Nesting large-eddy simulations within mesoscale simulations in WRF for wind energy applications

Julie K. Lundquist

Jeff Mirocha, Branko Kosović

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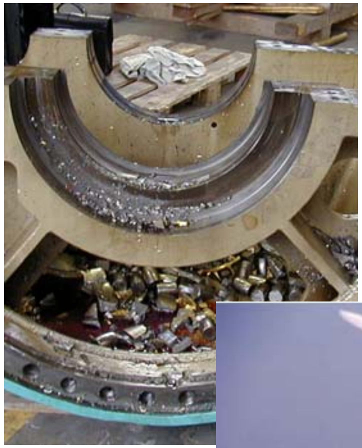
Lawrence Livermore National Laboratory

Accurate meteorological forecasts can maximize power generated from the wind, a clean and renewable energy source

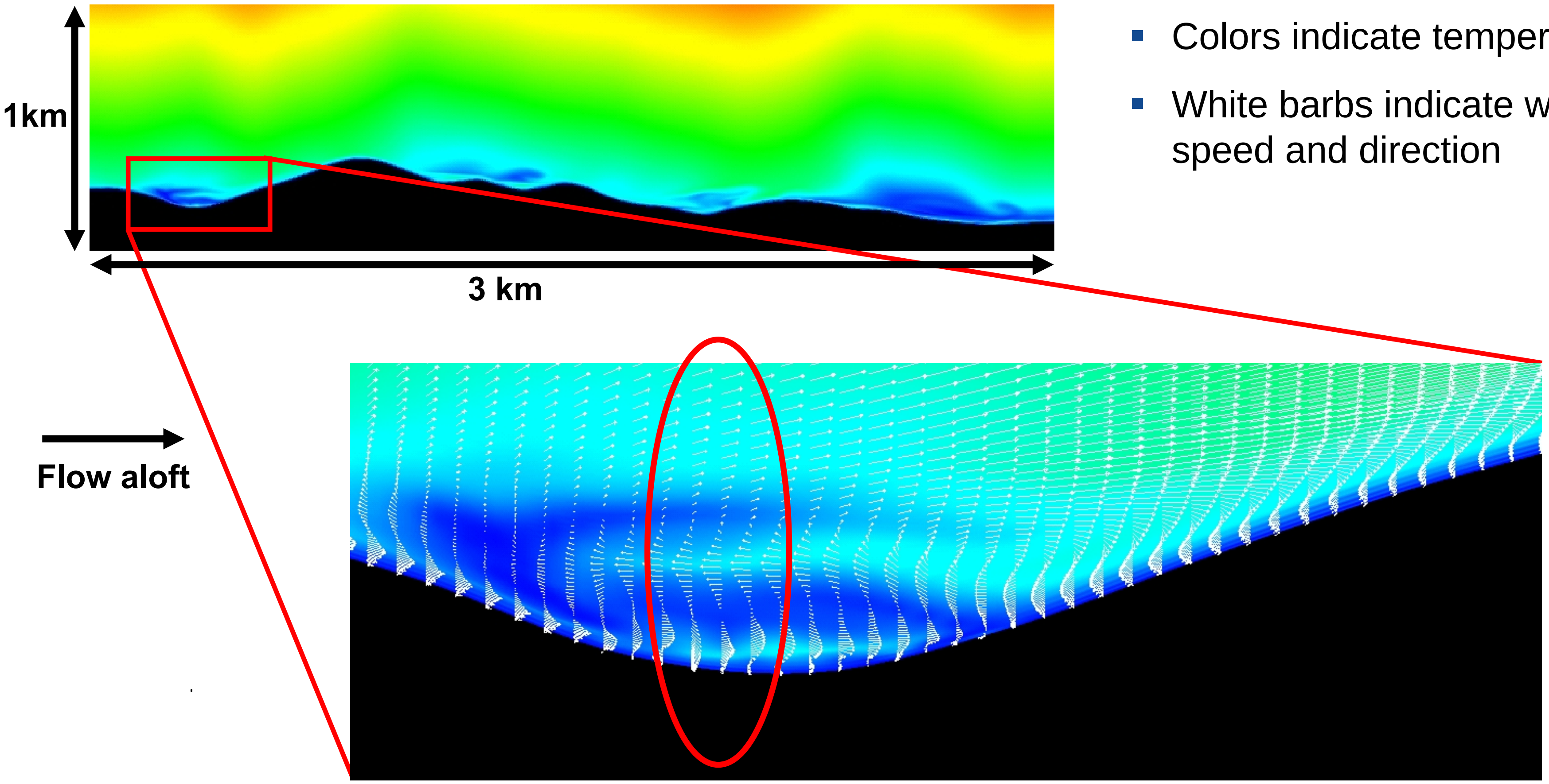
- **Turbine design** – what “inflow” characteristics affect large structures? (LES)
- **Wake Effects** – how does the atmosphere modify the wakes which cause “downwind” turbines to collect less energy than upwind turbines? (LES)
- **Turbine siting and resource assessment** in complex terrain – what locations are optimal for maximizing wind and minimizing turbulence? (LES-mesoscale)
- **Operational forecasting** – how can wind park owners and power grid operators anticipate wind energy to balance power supply and demand? (mesoscale with LES-based wind farm parameterizations)



Premature fatigue of a turbine’s main shaft bearing, courtesy S. Schreck, NREL

Large-eddy simulation can represent very local effects due to topography or stratification as experienced by individual eddies

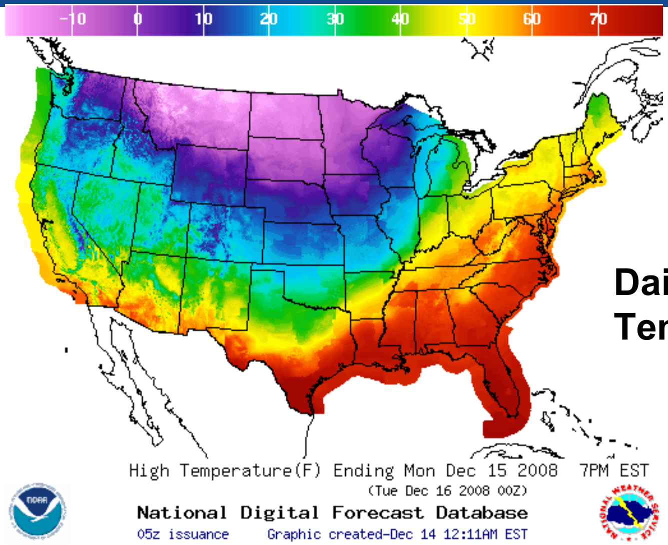
- Colors indicate temperature
- White barbs indicate wind speed and direction



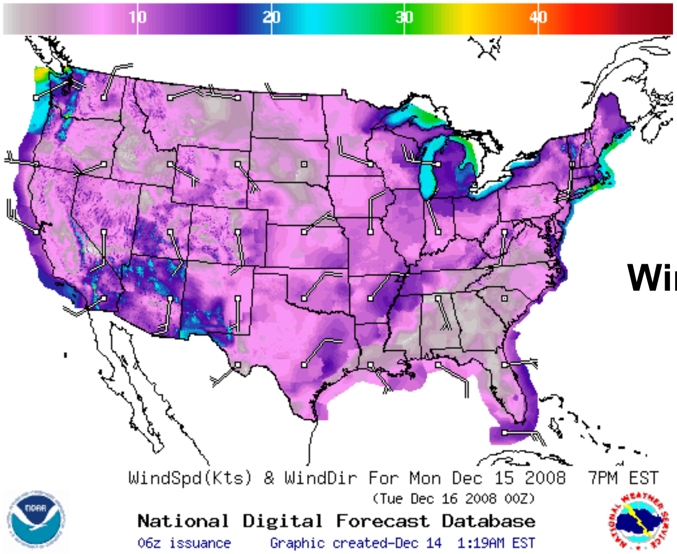
Flow reverses direction twice above the surface in this valley!

