MATERHORN
Large-eddy simulations for complex terrain

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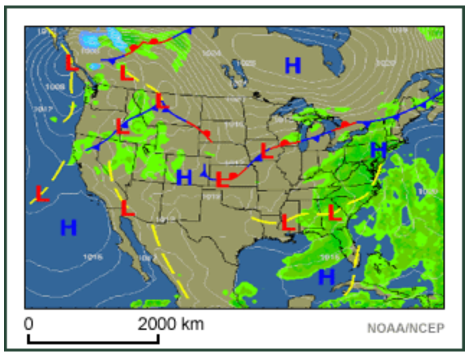
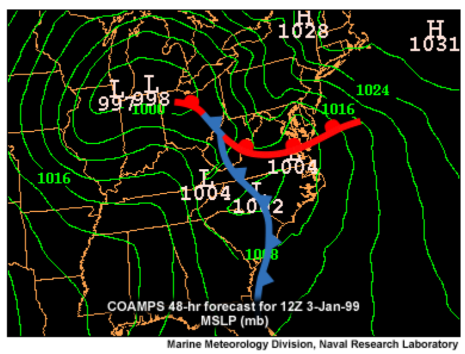
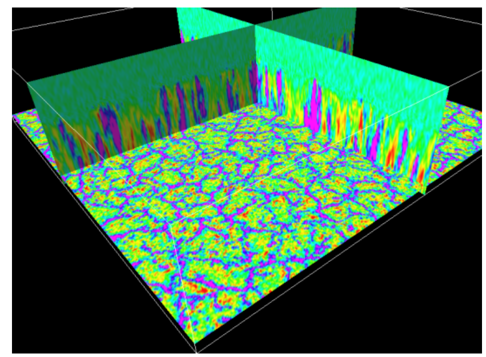
Overview

- From mesoscale to microscale
- Complex terrain
  - Immersed boundary method
  - Turbulence closure
- Stable boundary layer flows

Numerical modeling







Synoptic
L > 2000 km

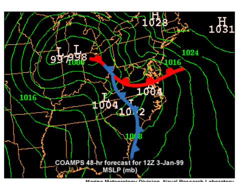
Meso-scale
L ~ 2-2000 km

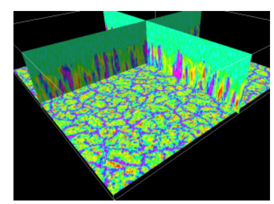
LES
L < 2 km

COMET MetEd, Sullivan 2005

Resolution gap?

- Push mesoscale models to higher resolution?
- Or increase domain size for LES?
- Is there a conflict?



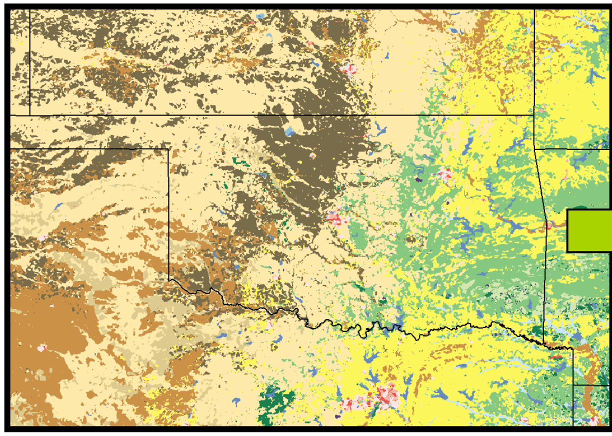


Meso-scale
L ~ 2-2000 km

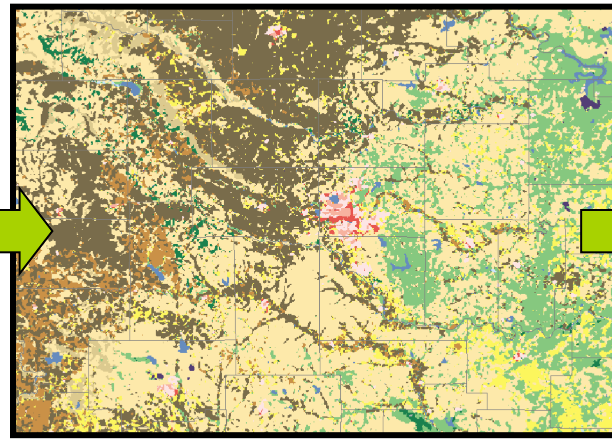
"Terra incognita"
Wyngaard (JAS 2004)

LES
L < 2 km

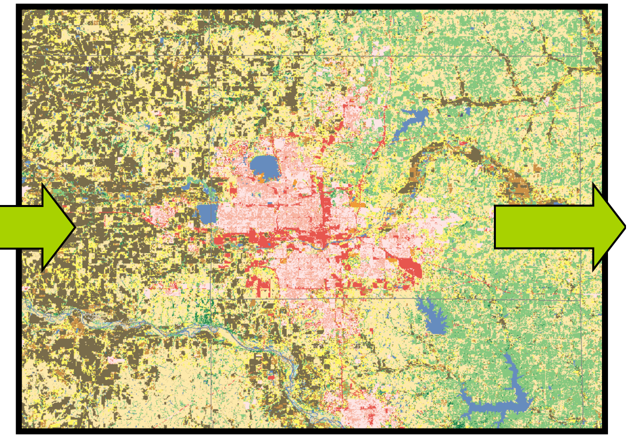
How to get from mesoscale to microscale



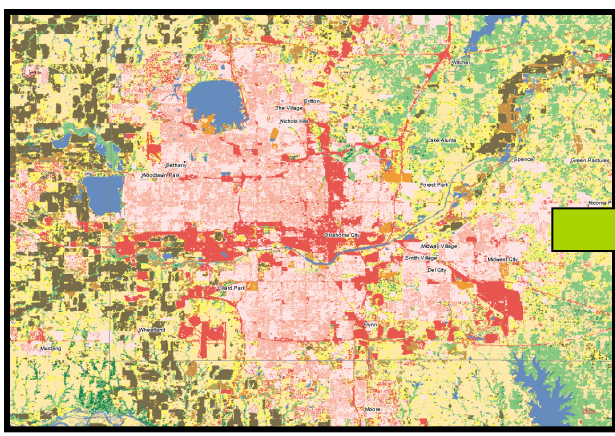
3 km (horizontal resolution)



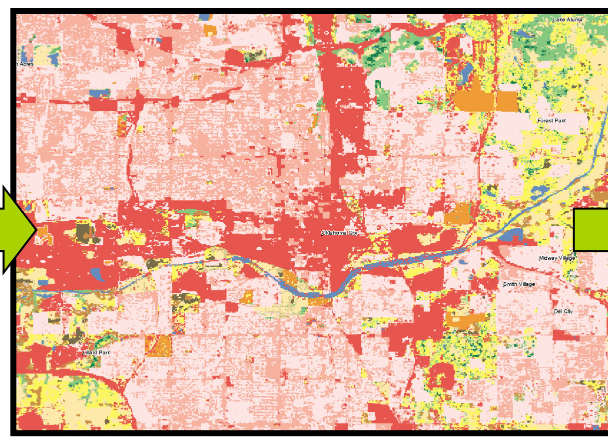
1 km



350 m



100 m

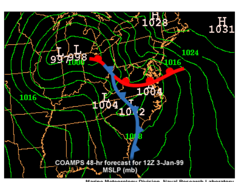


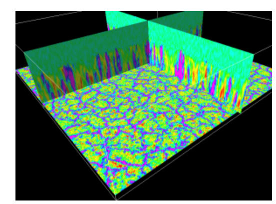
30 m

5-10 m

Challenges in the "Terra incognita"

- Steep topography
  - Terrain-following coordinate system
- Turbulence modeling
- Land-surface fluxes – similarity theory
- Lateral boundary forcing
- Other physics parameterizations

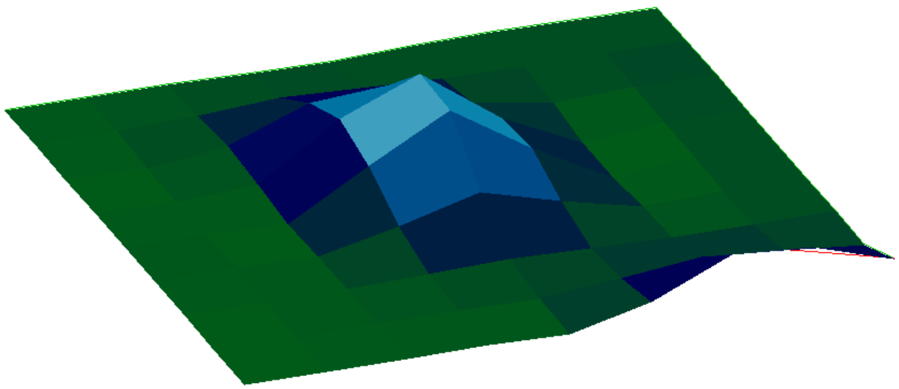




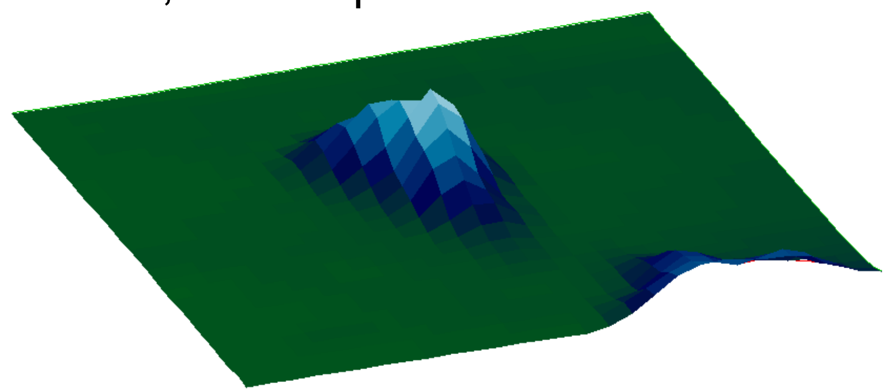
Meso-scale	"Terra incognita"	LES
L ~ 2-2000 km	Wyngaard (JAS 2004)	L < 2 km

