An Improved Multi-Scale Modeling Framework for WRF Over Complex Terrain

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David Wiersema

Civil & Environmental Engineering, UC Berkeley

Katherine Lundquist

Lawrence Livermore National Laboratory

Fotini Katopodes Chow

Civil & Environmental Engineering, UC Berkeley

Lawrence Livermore National Laboratory

Bay Area Air Quality Management District

The University of California Berkeley 1868

Outline

- Neighborhood-scale air quality modeling
- Introduction to multi-scale modeling
- Weather Research and Forecasting (WRF) model
- The immersed boundary method and WRF
- Vertical grid nesting in WRF
- WRF to WRF-IBM grid nesting (in development)

San Francisco Air Quality Modeling

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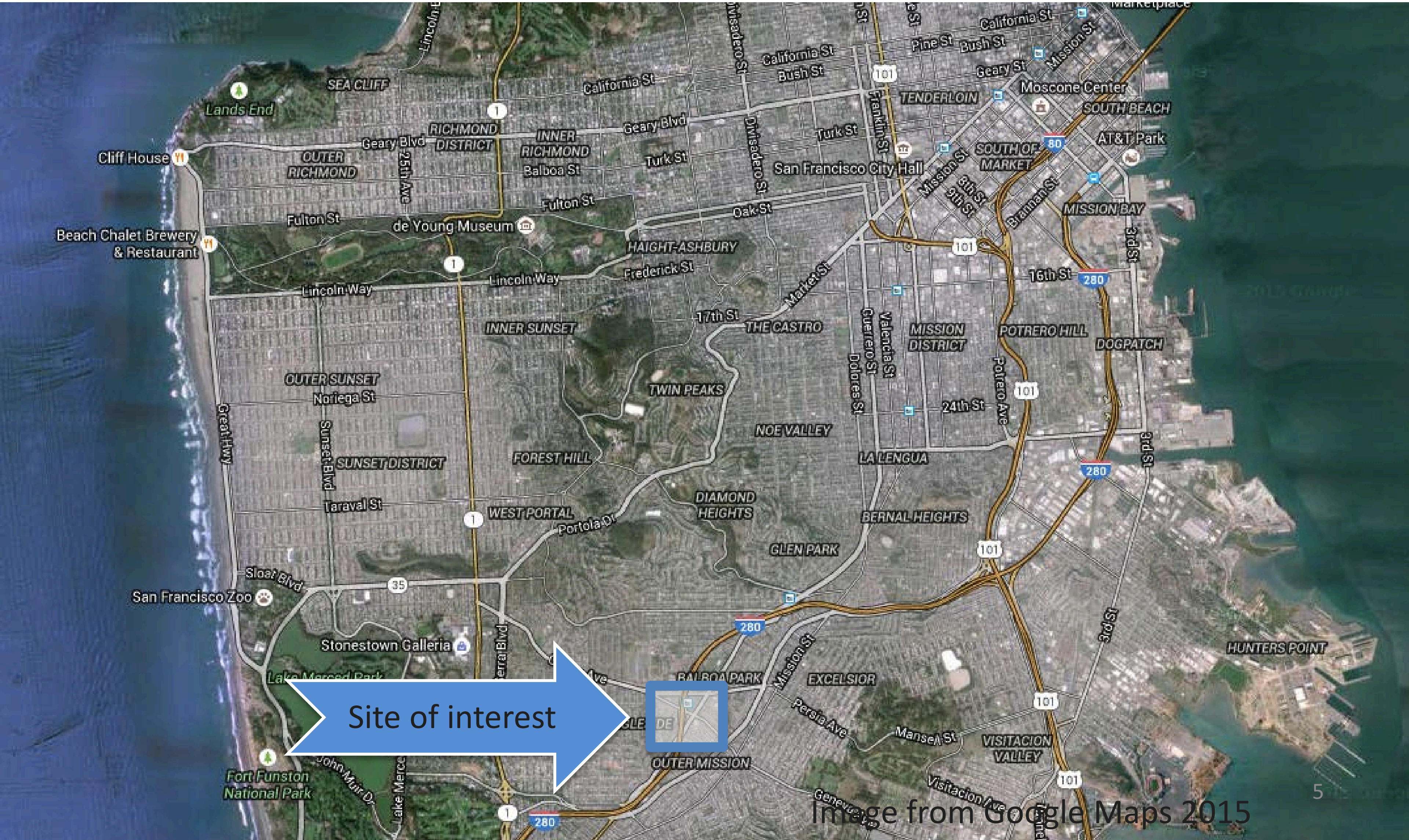


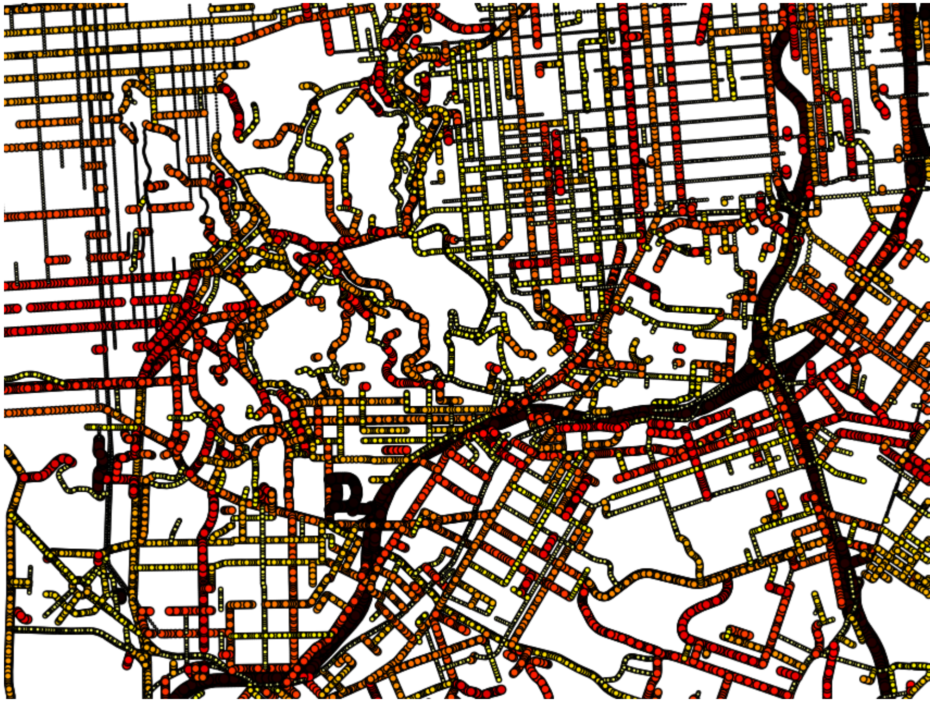
San Francisco Air Quality Modeling

Urban Topography

- LiDAR dataset of building heights above ground level
  - Provided by the San Francisco Department of Public Health
- Combined with National Elevation Dataset 1/3rd arc-second ground topography

PM2.5 Emissions

- Provided by the Bay Area Air Quality Management District.
- ~2m resolution.
- Weighted depending on the time of day and weekday.

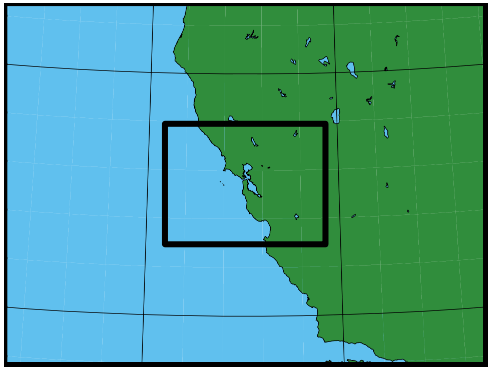


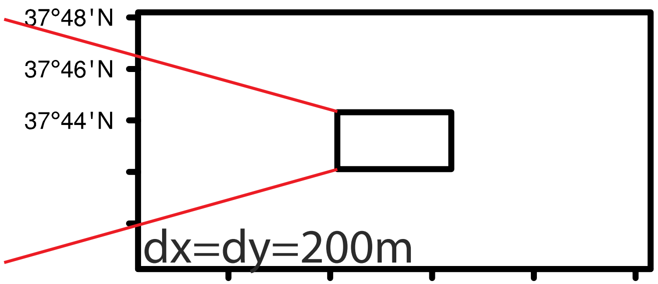
Options For Modeling of Urban Dispersion

1) Add atmospheric physics to a computational fluid dynamics (CFD) model.
2) Couple a CFD model to a numerical weather prediction (NWP) model.
3) Downscale to CFD-scales within a NWP model.