Mesoscale numerical weather prediction models excel at predicting “weather”

- Mesoscale models capture the evolving pressure gradients over regions ~ 1000s of km
- Historically, mesoscale model evaluations and improvements have focused on surface temperature and precipitation improvements, not winds in the lowest 200m
- Mesoscale boundary-layer parameterizations have least predictive capability in stable conditions, complex terrain, or over complex and varied surfaces



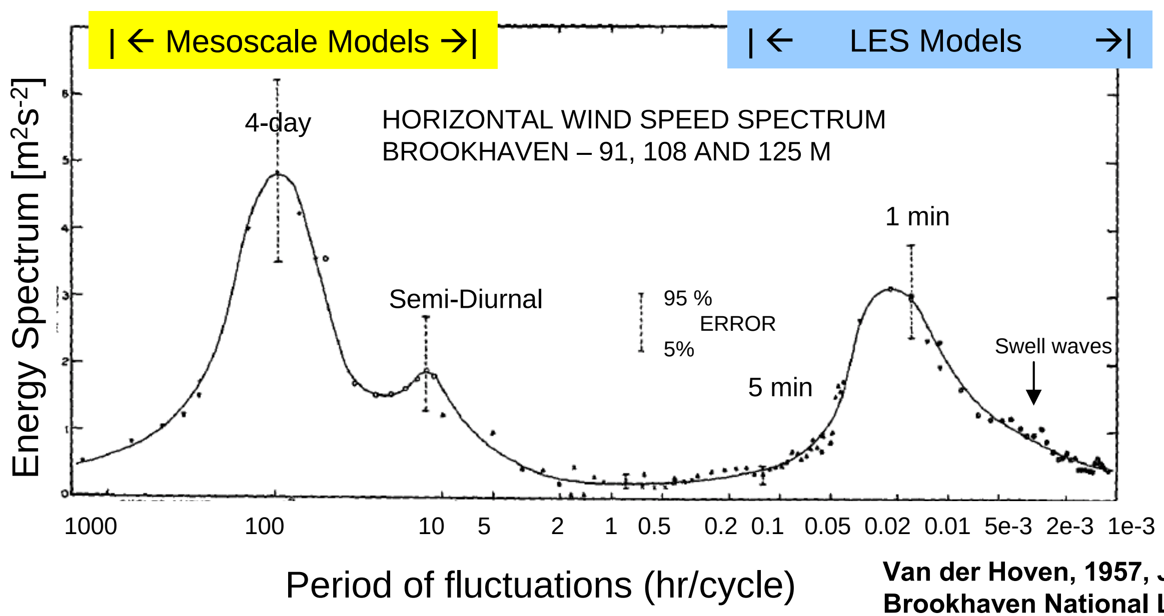
Daily High Temperature



Winds

Nesting large-eddy simulations within mesoscale simulations utilizes the strengths of each

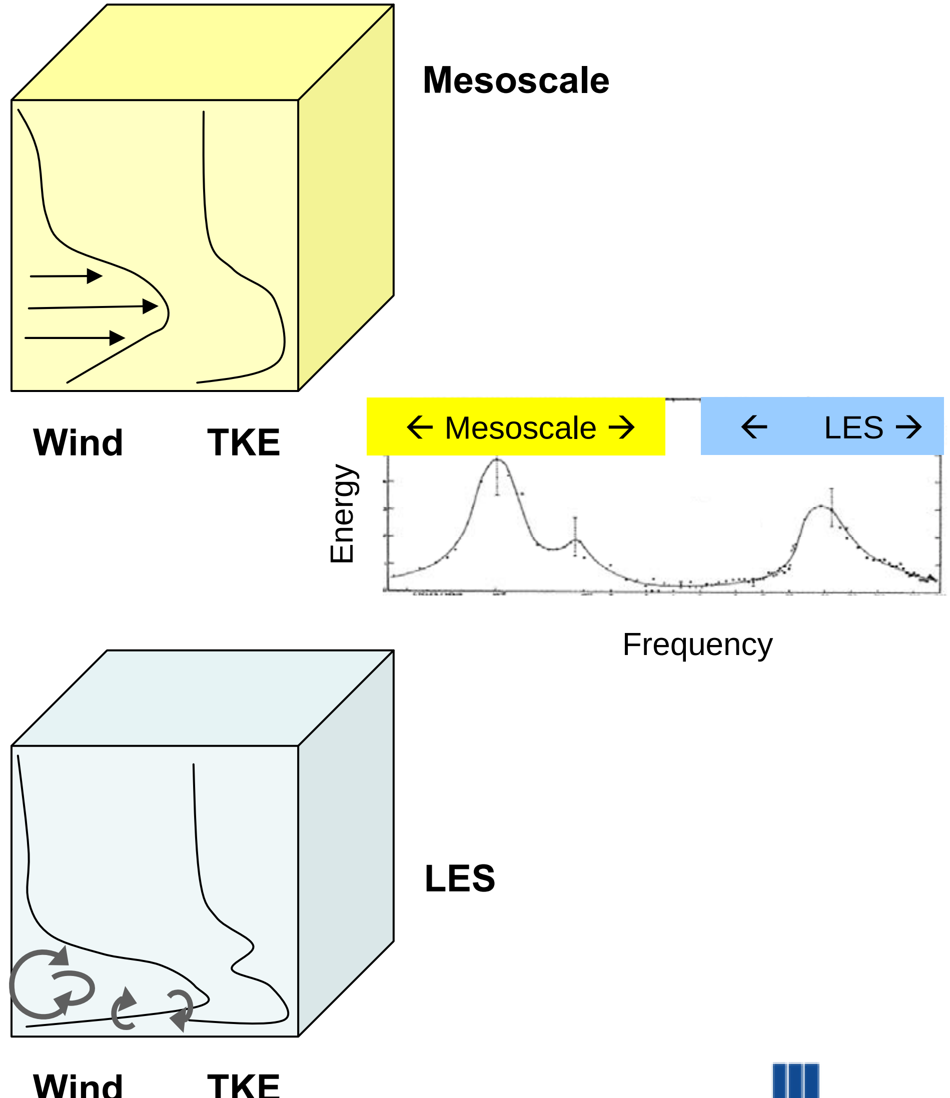
- Large-eddy simulation (LES) represents micro-meteorological turbulence more exactly by representing full spectrum of turbulence
- Although WRF 3.0.1 provides two subfilterscale turbulence models, several others have been developed and/or implemented at LLNL for use in WRF LES capability (see Kirkil et al. poster, P2B.2)
- A robust LES model can provide guidance to improving mesoscale parameterizations



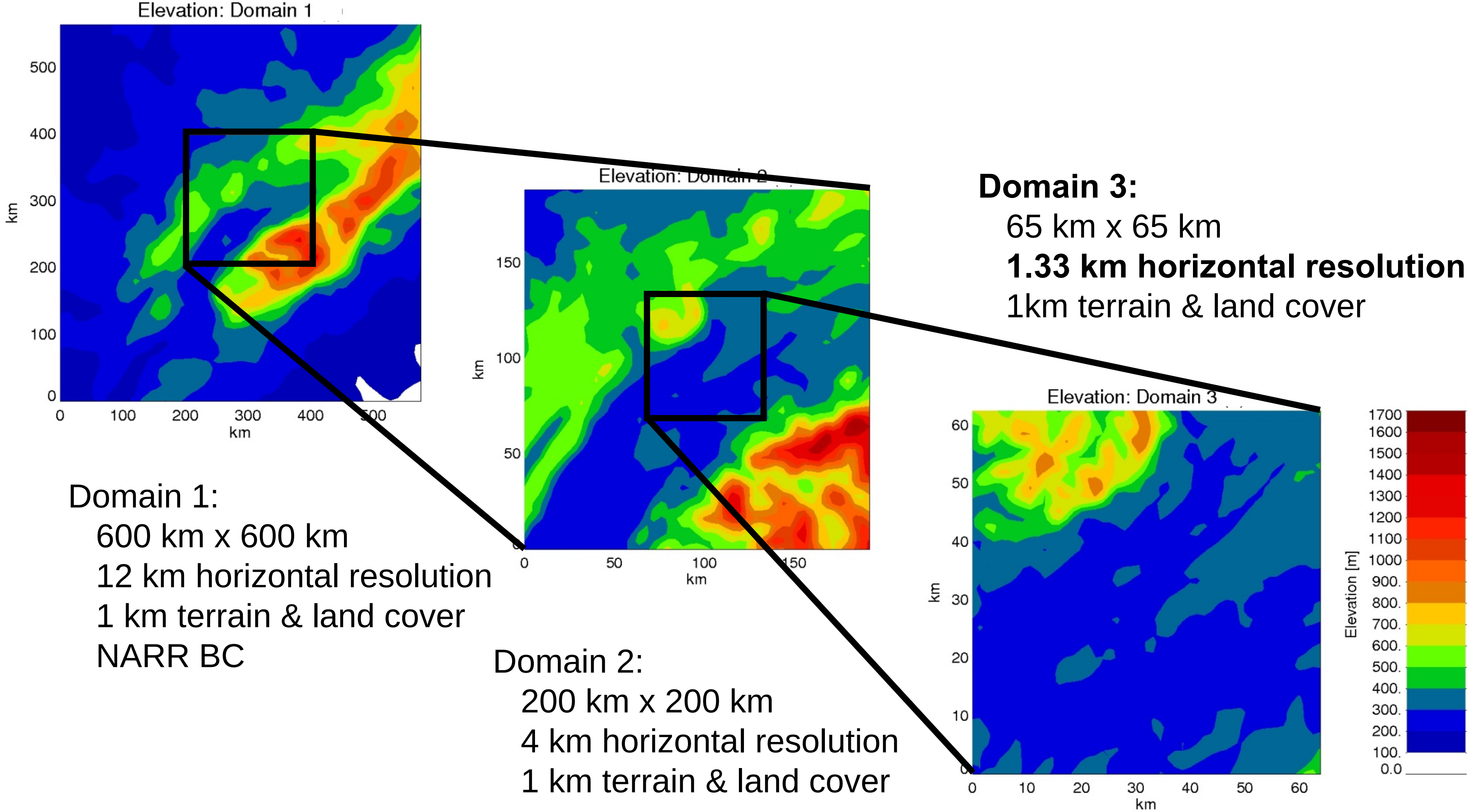
Van der Hoven, 1957, *JAM,* based on data from Brookhaven National Lab at 90-125m height

But this nesting must be addressed with care

- **One-way** or two-way nesting?
- Is the representation of terrain appropriate (see K.A. Lundquist et al., Thursday @ 2:15, talk 6.4)?
- Which PBL scheme is more appropriate?
  - MYJ provides “TKE”, but that means different things to mesoscale and to LES
- Does the LES represent the turbulence spectrum appropriately? (See previous talk, Mirocha et al.)
- Is the subfilterscale model robust to atmospheric conditions (stable conditions)?
- Is the LES sufficiently spun up? Are artificial inertial oscillations present?