Increasing resolution ➡ steeper slopes

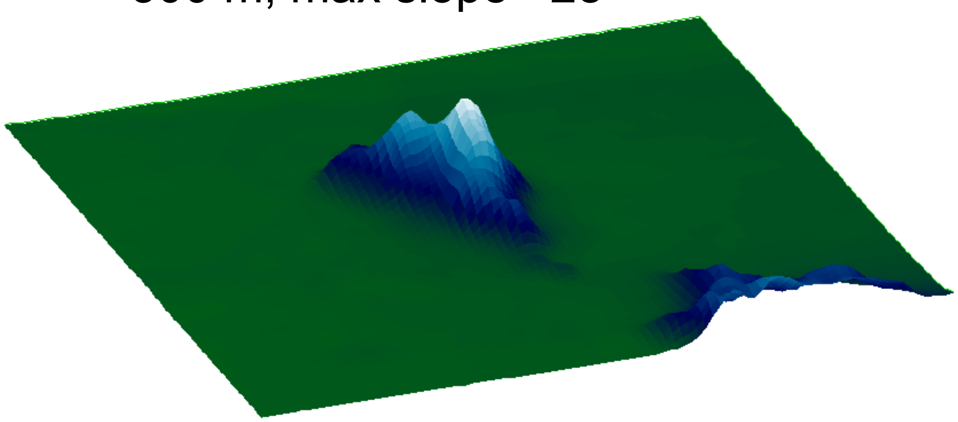
3 km, max slope ~4°



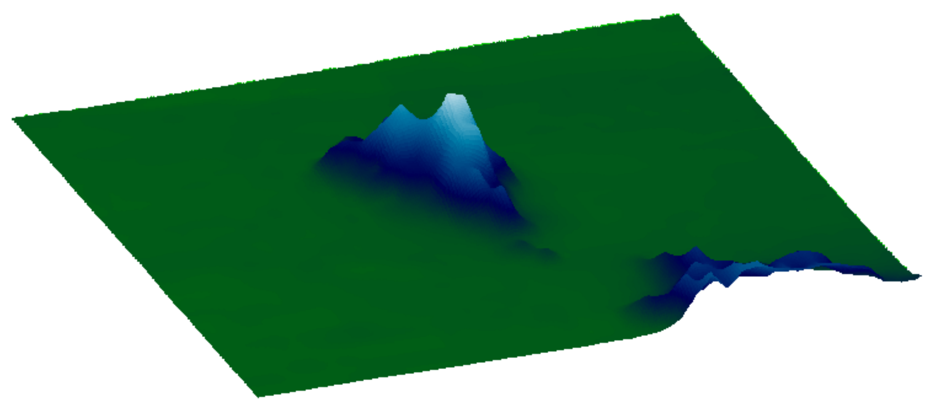
1 km, max slope ~14°



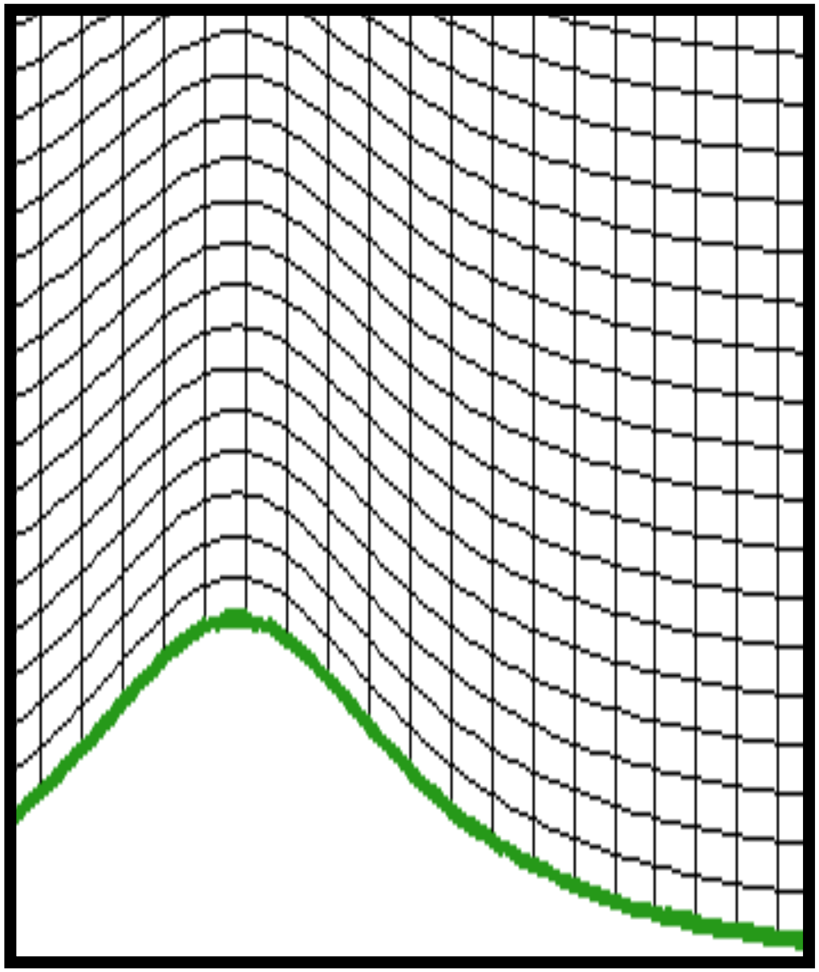
300 m, max slope ~28°



100 m, max slope ~32°



Terrain slope limit

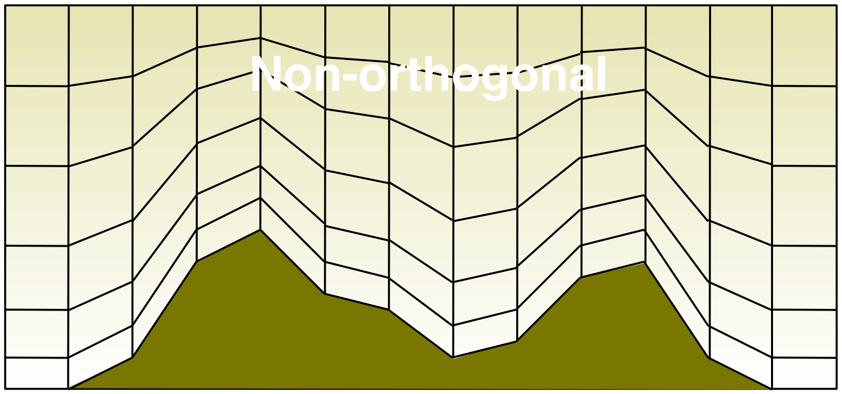


Terrain-following coordinates

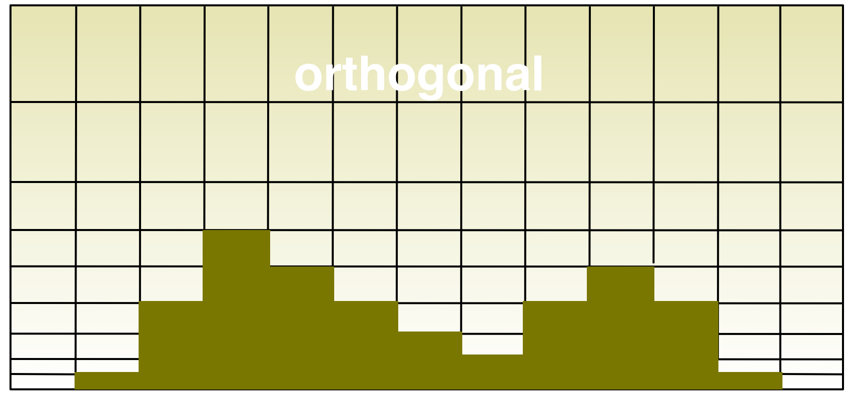
- Horizontal pressure gradient errors
  - 45° limit, usually ~30° starts causing problems (e.g. Mahrer 1984)
- Grid aspect ratio limitations
- Numerical stability

Vertical coordinate systems

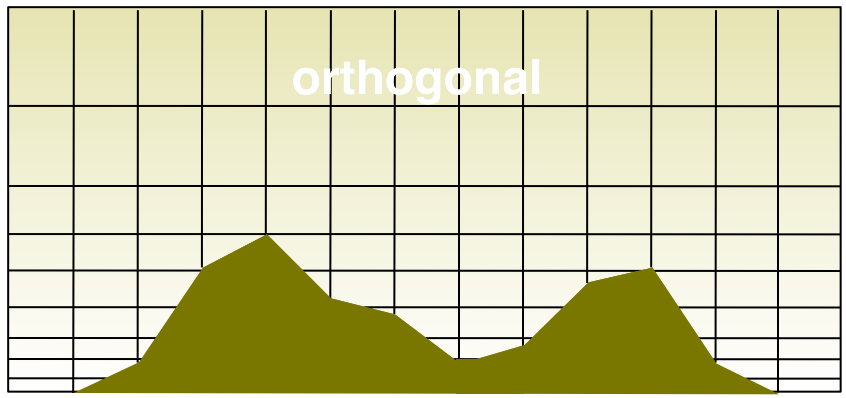
sigma, or terrain-following



eta, or "step mountain"