Multi-Scale Atmospheric Modeling

- Resolves features between synoptic-scale and turbulent-scale.





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dx=dy=40m

Meso-Scale to Micro-Scale

Scale	Feature Size	Features Resolved
Meso-alpha	2000km – 200km	tropical cyclones, weather fronts
Meso-beta	200km – 20km	land-sea breeze, lake effect snow storms
Meso-gamma	20km – 2km	thunderstorm convection, large-scale terrain effects
Micro	1km – 1m	turbulent mixing, convection

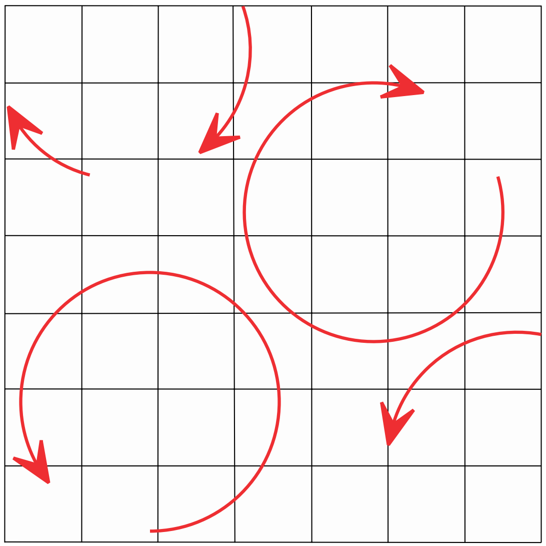
1980-1990

1950-1980

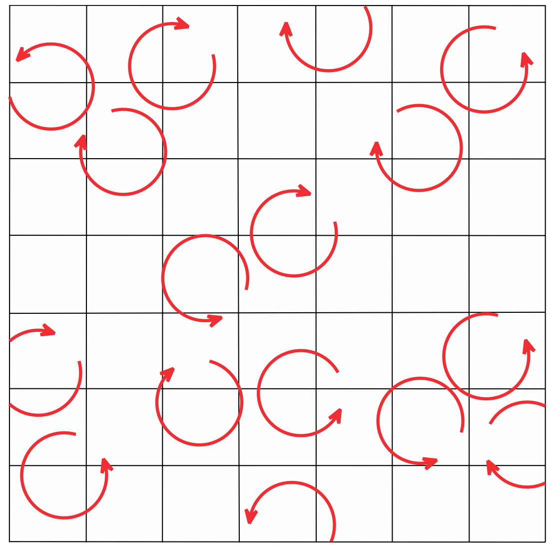
Current Generation Models

Wyngaard’s “Terra-Incognita”

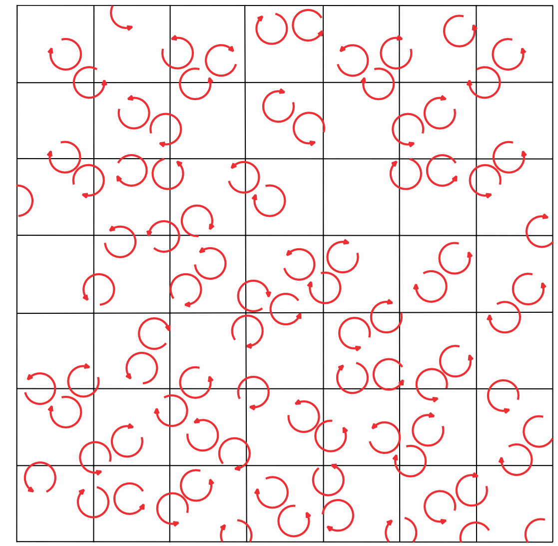
l/Δ >> 1
micro-scale

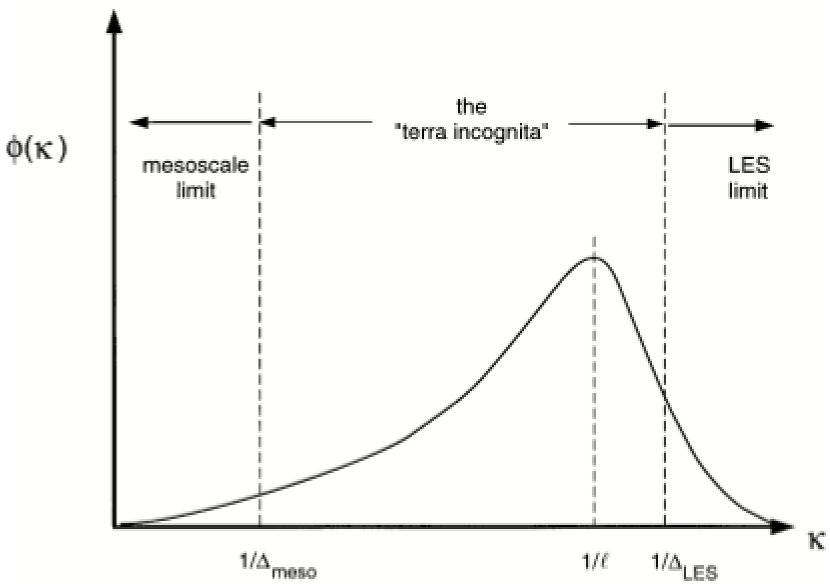


l/Δ ≈ 1



l/Δ << 1
meso-scale

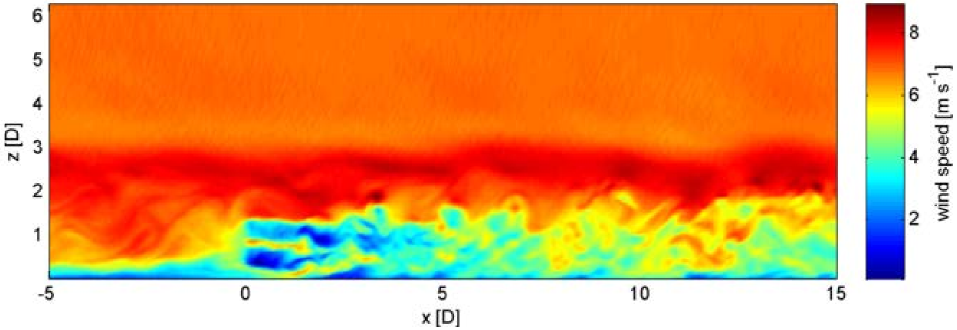




Wyngaard, J., 2004:
Toward numerical modeling in the “terra incognita”.
Journal of the Atmospheric Sciences, 61, 1816-1826.