Our one-way nesting of LES simulations within mesoscale simulations is initialized with three mesoscale nests



Domain 1:
- 600 km x 600 km
- 12 km horizontal resolution
- 1 km terrain & land cover
- NARR BC

Domain 2:
- 200 km x 200 km
- 4 km horizontal resolution
- 1 km terrain & land cover

Domain 3:
- 65 km x 65 km
- **1.33 km horizontal resolution**
- 1km terrain & land cover

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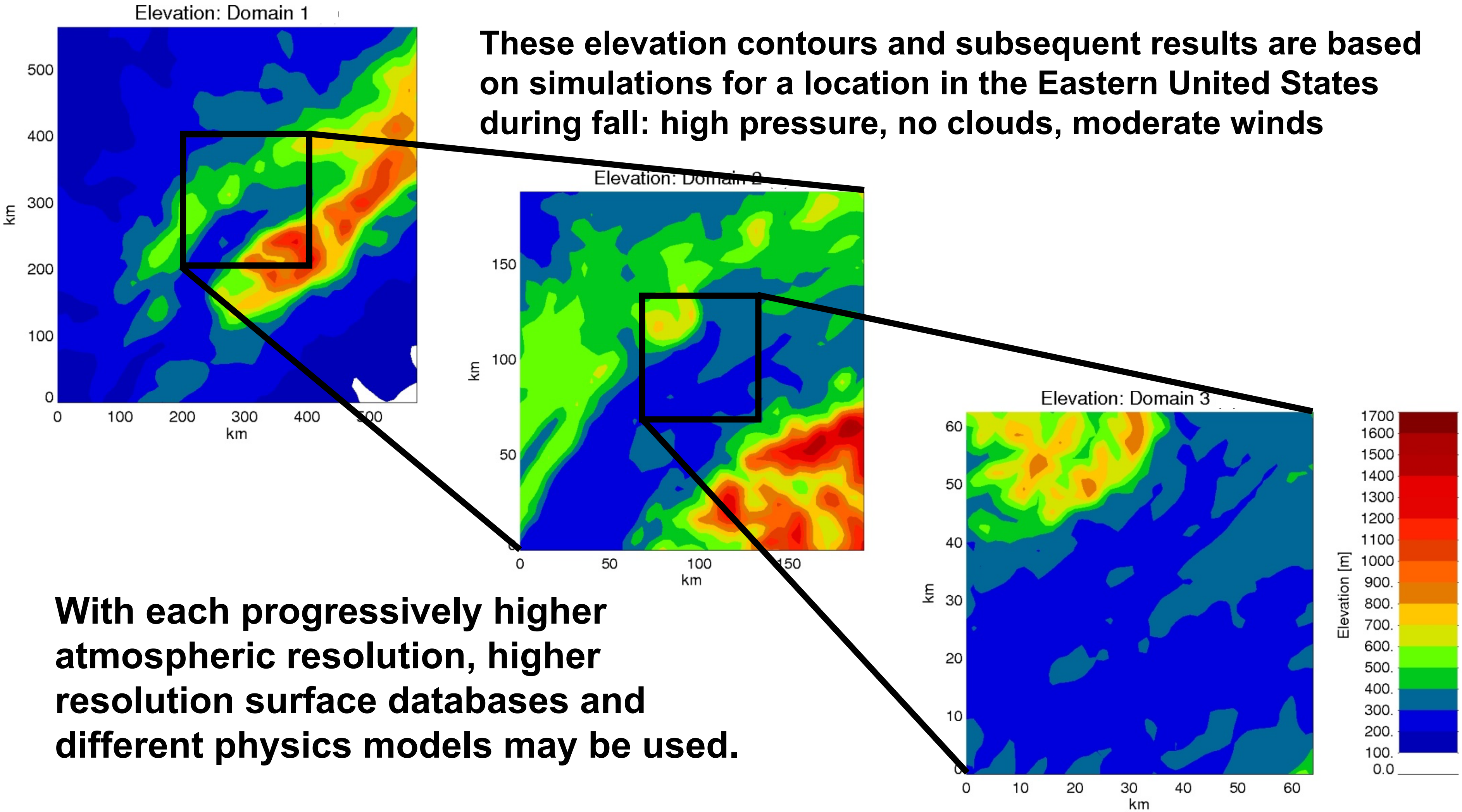
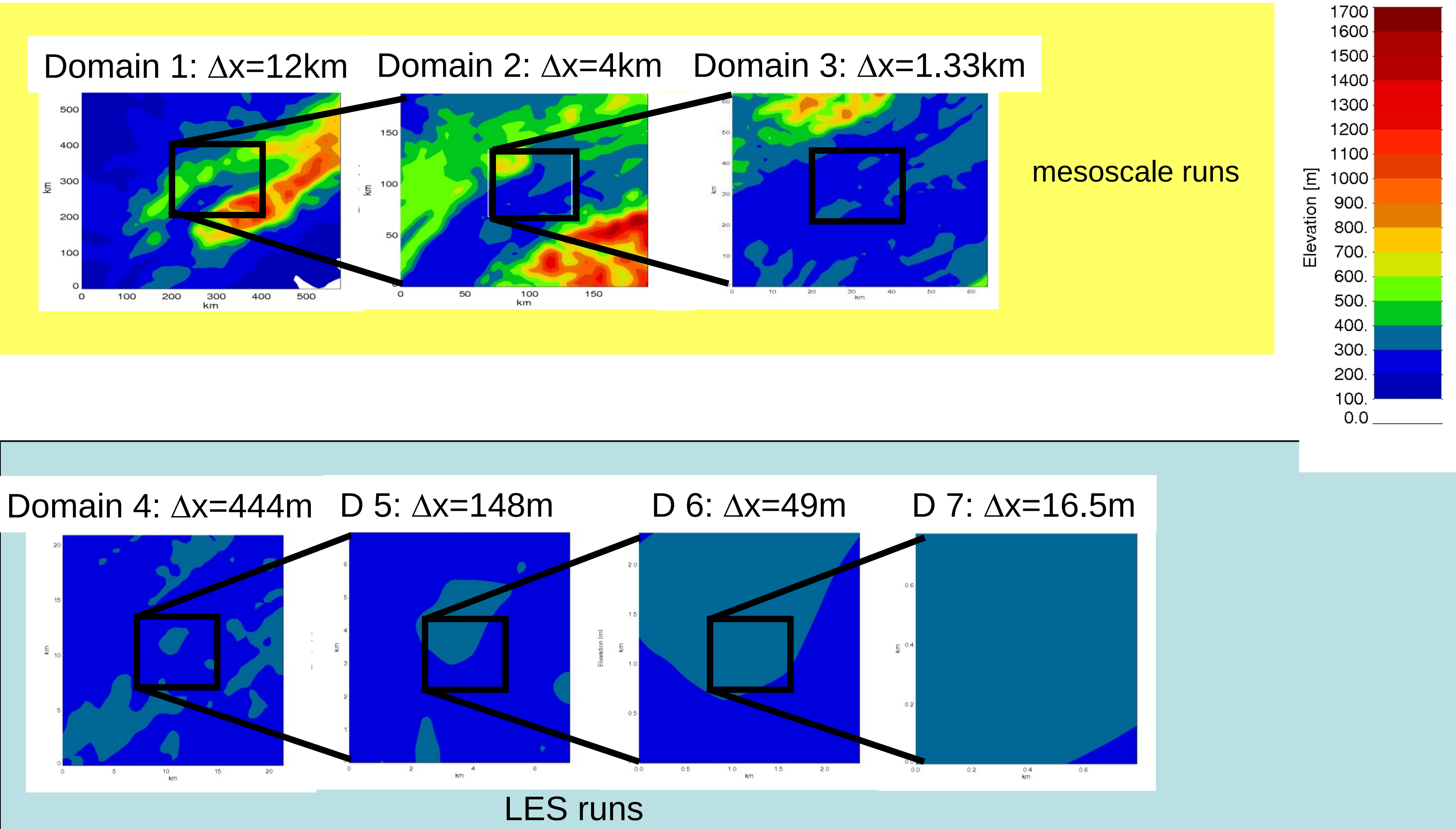
These elevation contours and subsequent results are based on simulations for a location in the Eastern United States during fall: high pressure, no clouds, moderate winds



With each progressively higher atmospheric resolution, higher resolution surface databases and different physics models may be used.