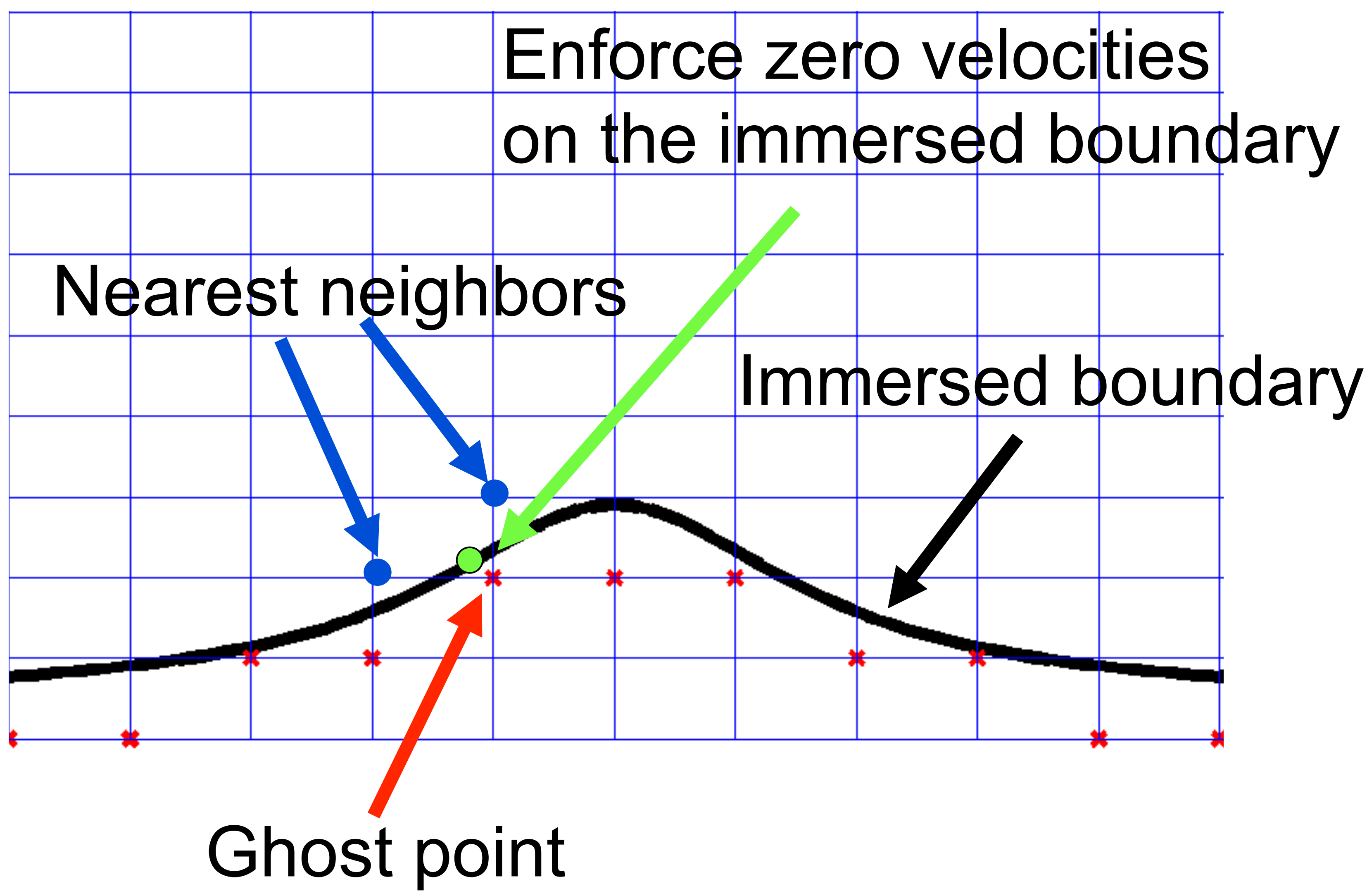


immersed boundary



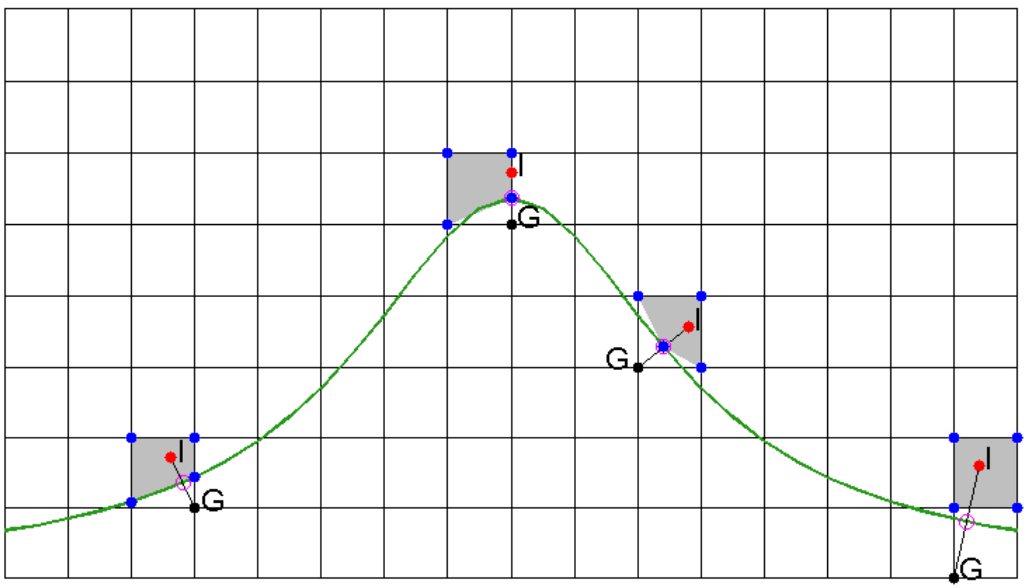
others include sigma-pressure, isentropic, and hybrids

Ghost-cell immersed boundary method



IBM - Boundary reconstruction

- IBM implemented in WRF
  - Lundquist et al. MWR 2010
- 2 different interpolation algorithms
- Handles highly complex topography



Lundquist et al. MWR 2010

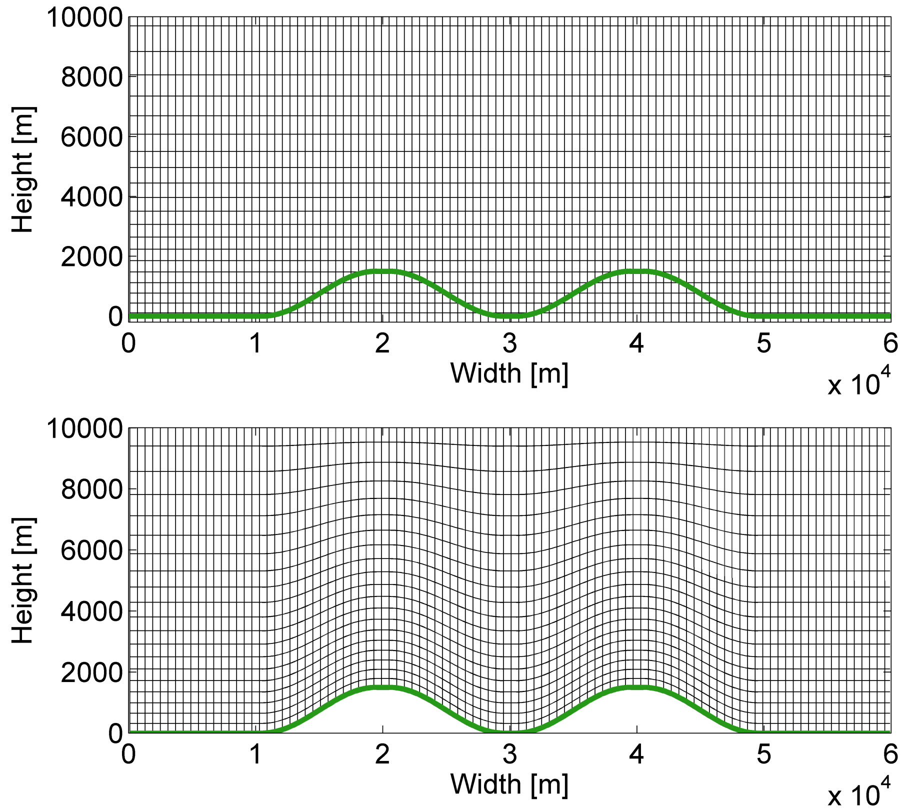
Idealized Valley Simulations

Domain Set-Up

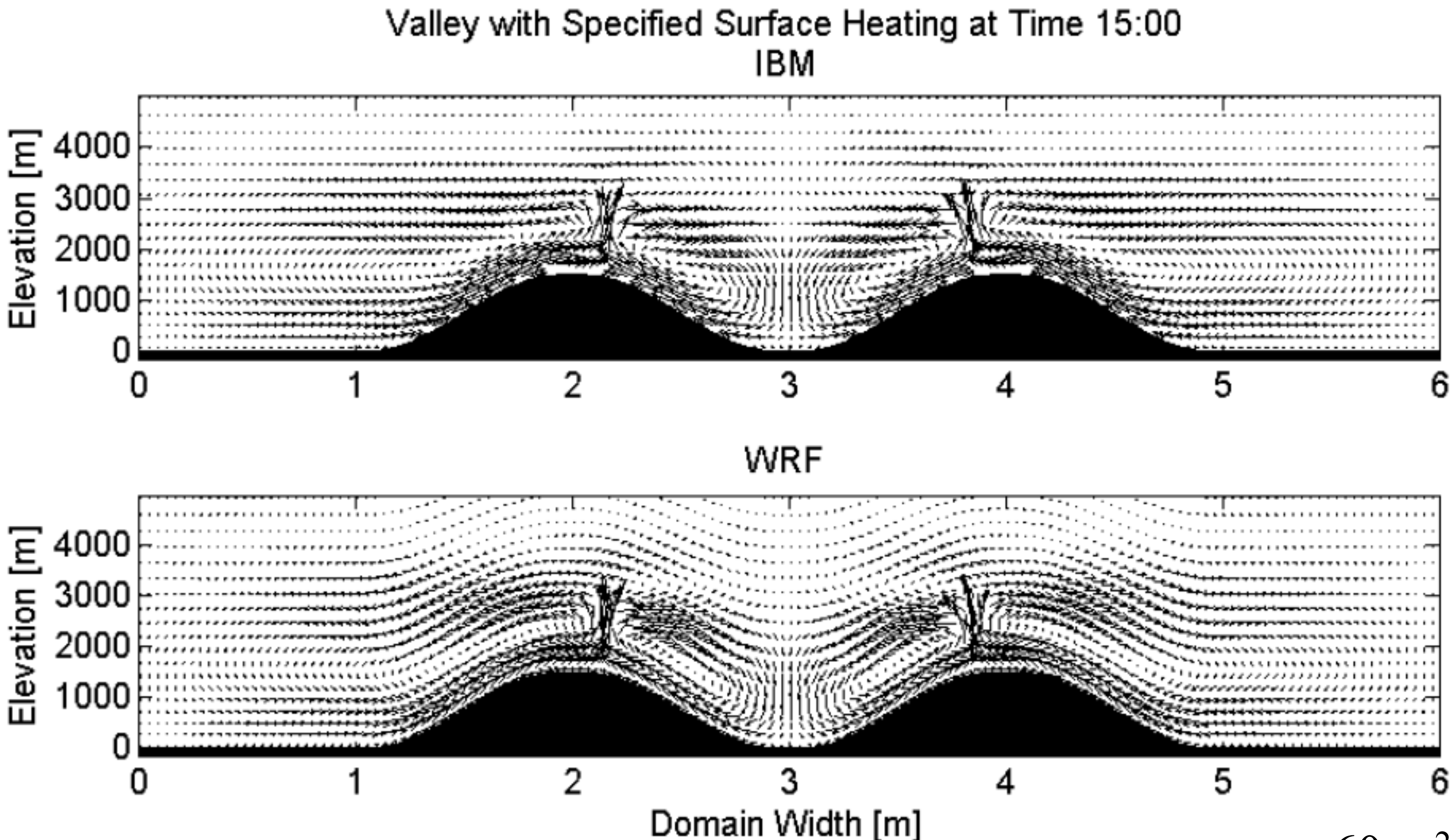
- (X,Y) = (60 km, 10 km)
- (N_x,N_y)=(301, 60)
- ΔX = ΔY = 200 m, ΔZ ~100 m
- Peak Height = 1.5 km
- Valley Width = 20 km