Potential Applications for Multi-Scale Modeling

- Wind energy forecasting and turbine siting
- Mountain meteorology
- Urban meteorology
- Dispersion modeling
- Operational forecasting (someday)



Aitken ML, Kosovic B, Mirocha JD, Lundquist JK, 2014: Large-eddy simulation of wind turbine wake dynamics in the stable boundary layer using the Weather Research and Forecasting model, *J. Renewable and Sustainable Energy*, 6

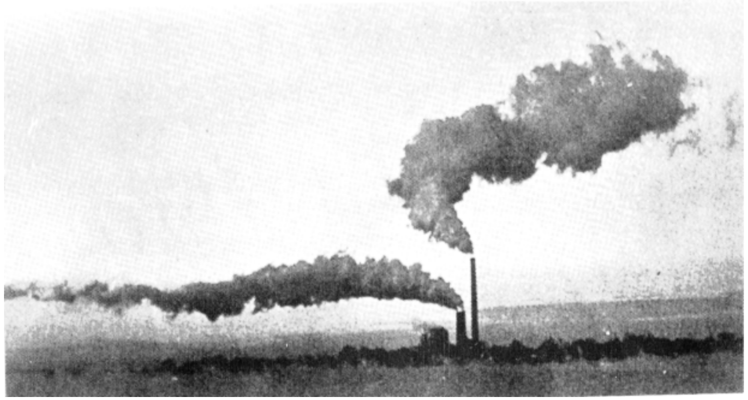
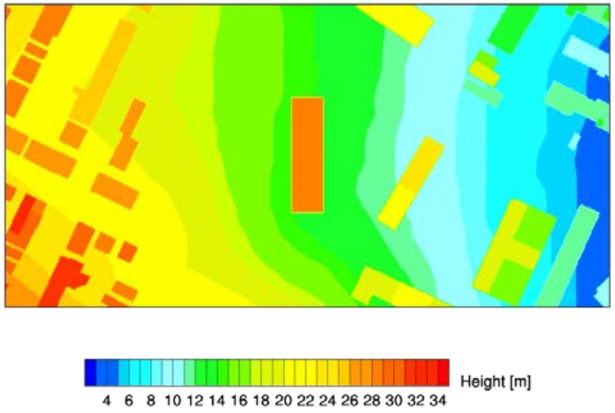


Photo credit: Ralph Turncotte. From Sea Breeze and Local Winds by John E. Simpson.

What's Needed for Multi-Scale Modeling?

- Meso-scale model
  - Weather Research and Forecasting (WRF) model
- Turbulence modeling at high resolutions
  - Large Eddy Simulation (LES)
- Ability to handle complex terrain
  - Immersed boundary method (WRF-IBM)
- Ability to downscale information
  - Vertical grid nesting in WRF
- Adaptive or scale-dependent parameterizations



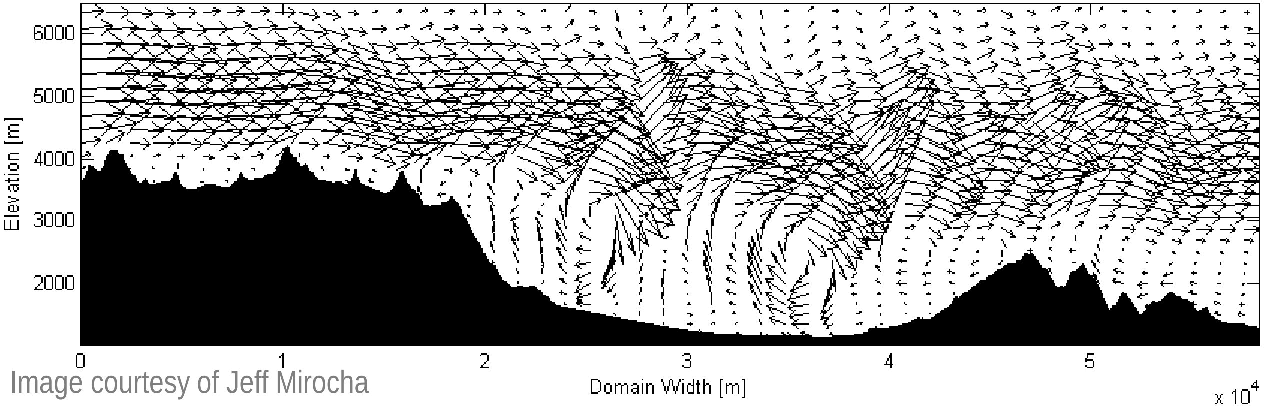
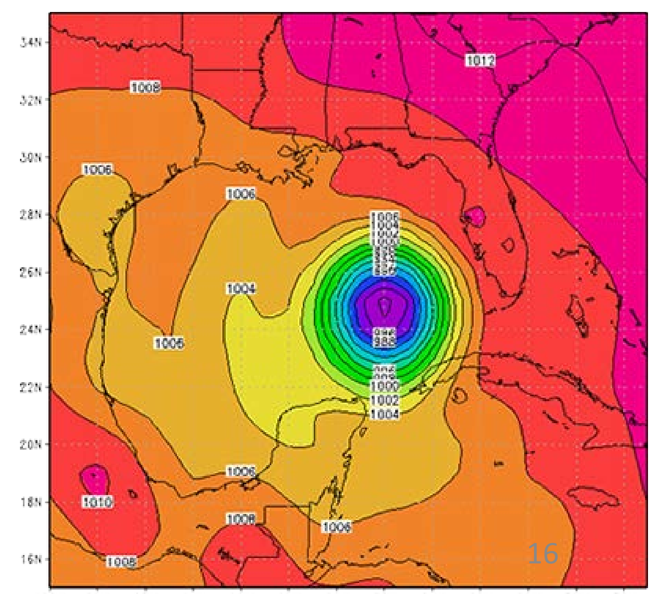


Image courtesy of Jeff Mirocha

Numerical Weather Prediction Model		Horizontal Resolution		Operational
		At Launch	Currently	
NGM	Nested Grid Model	90km		1987-2000
ECMWF	European Center for Medium-Range Weather Forecasting	125km	16km	1987+
RUC	Rapid Update Cycle	60km	13km	1994-2012
	Eta	29km		1995-2006
NAM	North American Meso-scale	12km		2006+
GFS	Global Forecast System	28km	13km	2002+
RAP	Rapid Update Cycle	13km		2012+
HRRR	High-Resolution Rapid Refresh	3km		2013+
FIM9.5	Flow-Following Finite-Volume	15km		2014+

The Weather Research and Forecasting Model

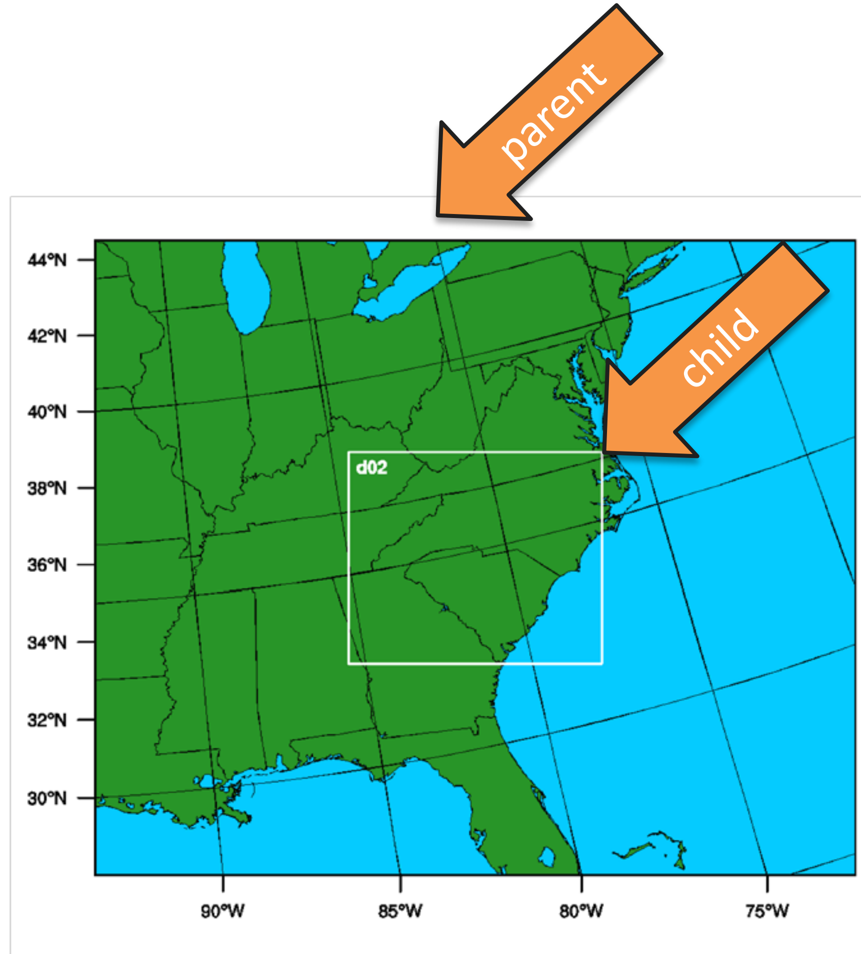
- Meso-scale, regional, numerical weather prediction (NWP) model
- Open-source, community developed
- Maintained by the National Center for Atmospheric Research
- Fully compressible and nonhydrostatic
- Large eddy simulation capable
- Parameterizations for land surface model physics, long and shortwave radiation, subgridscale cumulus development, microphysics, etc…
- Downscaling using grid-nesting