Results shown here are from a series of seven nested simulations with complex terrain in mesoscale, complex slopes in LES



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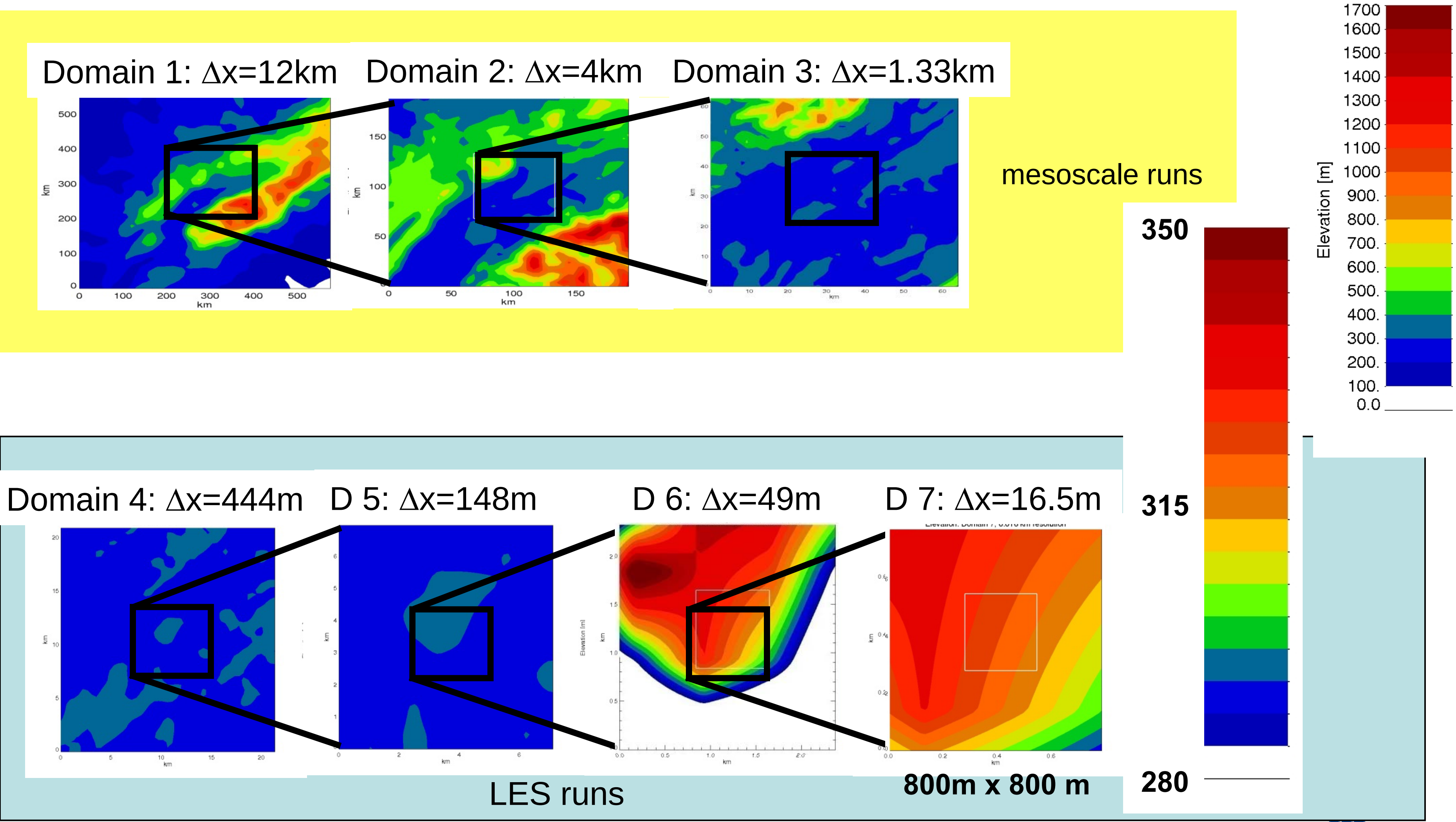
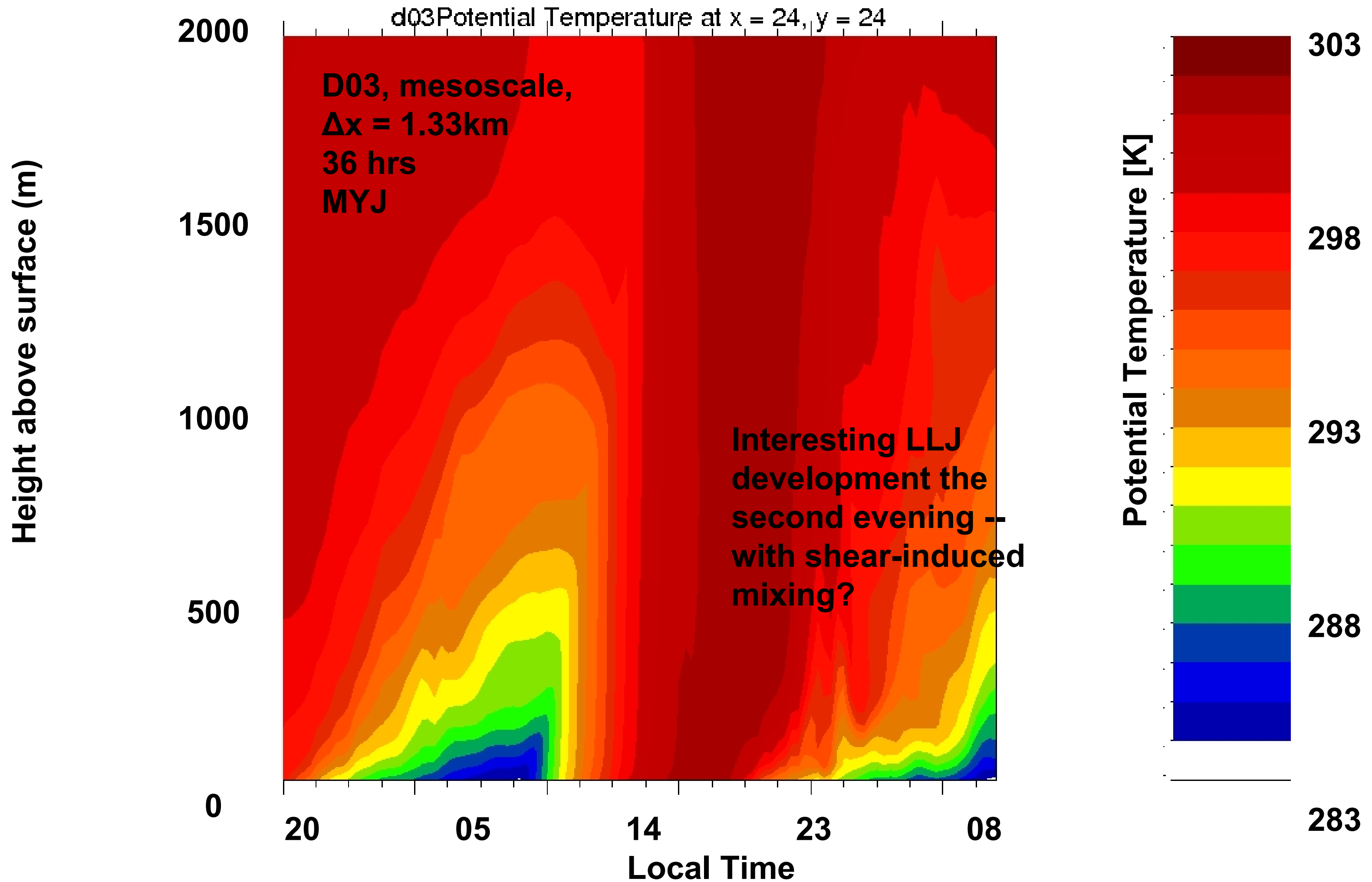
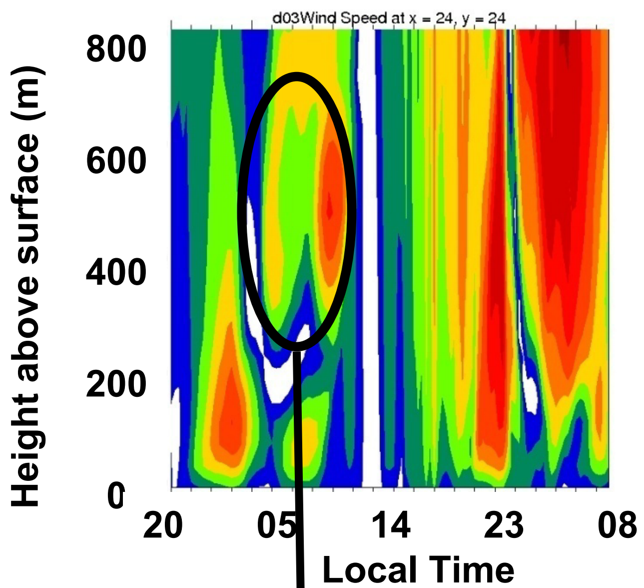


