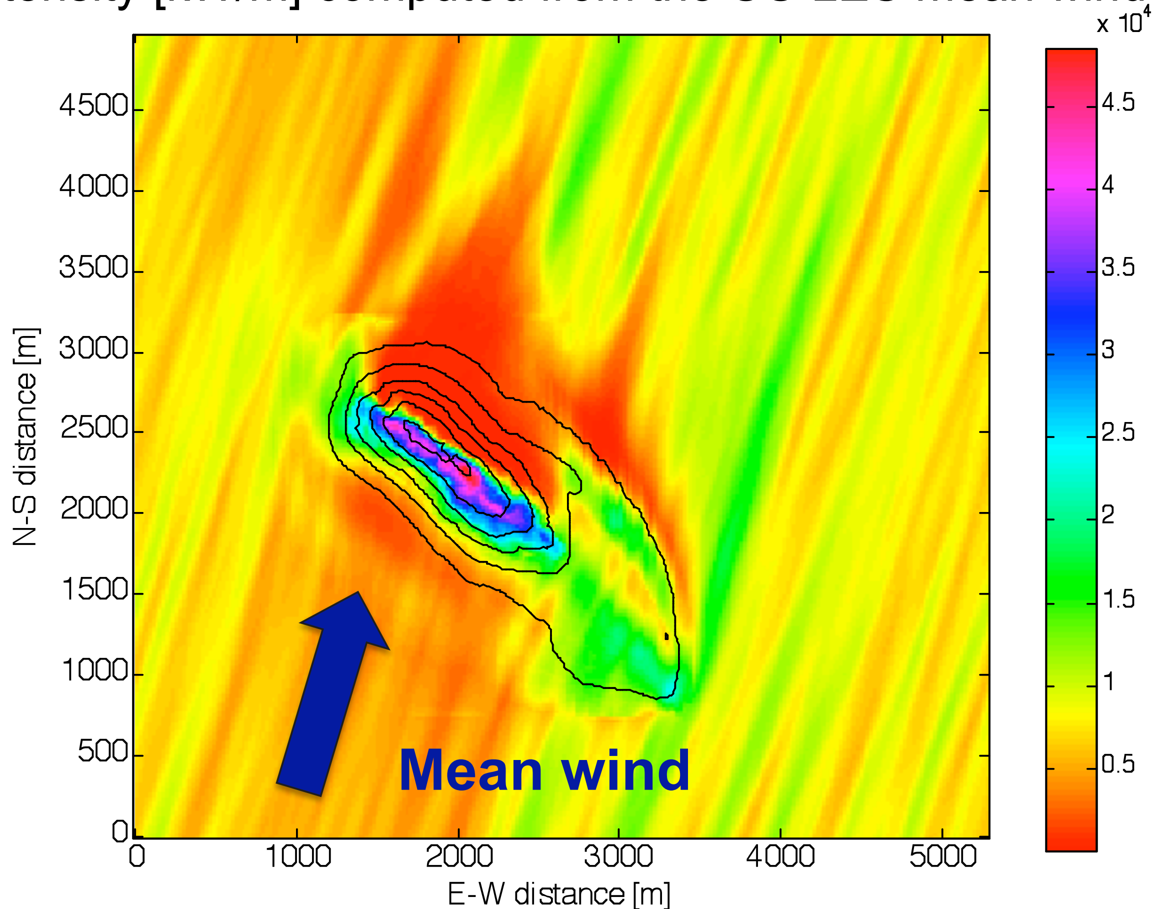


Quite a good agreement for the windward side (ASW60)

Evident discrepancies at the hill top where the speed is maximal

Simulated fireline intensity

Fireline intensity [kW/m] computed from the UU LES mean wind field at 10m



Summary

- All the CFD-based models (WRF-LES, UU LES, FDS) showed characteristic wind speed up on the windward slope and deceleration on the leeward side of the hill
- The WRF-LES overestimated the wind speed on the leeward side, while the UU LES and FDS underestimated it, as a consequence the ensemble average of WRF-LES and UU LES gives the best wind speed prediction with R=0.93 and MAE=1.09 m/s
- The deceleration on the leeward side of the hill is more rapid for the UU LES and FDS, than for the WRF-LES. One of possible reasons for that may be the Cartesian coordinate system used in UU LES and FDS vs. smooth, terrain following coordinate system implemented in WRF.
- Different lateral boundary conditions used by the WRF-LES and the UU LES and FDS, may also affect the simulation. Open boundary conditions used by the WRF-LES evidently reduces the turbulence in vicinity of inflow boundaries (south and west).
- We are on a good track, tested CFD-based models performs well in complex terrain, however simulation of the fully-developed turbulent flow downstream of the hill top is still a challenge.
- More field studies as well as direct numerical simulations are required to fully understand deficiencies of the currently used LES models in case of fully developed turbulen flows in complex terrain.

Thank you!

- Questions?