Images from http://www.mmm.ucar.edu/wrf/OnLineTutorial/CASES/SingleDomain

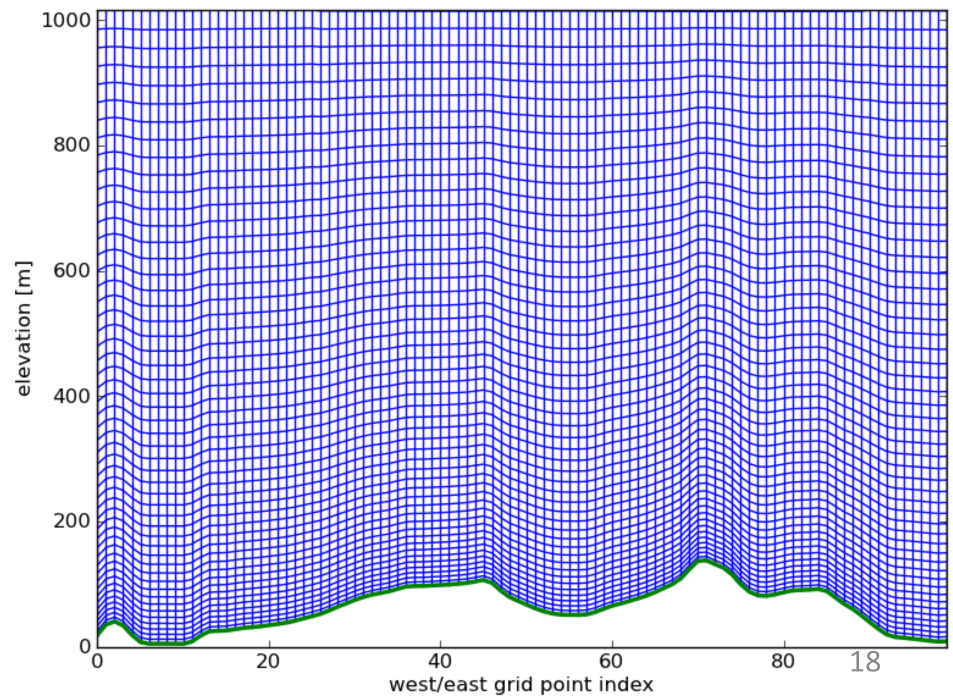
Downscaling With Grid Nesting

- Coarse-resolution "parent" grid provides data for initialization and boundary conditions of fine-resolution "child" grid.
- Enables large-scale features to influence the child domain.

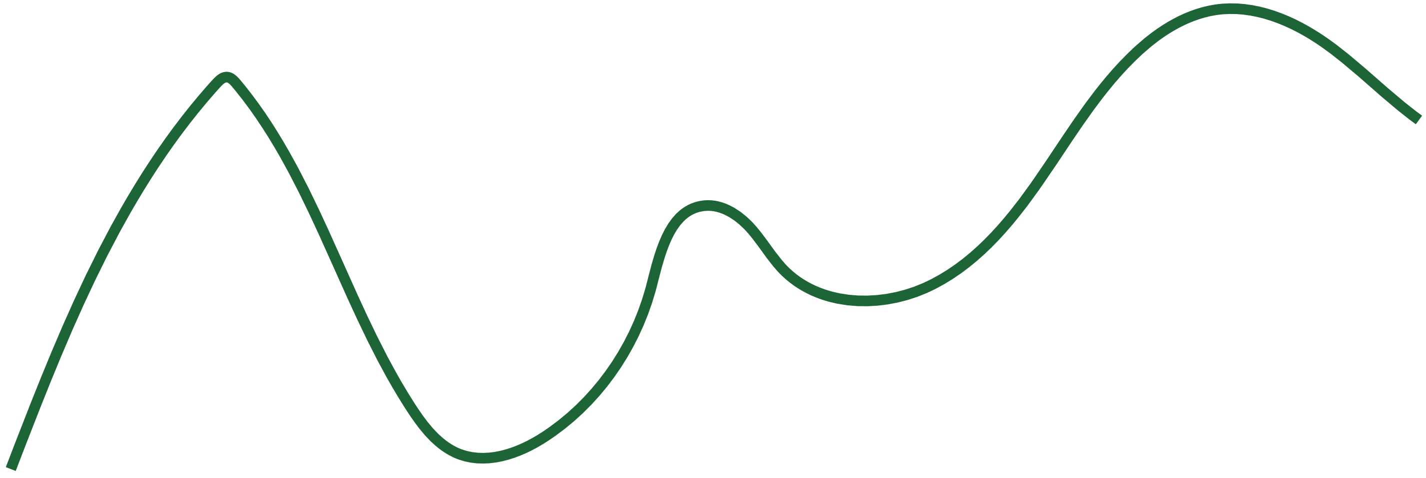


WRF's Vertical Coordinate

- Terrain-following and pressure-based.
- Grid skewness over steep slopes results in numerical errors and can cause model failure.
- Skewness only becomes an issue when terrain slopes are >25%, which only happens while approaching the micro-scale.



Resolved Slope & Grid Resolution



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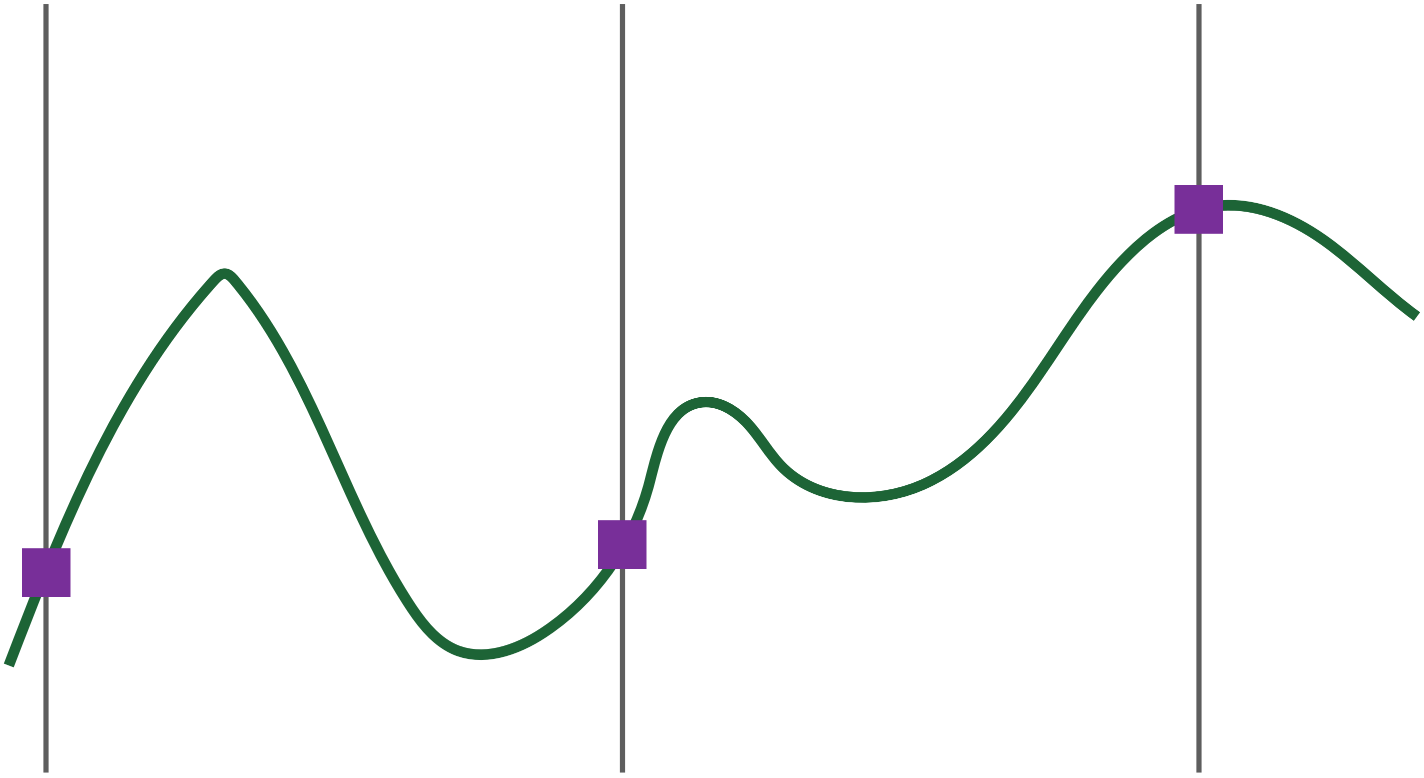