Time-height cross sections from the center of each domain enable comparison of mesoscale and LES simulations

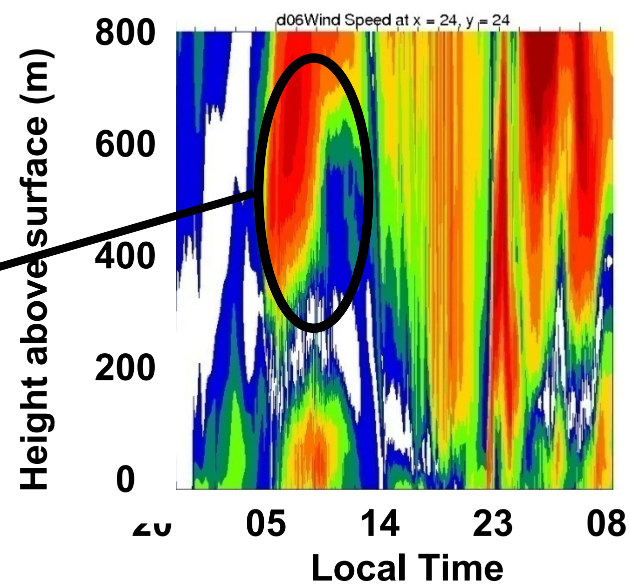


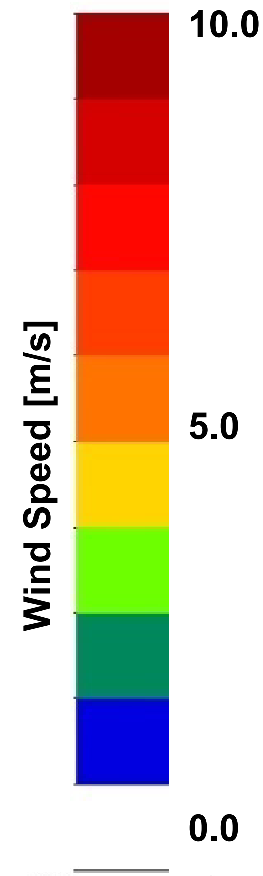
LES winds differ from mesoscale winds in both timing and intensity – the increased resolution seems to allow for fundamentally different dynamics



D03, mesoscale,
Δx = 1.33km
MYJ
36 hrs

D06, LES,
Δx = 49m
TKE SFS closure
36 hrs





Mesoscale shows winds aloft increasing through the morning, while LES shows a decrease aloft

LES winds differ from mesoscale winds in both timing and intensity – the increased resolution seems to allow for fundamentally different dynamics

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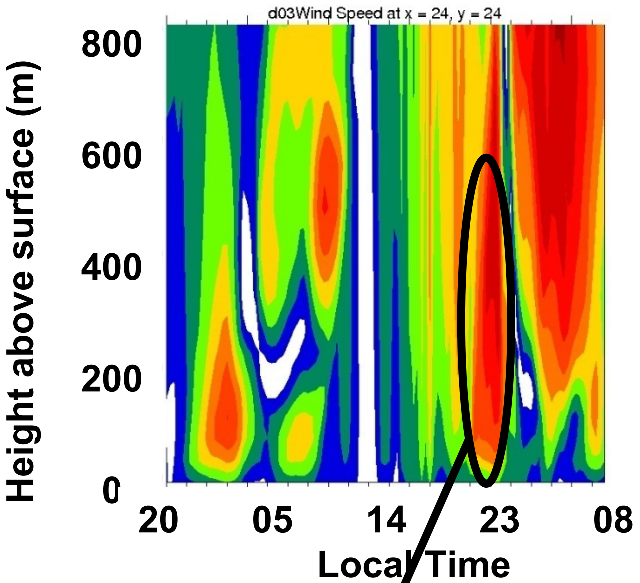

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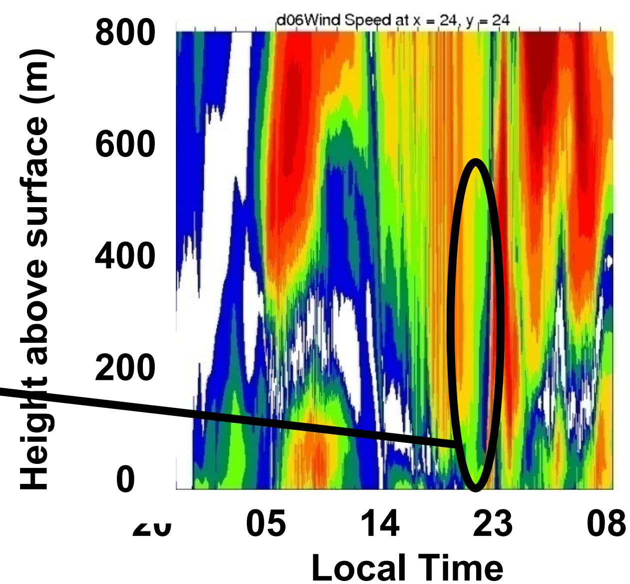
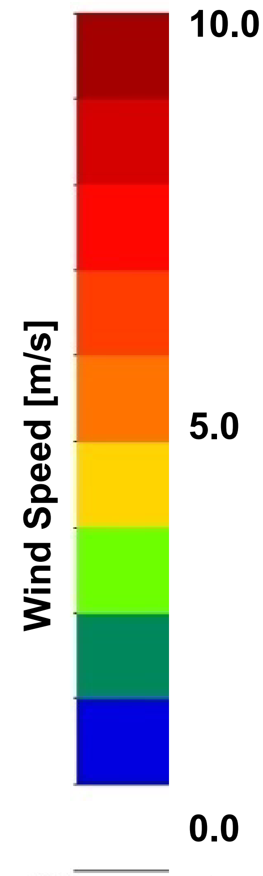
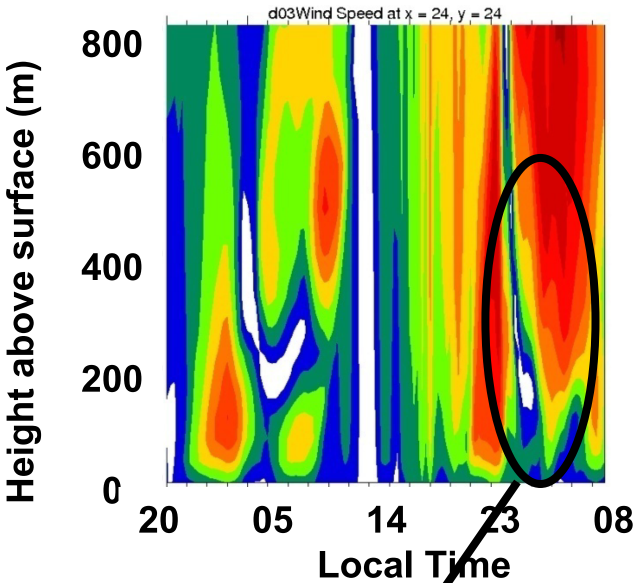




LES shows increased variability in early LLJ development with quiescent period early and delayed onset of stronger winds

LES winds differ from mesoscale winds in both timing and intensity – the increased resolution seems to allow for fundamentally different dynamics