Initialization

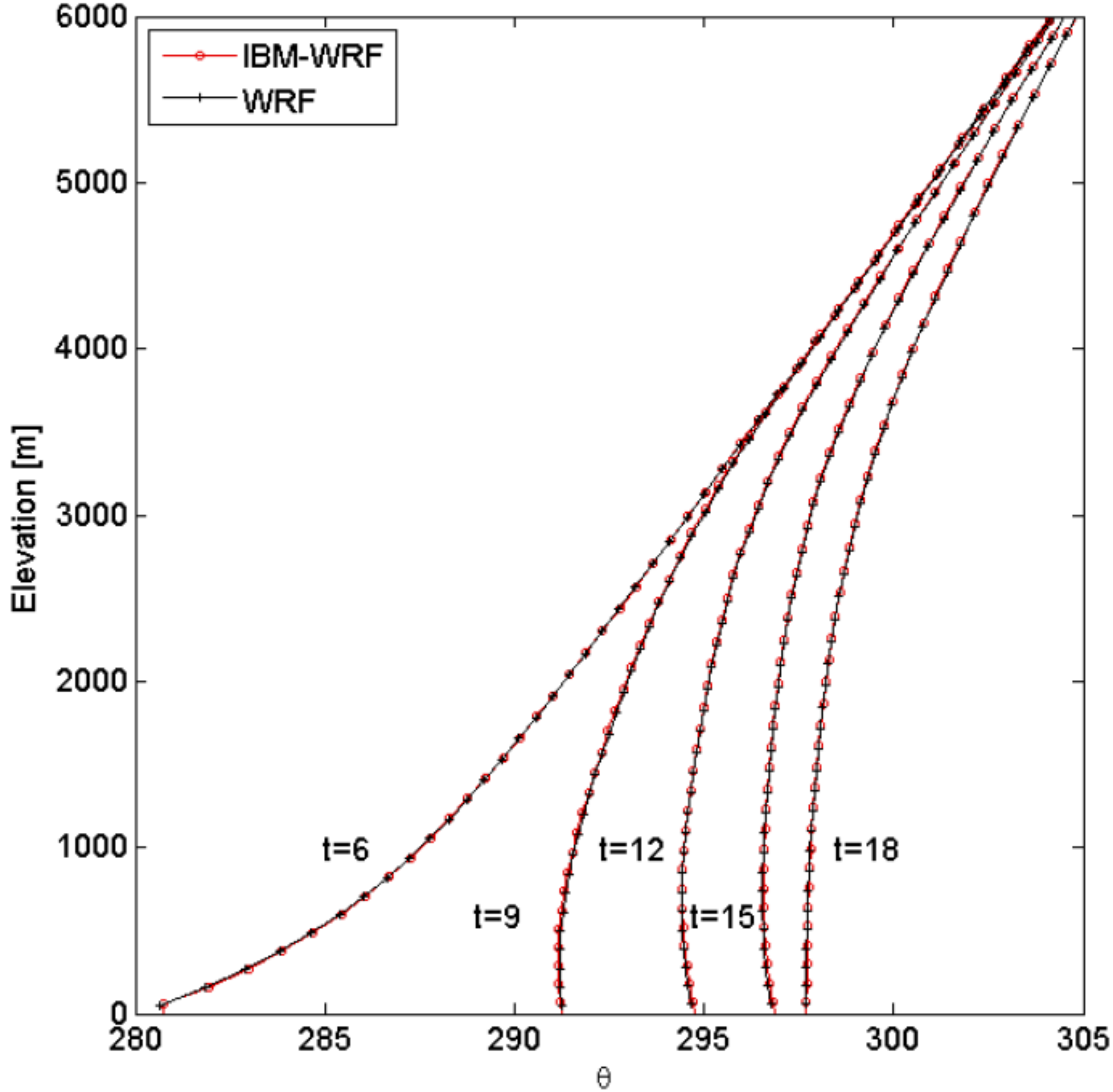
- (U,V,W) = (0,0,0)
- Stable Potential Temp.
- 40% Relative Humidity