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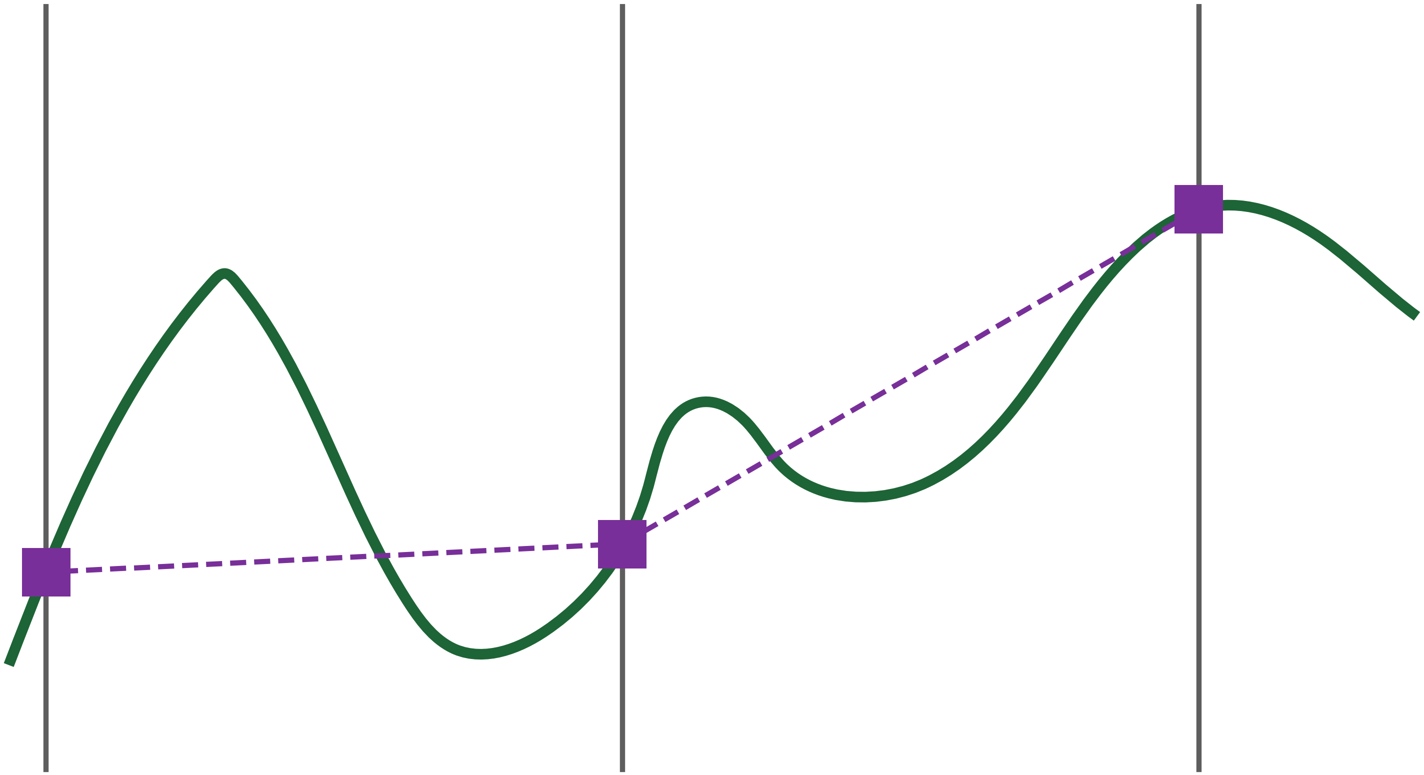