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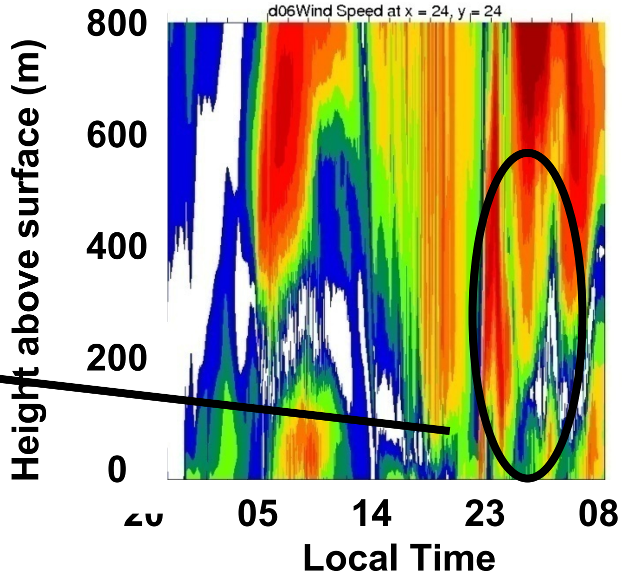
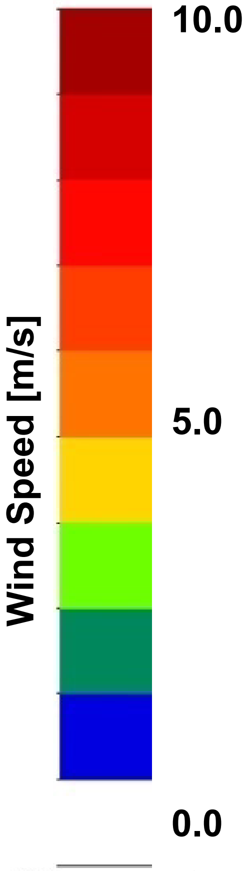
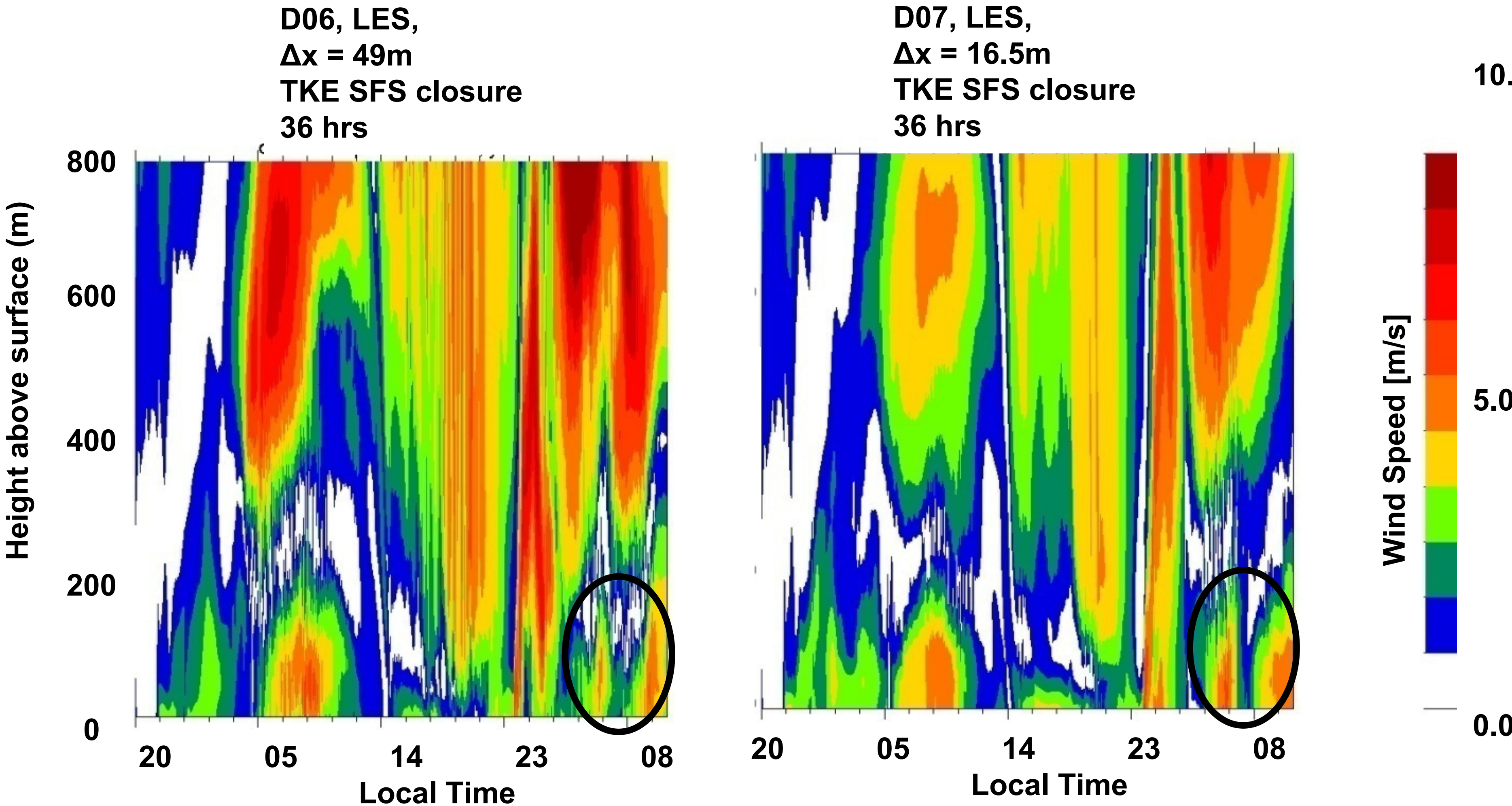


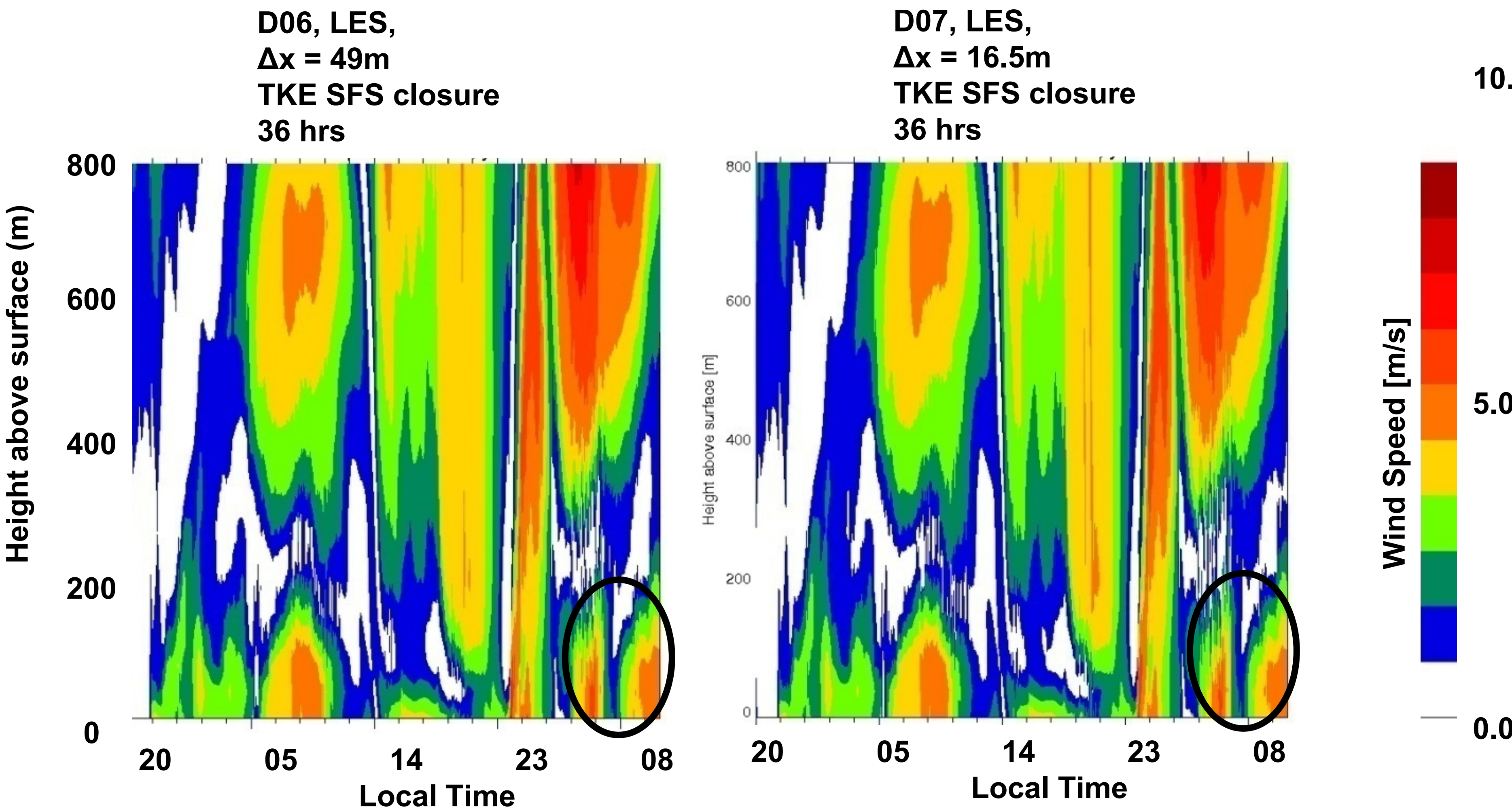


LES suggests LLJ does not propagate below 200m through most of the night, in contradiction to mesoscale prediction

Comparison of two LES domains indicates different representations of surface-based mixing – finer resolution shows more persistent mixing (for MYJ)



YSU results are strikingly consistent across range of scales – surface-based nocturnal mixing looks almost the same!