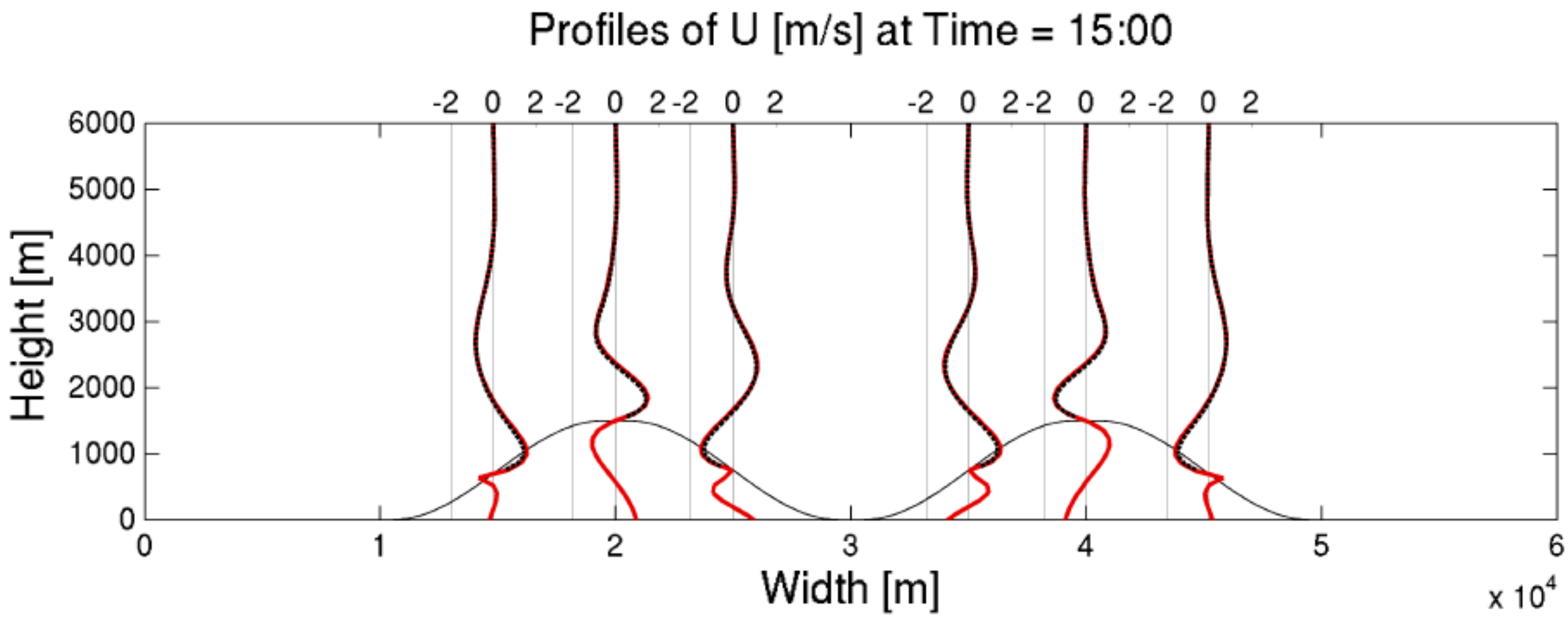
Thermally-driven valley flows

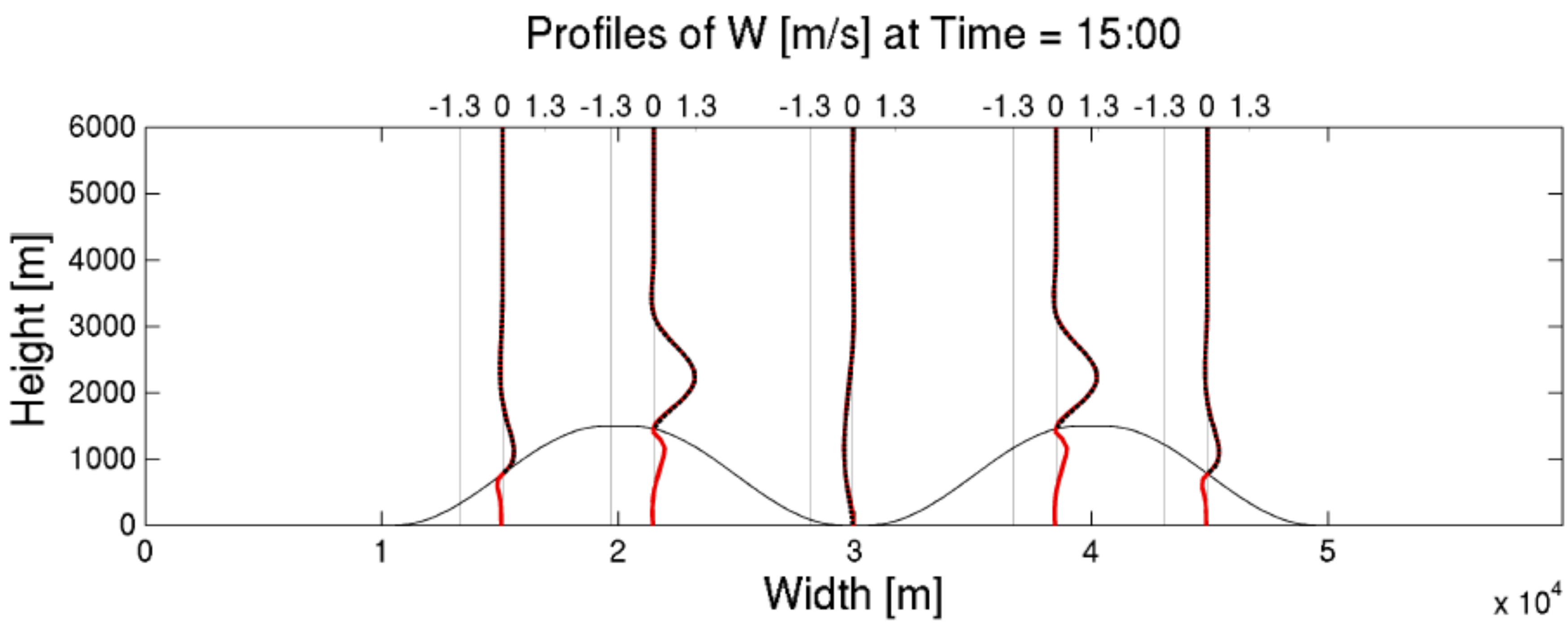


$\nu_T = 60\ m^2/s$



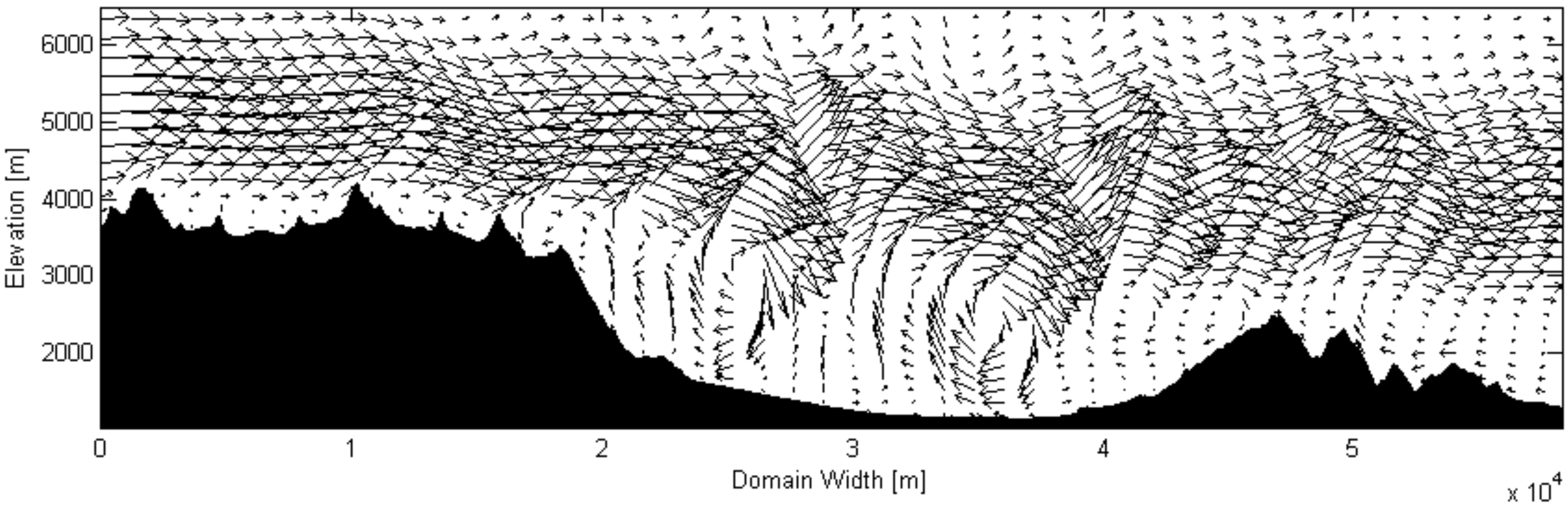
IBM-WRF
WRF
6000
5000
4000
3000
2000
1000
0
Elevation [m]
280
285
290
295
300
305
θ
t=6
t=9
t=12
t=15
t=18


Profiles of U [m/s] at Time = 15:00
-2 0 2 -2 0 2 -2 0 2 -2 0 2 -2 0 2 -2 0 2
Height [m]
6000
5000
4000
3000
2000
1000
0
0 1 2 3 4 5 6
Width [m]
x 10^4

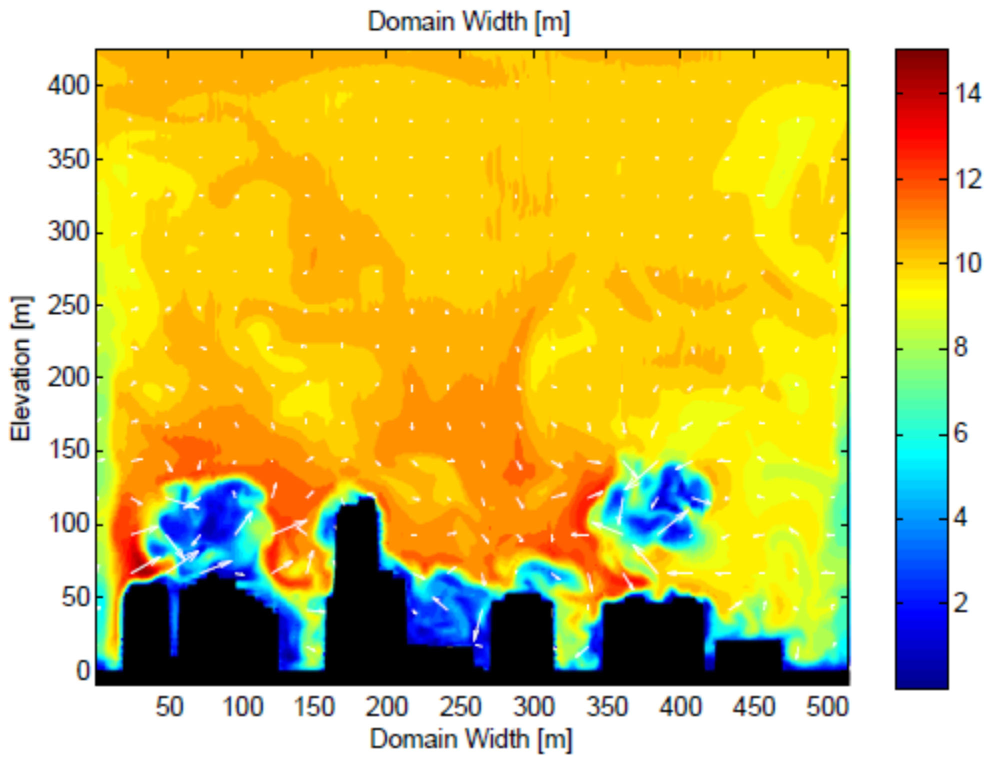

Profiles of W [m/s] at Time = 15:00
-1.3 0 1.3 -1.3 0 1.3 -1.3 0 1.3 -1.3 0 1.3 -1.3 0 1.3
Height [m]
6000
5000
4000
3000
2000
1000
0
0 1 2 3 4 5
Width [m]
x 10^4

IBM-WRF: 2D Owens Valley, CA

- Terrain with slopes of up to 60 degrees
- IBM allows explicit resolution of this terrain at 100 m resolution
- Does not run with regular WRF

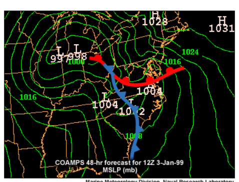


WRF-IBM – OKC urban dispersion

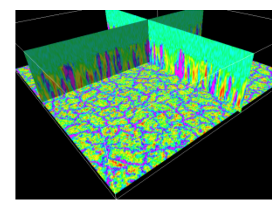


Challenges in the "Terra incognita"

- Steep topography
  - Terrain-following coordinate system
- Turbulence modeling
- Land-surface fluxes – similarity theory
- Lateral boundary forcing
- Other physics parameterizations



Marine Meteorology Division, Naval Research Laboratory



Meso-scale
L ~ 2-2000 km

"Terra incognita"
Wyngaard (JAS 2004)

LES
L < 2 km

Turbulence modeling

Mesoscale models

- $\Delta x > L$
- $\Delta x \sim$ 2-10 km
- "None" of turbulence resolved
- Reynolds-averaged Navier-Stokes (RANS) closure models

Large-eddy simulation

- $\Delta x < L$
- $\Delta x < 1$ km
- Energy-containing turbulence resolved
- Closure model depends on filter width, Δ_f

Turbulence modeling

- Dynamic Reconstruction Model (DRM)
  - Explicit filtering and reconstruction

$$\tau_{ij} = \overline{\tilde{u}_i^\star \tilde{u}_j^\star} - \overline{\tilde{u}}_i \overline{\tilde{u}}_j - 2C_\epsilon \Delta^{4/3} \overline{\tilde{S}}_{ij}$$