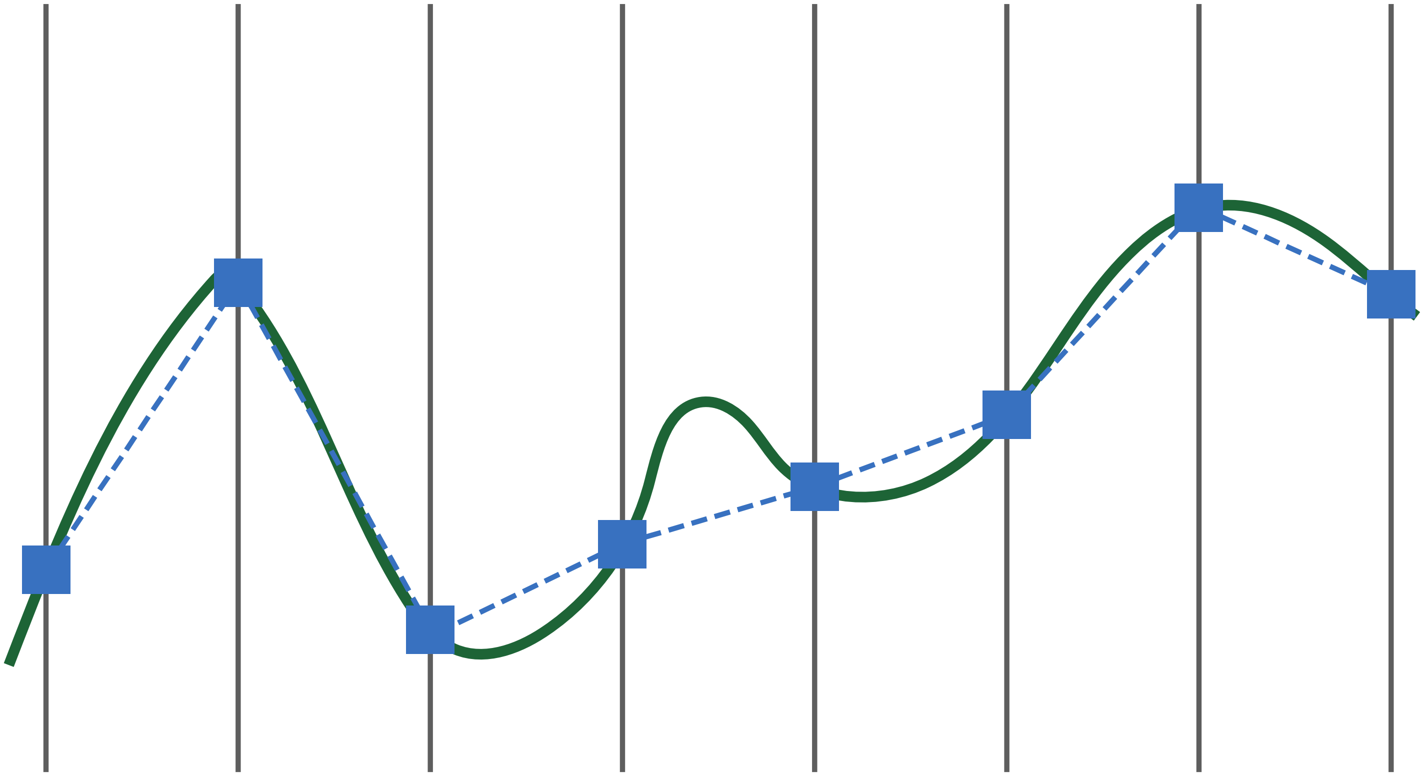

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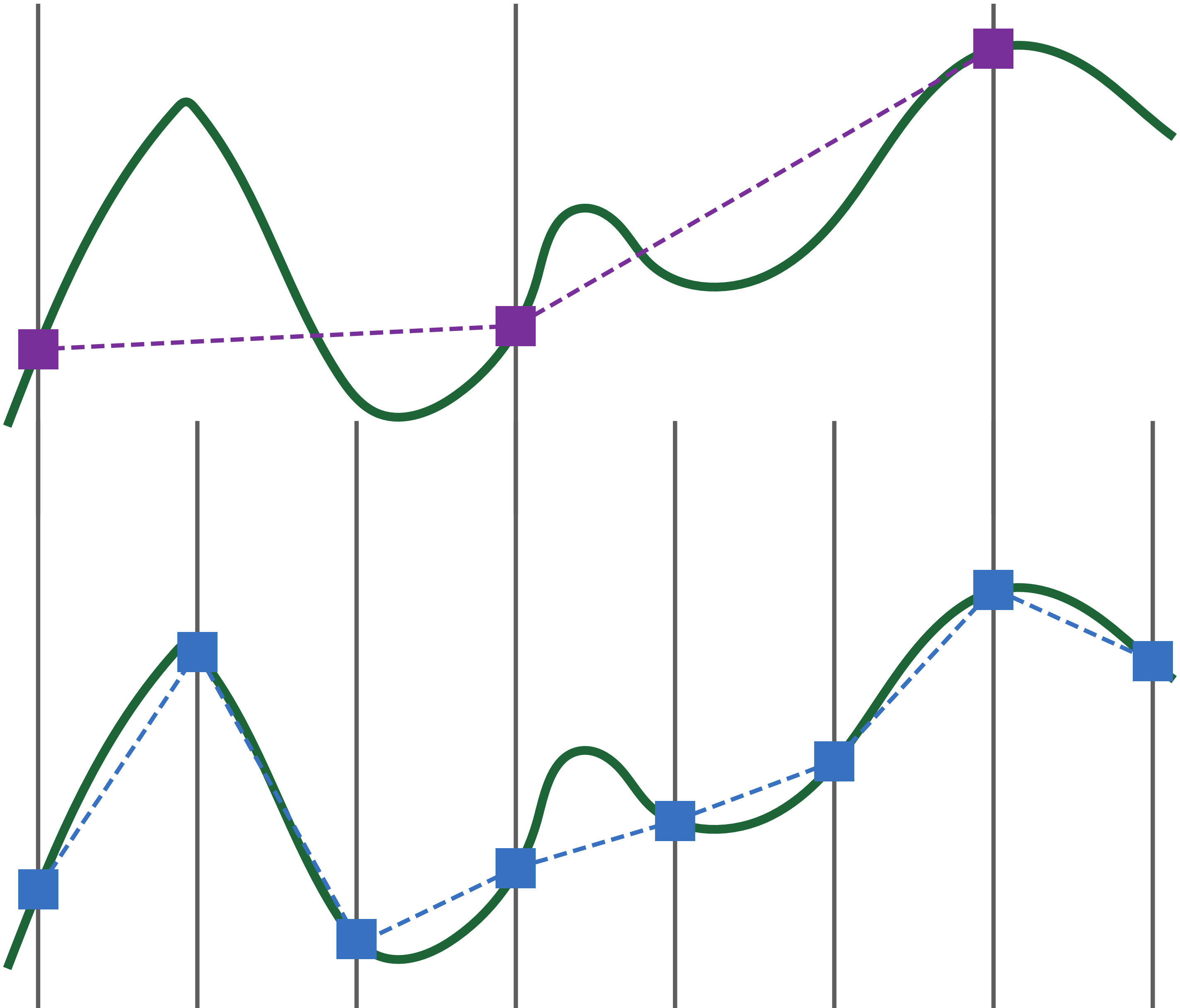
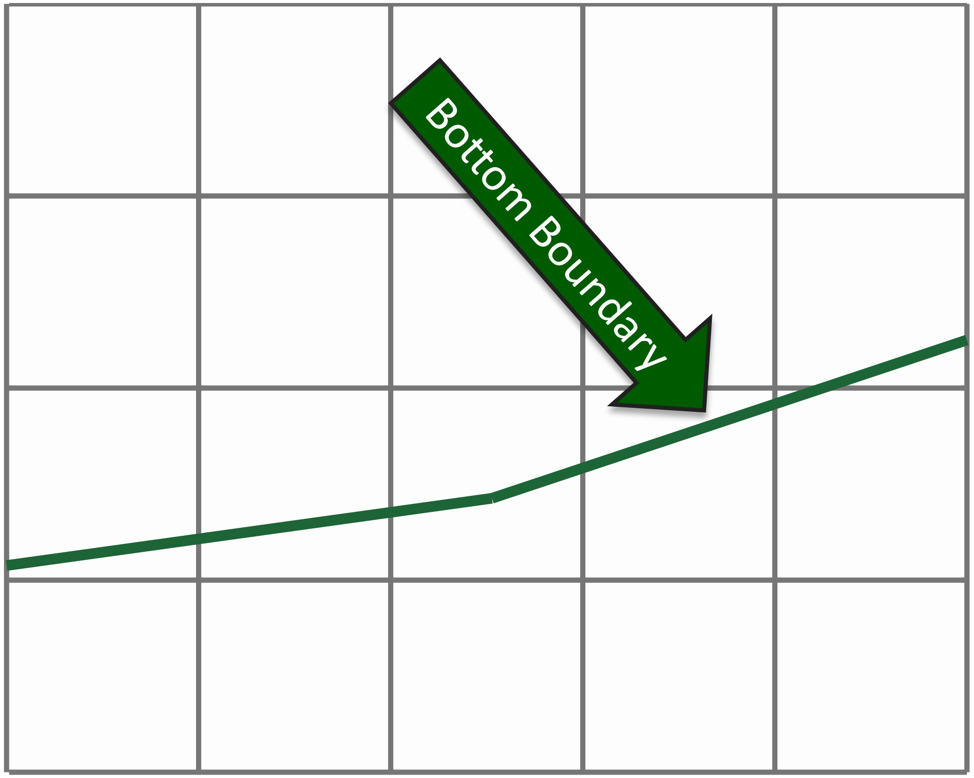
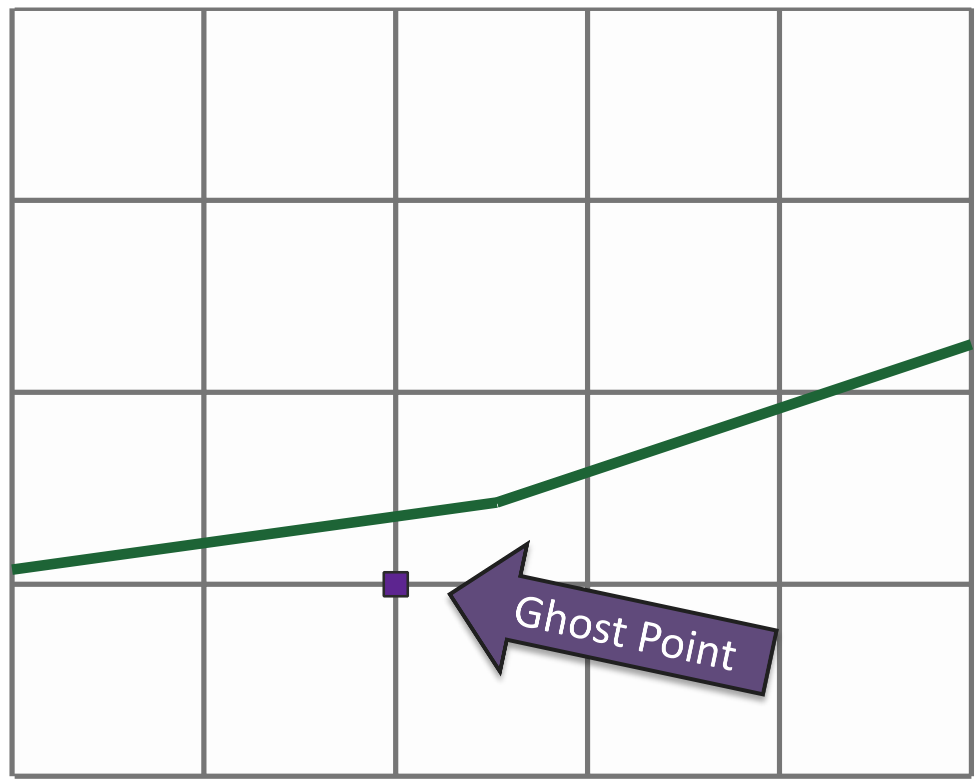