Nesting LES within mesoscale simulations can yield a powerful and accurate forecasting tool to enhance power collection from the wind

- Nesting enables consideration of both weather and boundary-layer phenomenon, including topographic effects ~ 10s of meters (although we have smoothed terrain for this example)
- One-way nesting is our preferred approach – two-way nesting seemed to induce nonsensical CFL violations in outer grids
- Caution must be taken:
  - Some PBL schemes provide TKE to inner LES nests, but this could be problematic: YSU results are more scale-independent, probably not because of real variability but because all TKE is LES TKE, not also mesoscale TKE
  - Also be aware of: spurious numerical inertial oscillations (not the real ones), aspect ratio, resolution of entire turbulent specturm,
- Both models (PBL and SFS) should be capable of handling complex terrain, stable conditions, etc. (see 6.4 and P2B.2)
- **Observations *from the site of interest* are vital for validation**

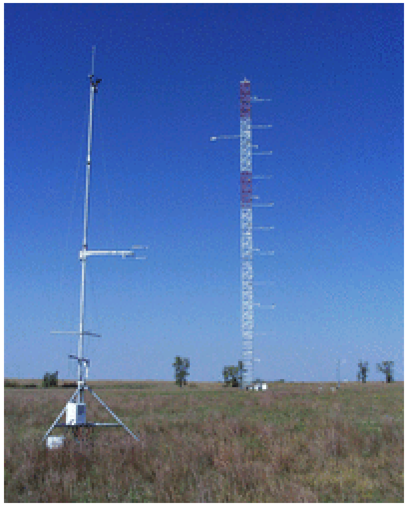
Questions?

Julie K. Lundquist
Atmospheric, Earth, and Energy Division
Lawrence Livermore National Laboratory

lundquist1@llnl.gov
Voice: 925/422-1805

What observations are required for validation of these simulations?

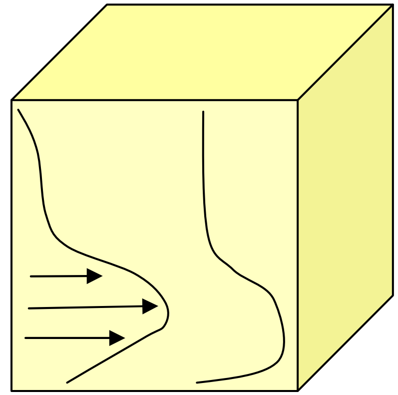
- Simplest: wind profiles upwind of the wind farm
  - Tradeoff between spatial and temporal resolution
  - Ideal observations would ~10m vertical resolution between the surface and 200m at time intervals ~ 1 minute
- Temperature & pressure profiles in the lowest 200m enable characterization of atmospheric stability
- Turbulence measurements (in situ and/or remote sensing) help diagnose if models are correct for the right reason



But limitations of each approach must be addressed with care

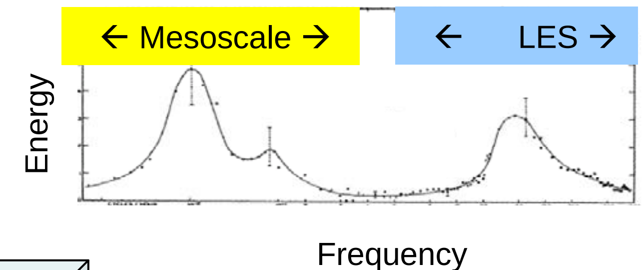
- Mesoscale model:
  - Are you providing appropriate “weather”, including PBL dynamics, to the LES?
  - “TKE” means different things to mesoscale and to LES

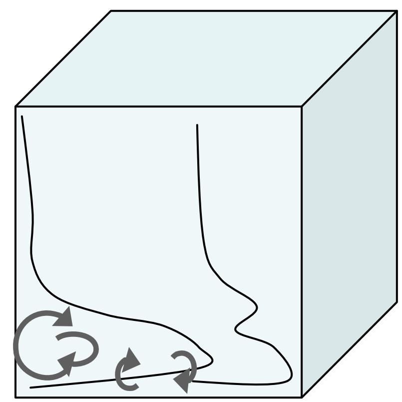
- Large-eddy simulations
  - Does the LES appropriately use the pressure gradients provided by the mesoscale model?
  - Does the LES appropriately use the TKE at the boundary provided by the mesoscale model?
  - How does an LES “spin up” its TKE from the mesoscale TKE?
    — Inertial oscillations
  - Are you using appropriate resolution and aspect ratio?
    — Check turbulence spectra