Chow et al. JAS 2005

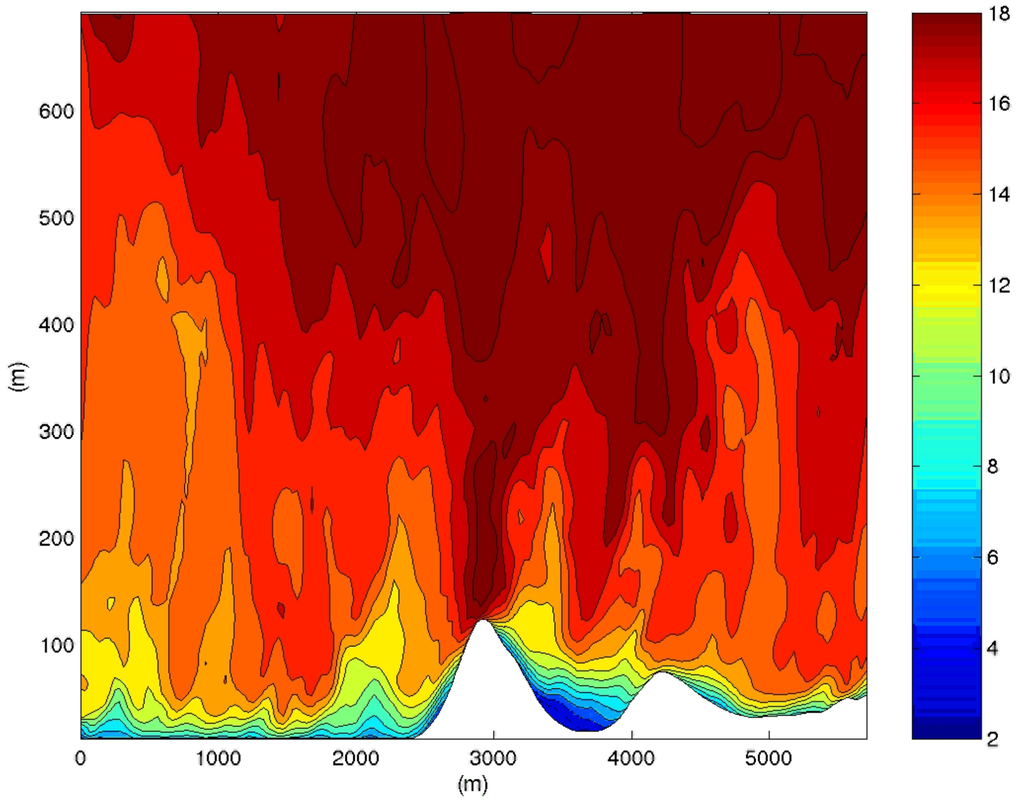
- 1.5-order TKE closure
  - Eddy viscosity
  - No backscatter

$$\tau_{ij} = -2\nu_T \overline{\tilde{S}}_{ij}$$

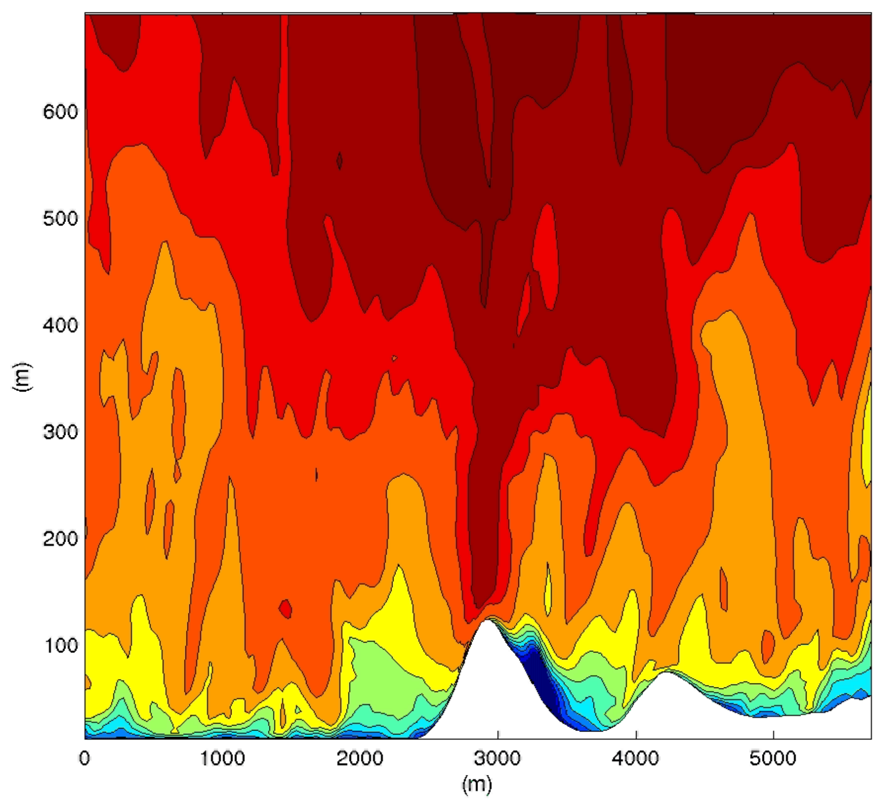
Askervein Hill

Streamwise velocity contours (m/s)

(Chow and Street, JAMC 2009)