The Immersed Boundary Method



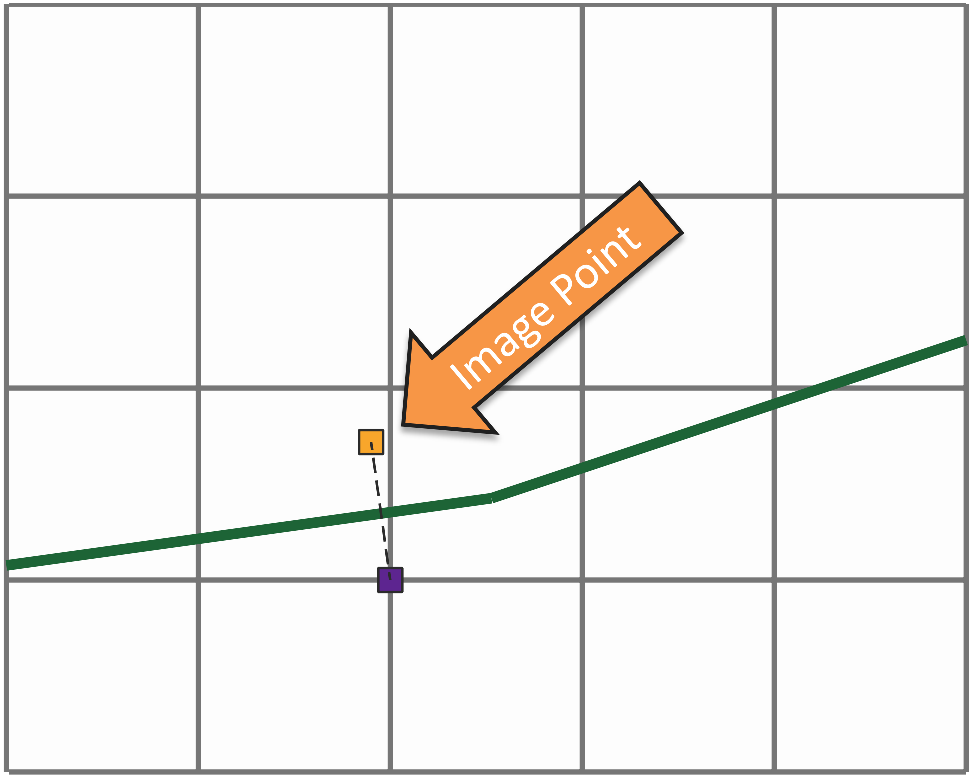
The Immersed Boundary Method

- To set the value of a ghost point,



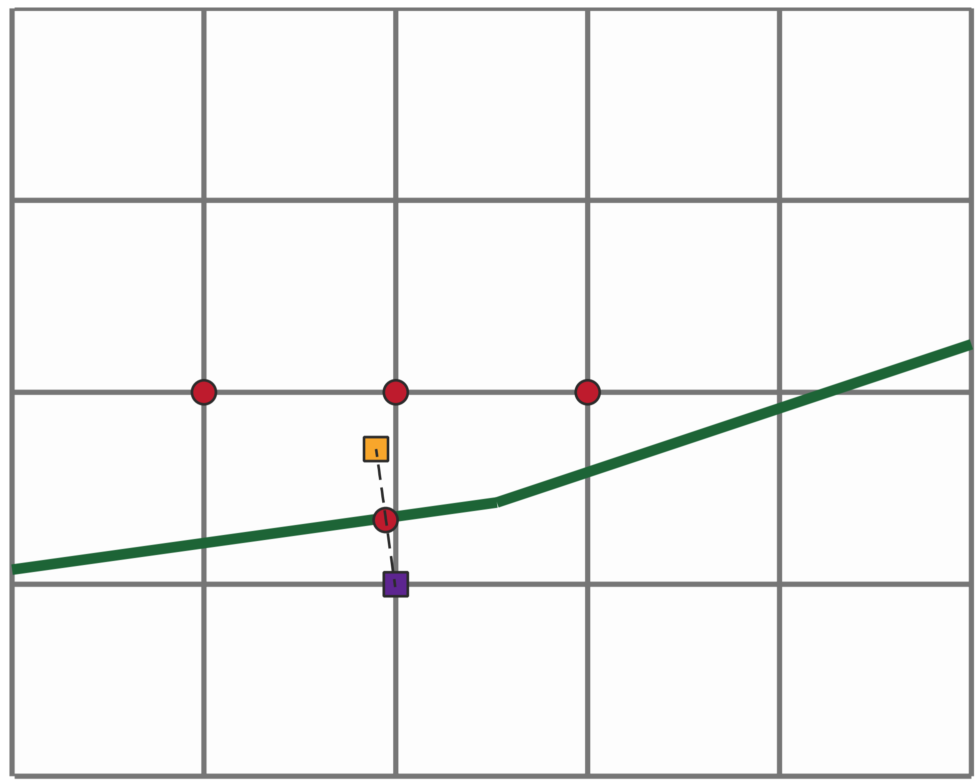
The Immersed Boundary Method

- To set the value of a ghost point,
- Locate the image point by reflecting the ghost point across the interface



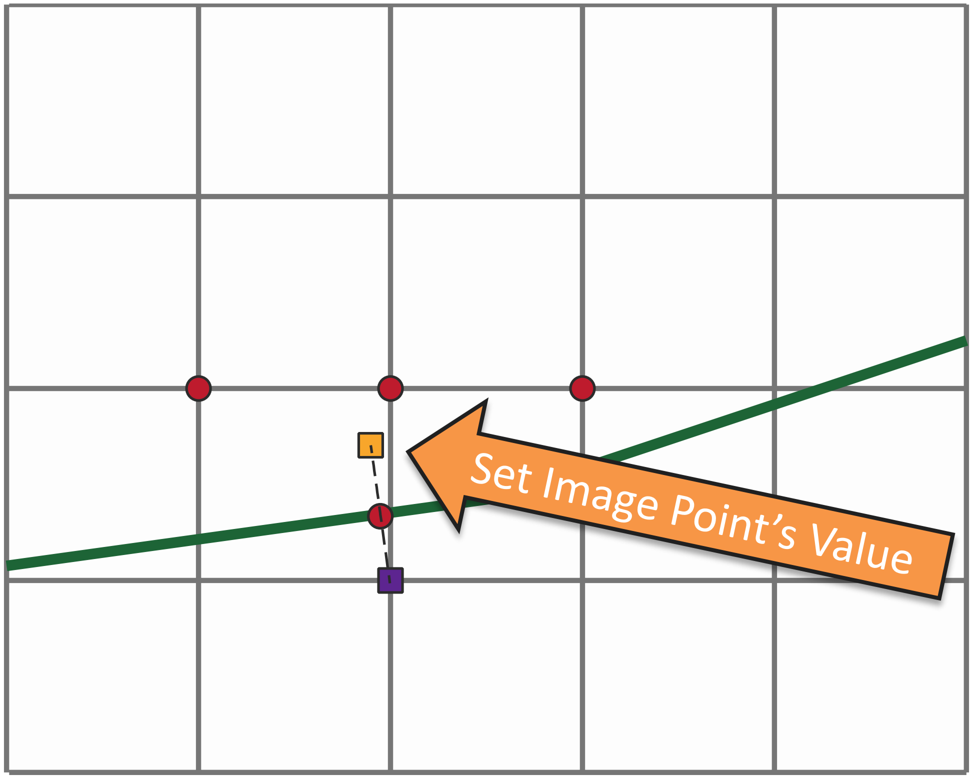
The Immersed Boundary Method

- To set the value of a ghost point,
- Locate the image point by reflecting the ghost point across the interface
- Determine the nearest computational nodes to the image point