Mesoscale

Wind **TKE**

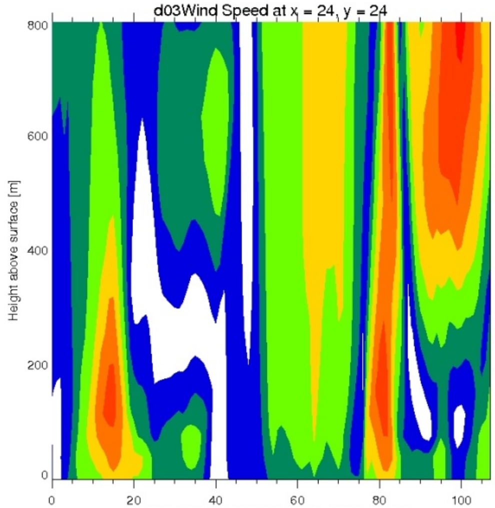


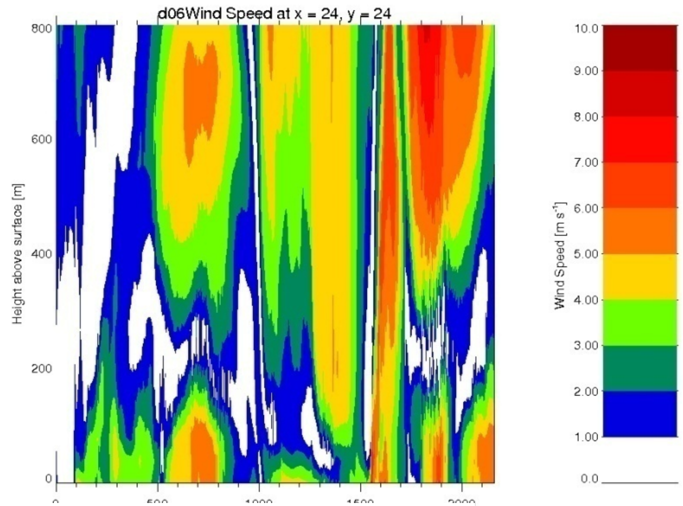


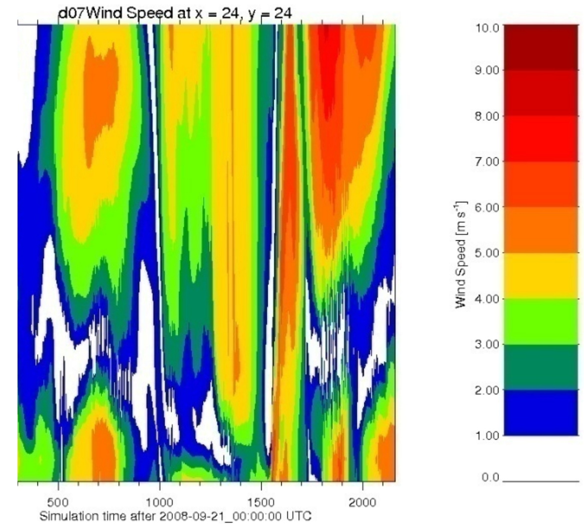
LES

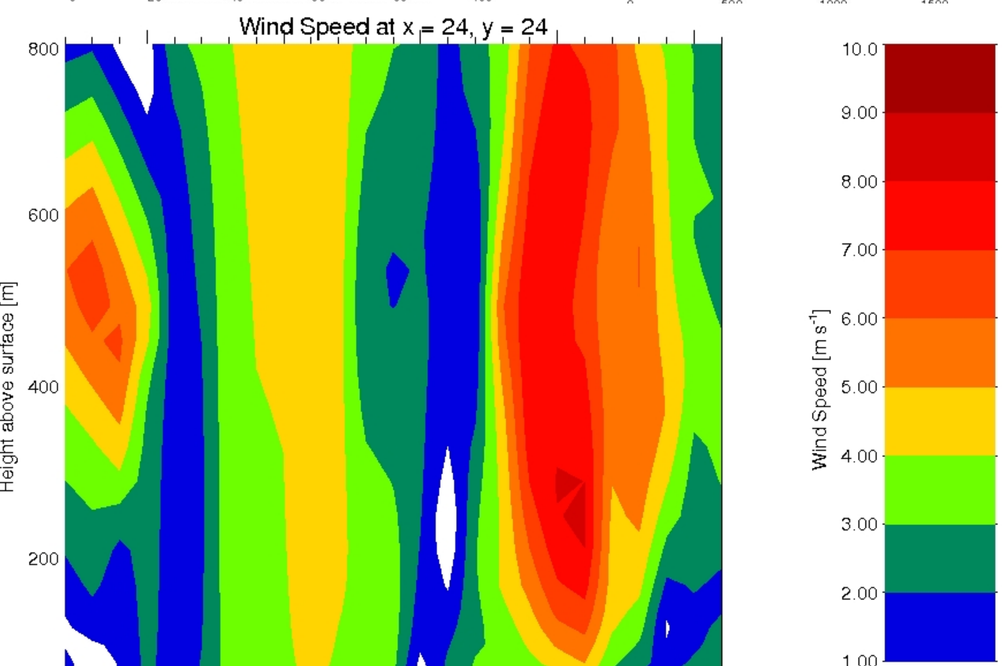
Wind **TKE**

YSU -> TKE Wind Speed



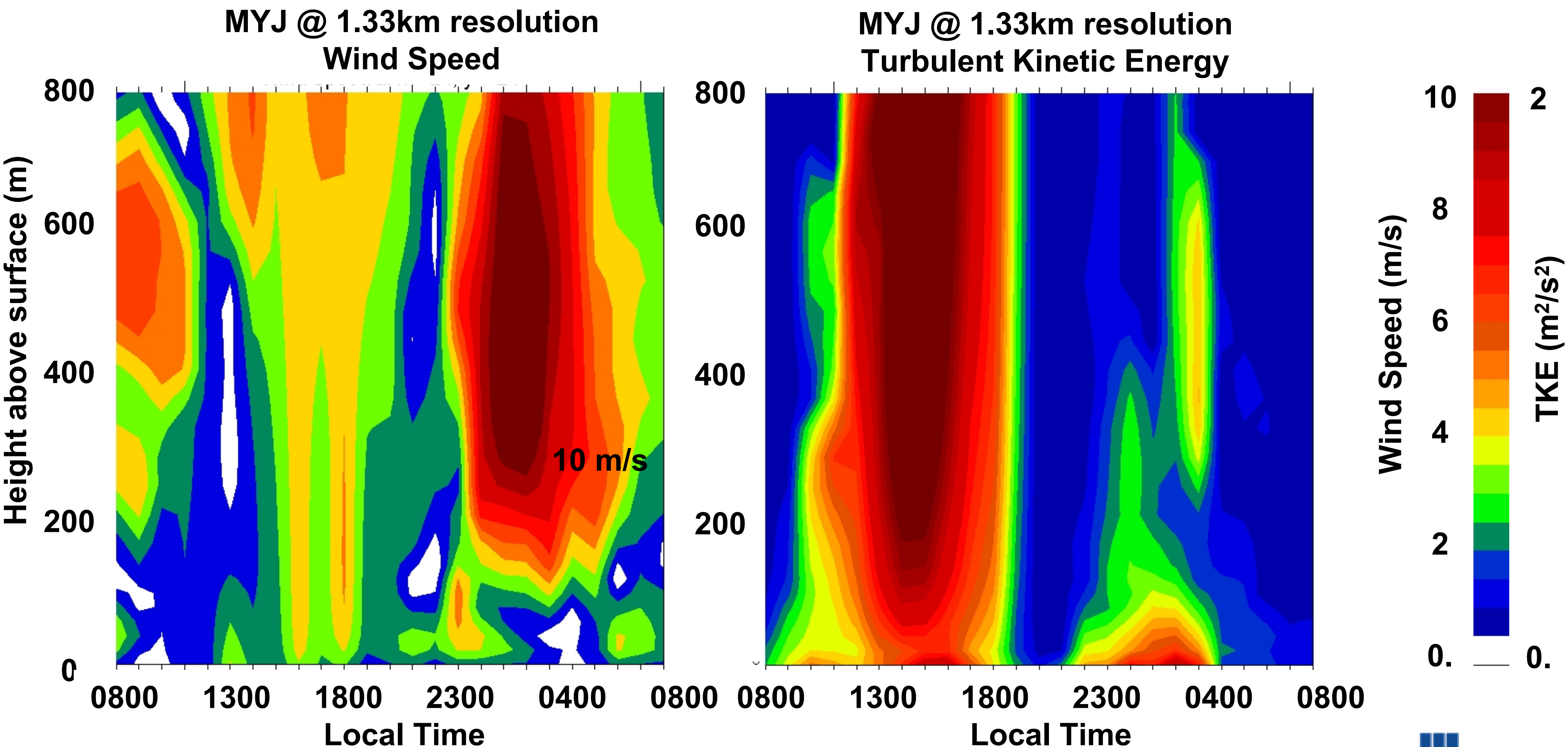






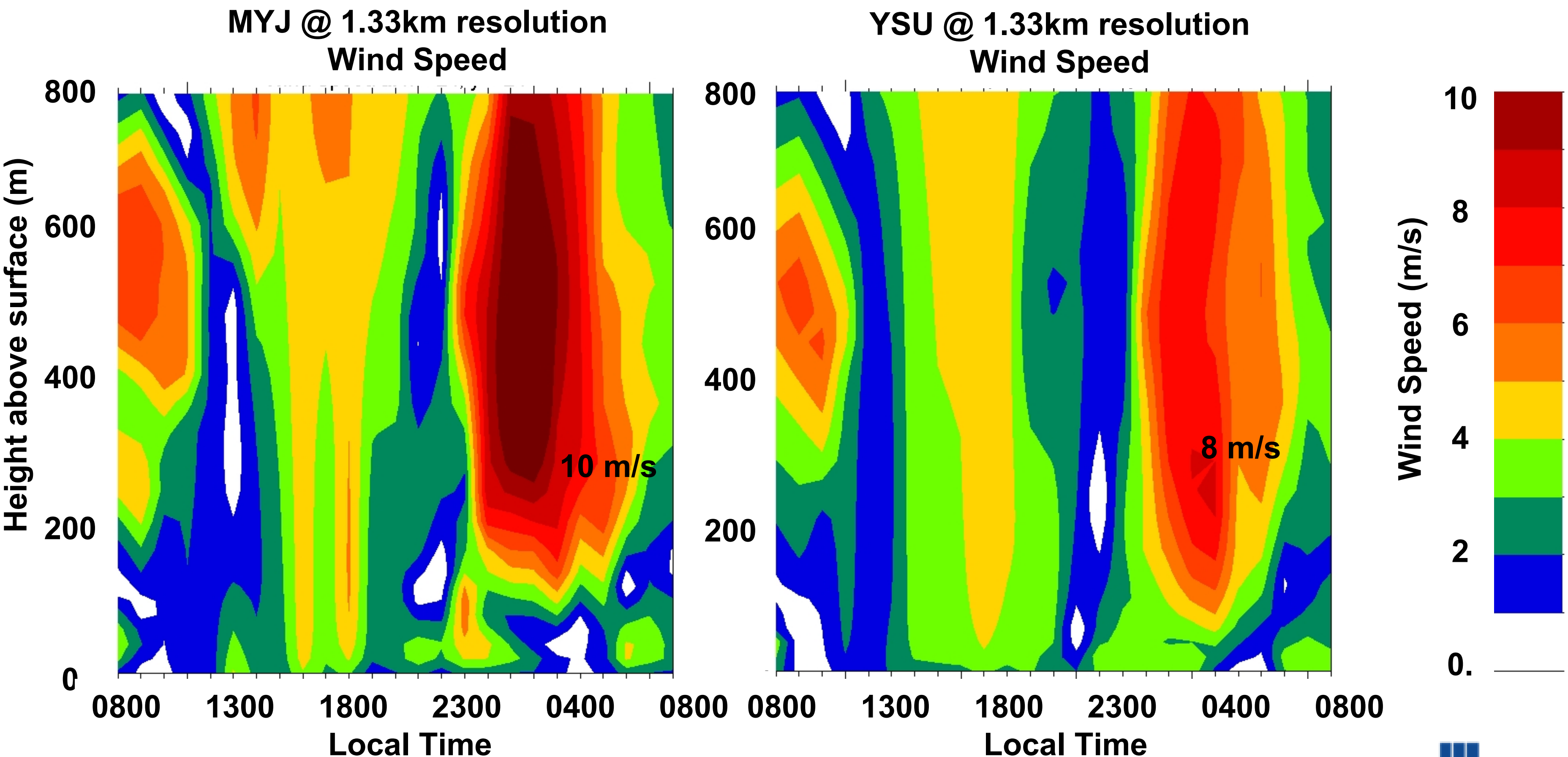
Classical stable boundary layer development is apparent in simulation results

Contours of wind speed (left) and turbulent kinetic energy (right) for hours 12- 36 of the previously-shown simulation: NARR forcing, nesting 12km → 4km → 1.33km



Use discretion and validation in choosing mesoscale boundary-layer turbulence parameterization – we see large differences on low-level shear

Contours of wind speed for hours 12-36 from same model (WRF), same forcing (NARR), Same resolution (12km → 4km → 1.33km) , but with different boundary-layer parameterizations (MYJ vs YSU).



LES results exhibit different jet behavior – next steps include validation

Contours of wind speed for hours 12- 36 of the previously-shown simulation: NARR forcing, nesting 12km → 4km → 1.33km →150m resolution. LES results (right) are from a one-way nest, using the TKE subgridscale model at hourly output.