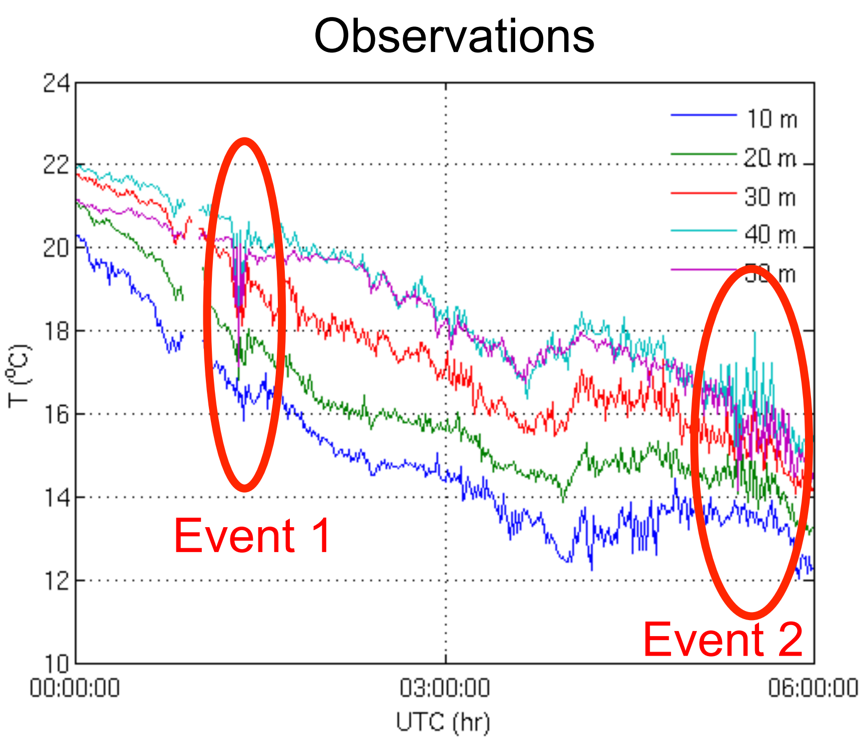


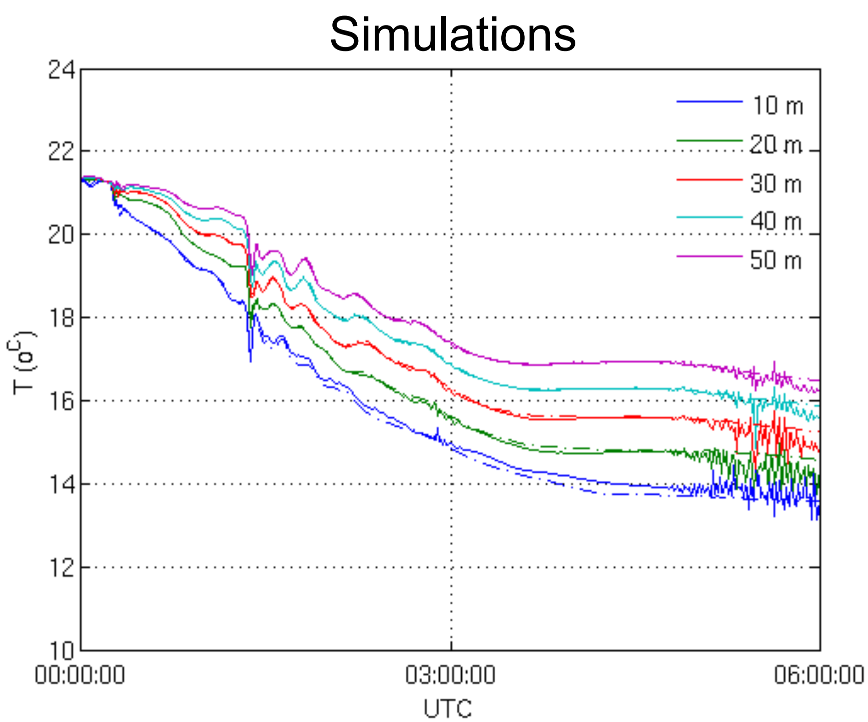
TKE-1.5



DRM-ADM0

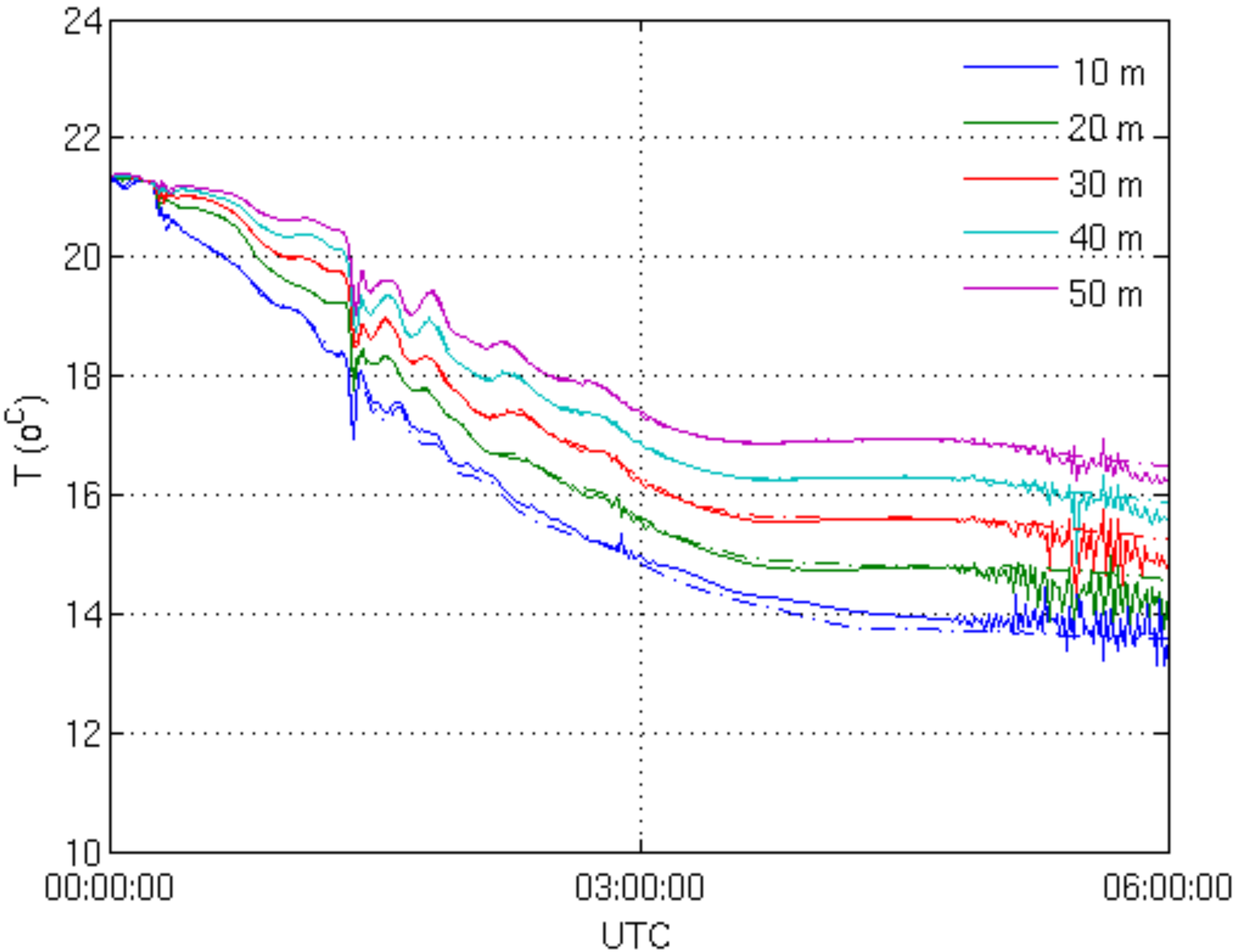
CASES-99 - temperature





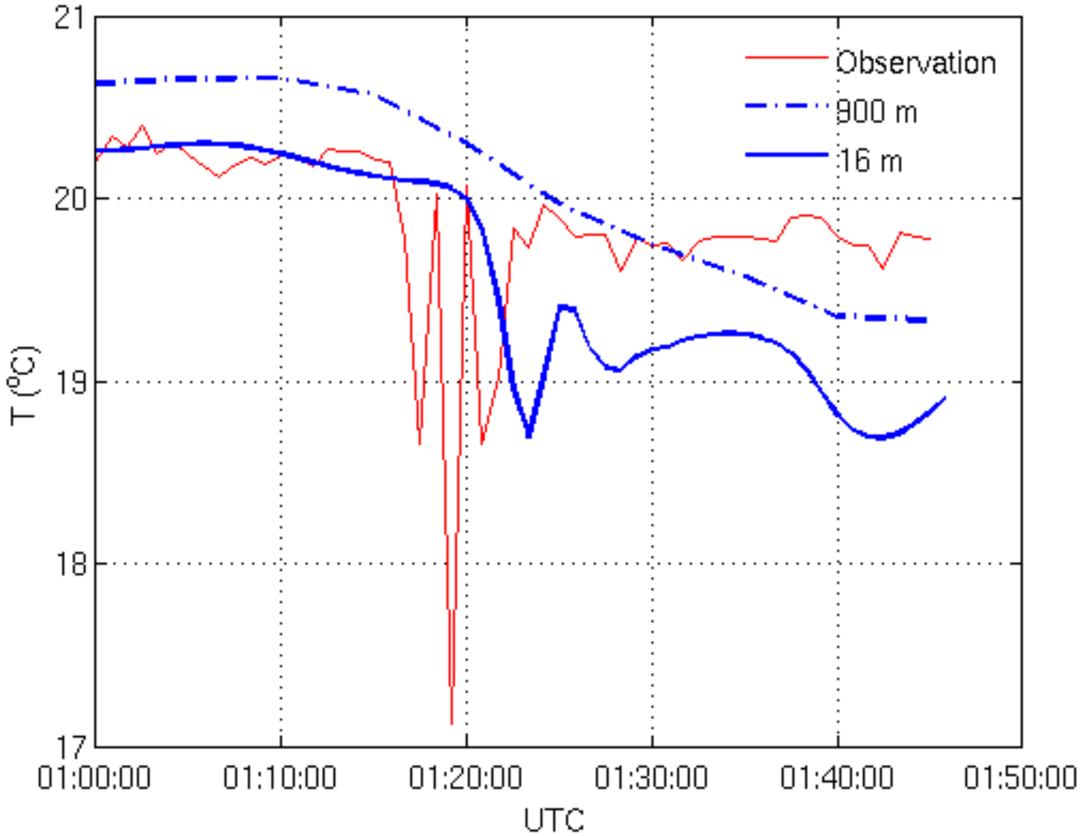
DRM – solid
TKE-1.5 - dashed

(Zhou and Chow)

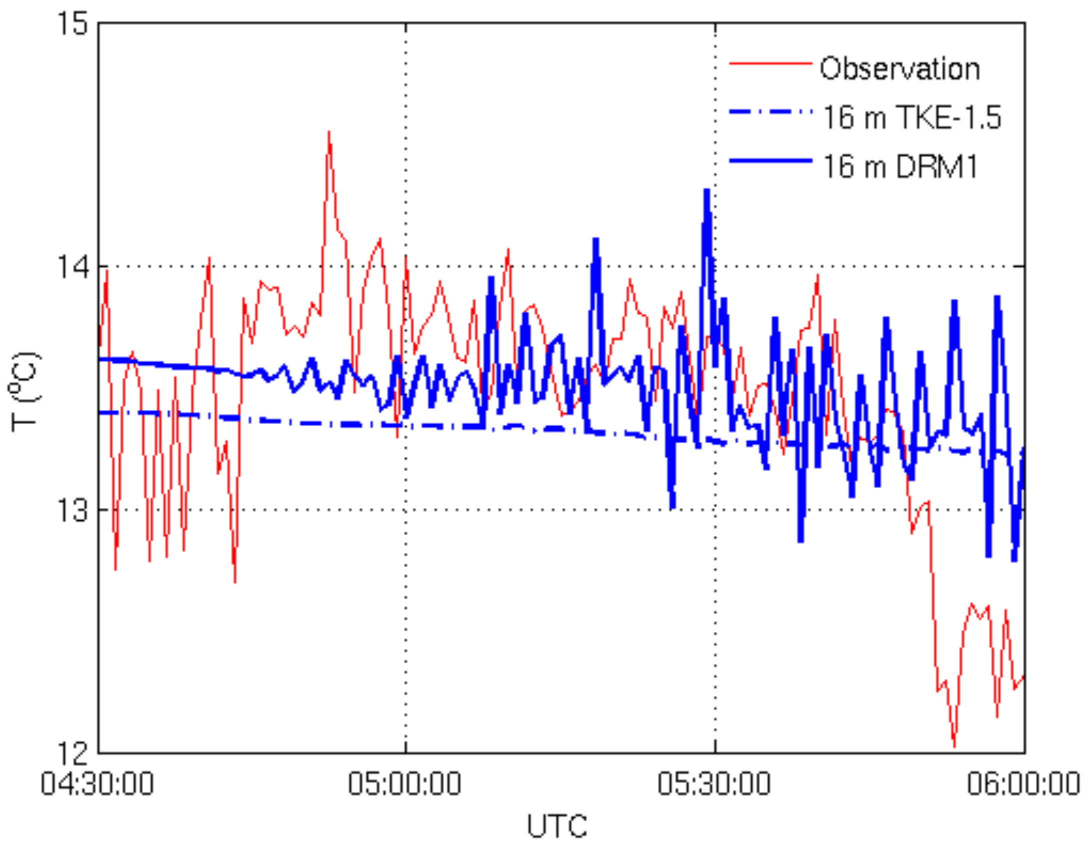


24
22
20
18
16
14
12
10
T (o^C)
00:00:00
03:00:00
06:00:00
UTC
10 m
20 m
30 m
40 m
50 m

Event 1 – captured at 16 m res

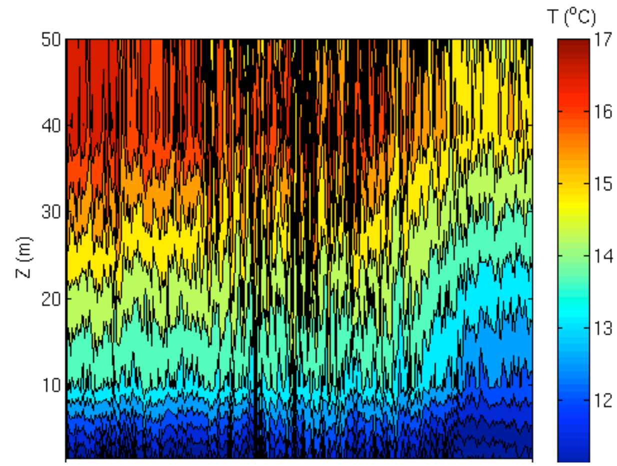


Event 2 – captured by DRM at 16 m

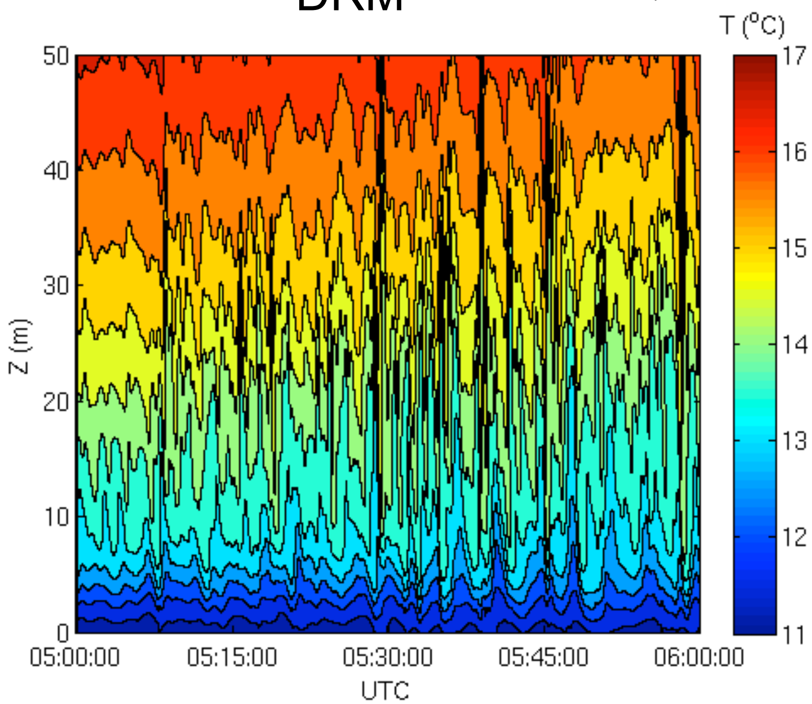


Event 2 – turbulence model choices

Observations



DRM



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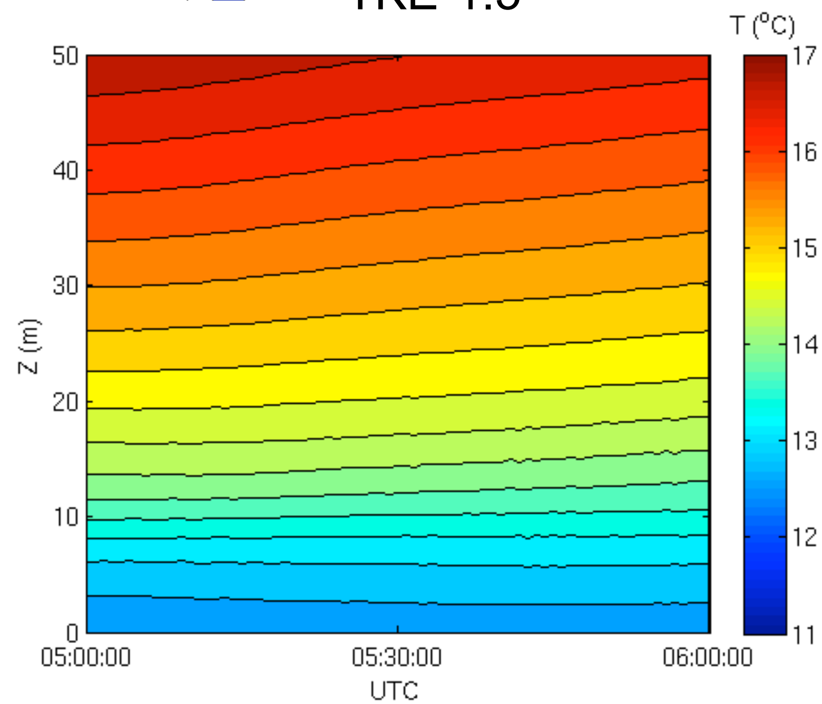
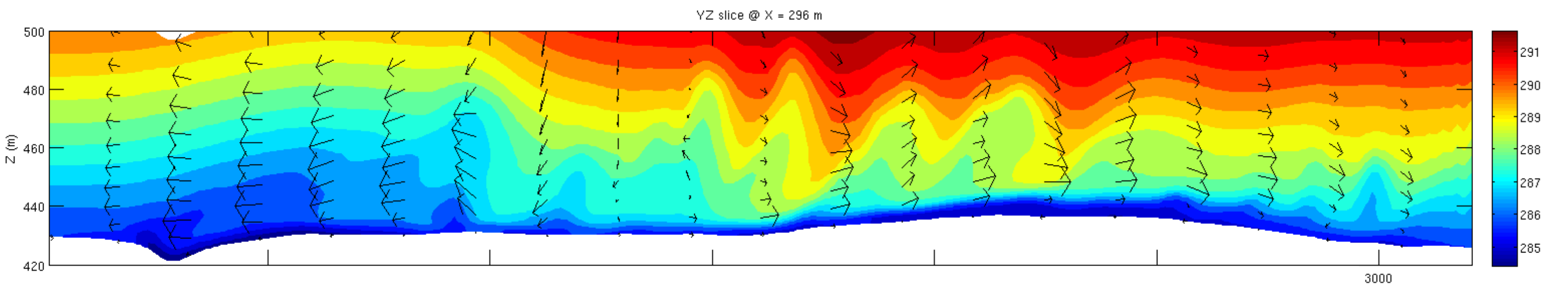
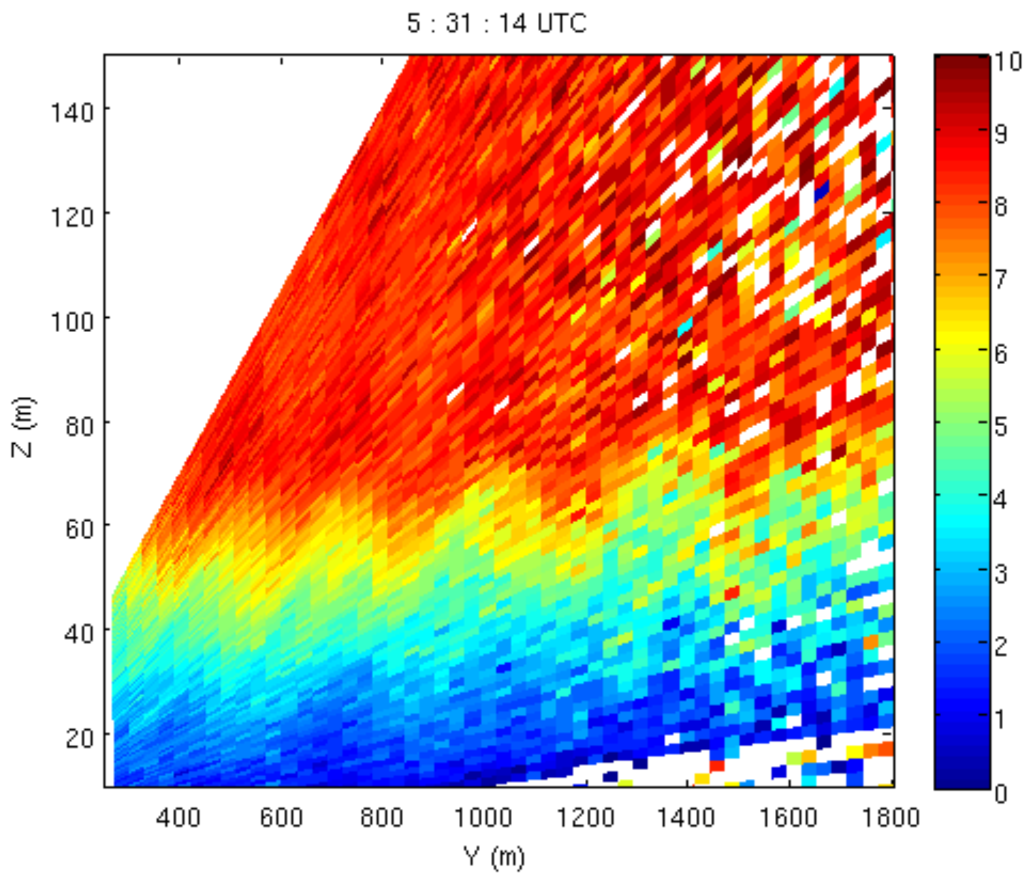


Kelvin-Helmholtz billows

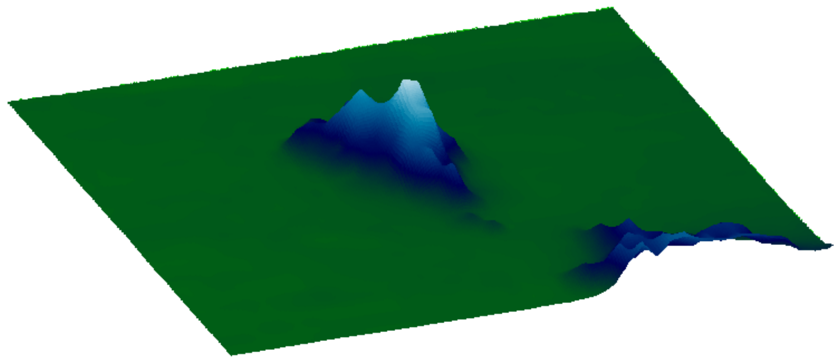
DRM



Lidar



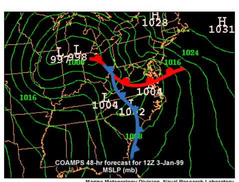
What we are doing



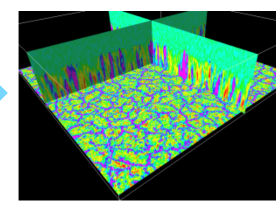
- Weather and Research Forecasting (WRF) model
  - Mesoscale to microscale
- One tool for all scales
  - Improved turbulence models for LES
  - Immersed boundary method for steep terrain

MATERHORN: addressing challenges in the "Terra incognita"

- Steep topography
- Turbulence modeling
- Land-surface fluxes – similarity theory



DRM and IBM-WRF



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