The Immersed Boundary Method

- To set the value of a ghost point,
- Locate the image point by reflecting the ghost point across the interface
- Determine the nearest computational nodes to the image point
- Set the image point's value by interpolation



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- To set the value of a ghost point,
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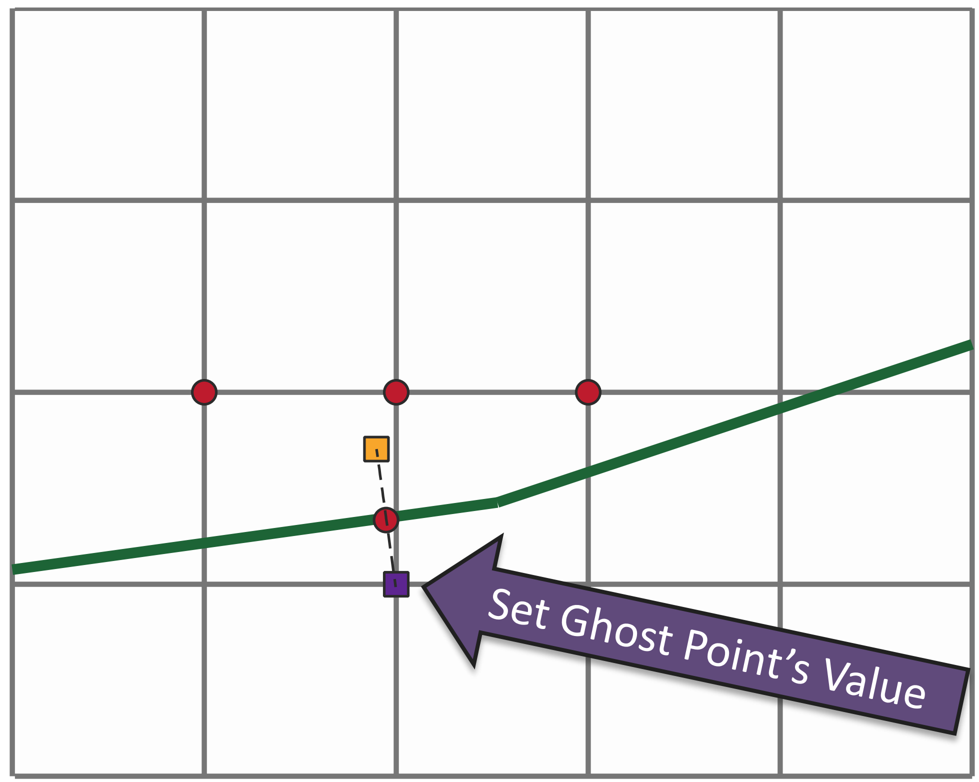
- Using image point's value, determine forcing at ghost point to maintain the desired boundary condition



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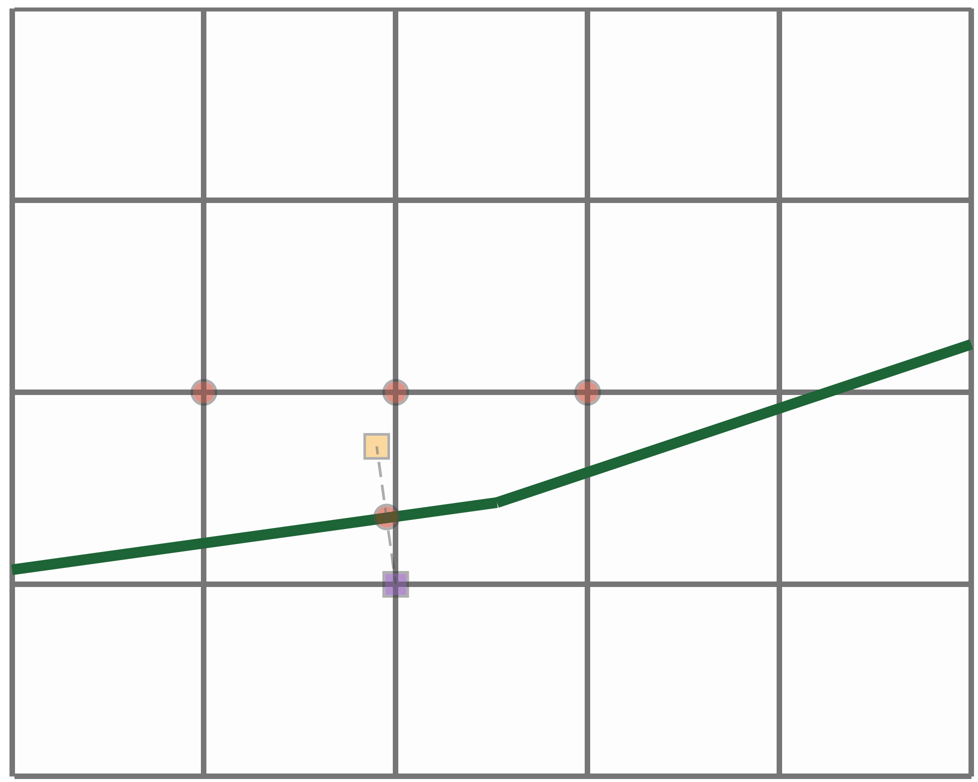

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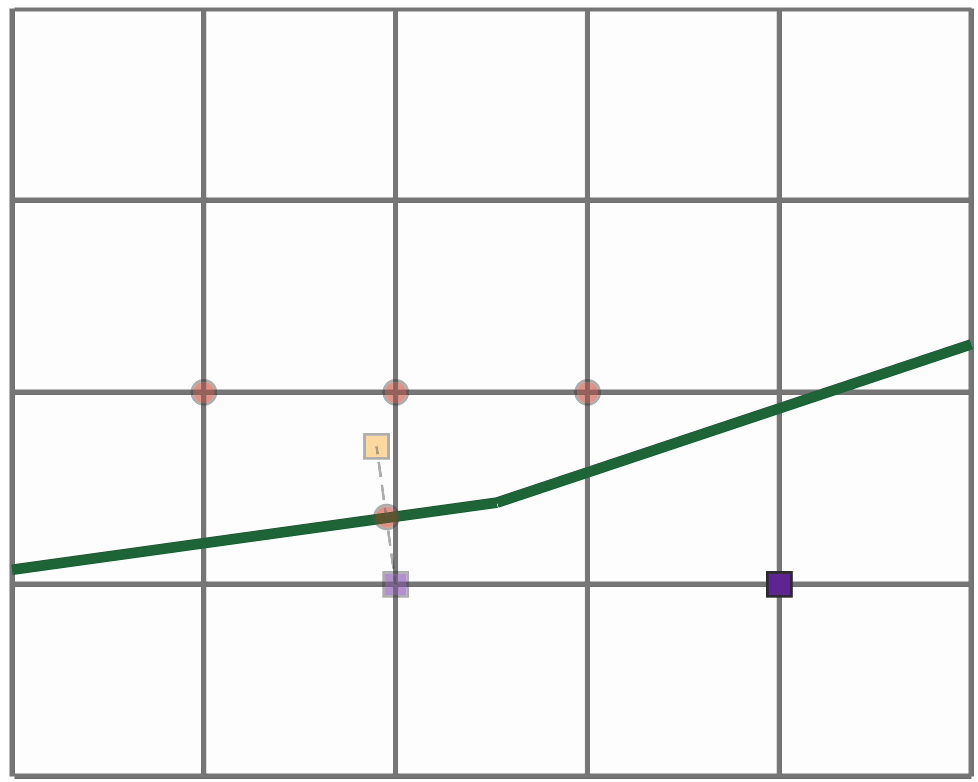

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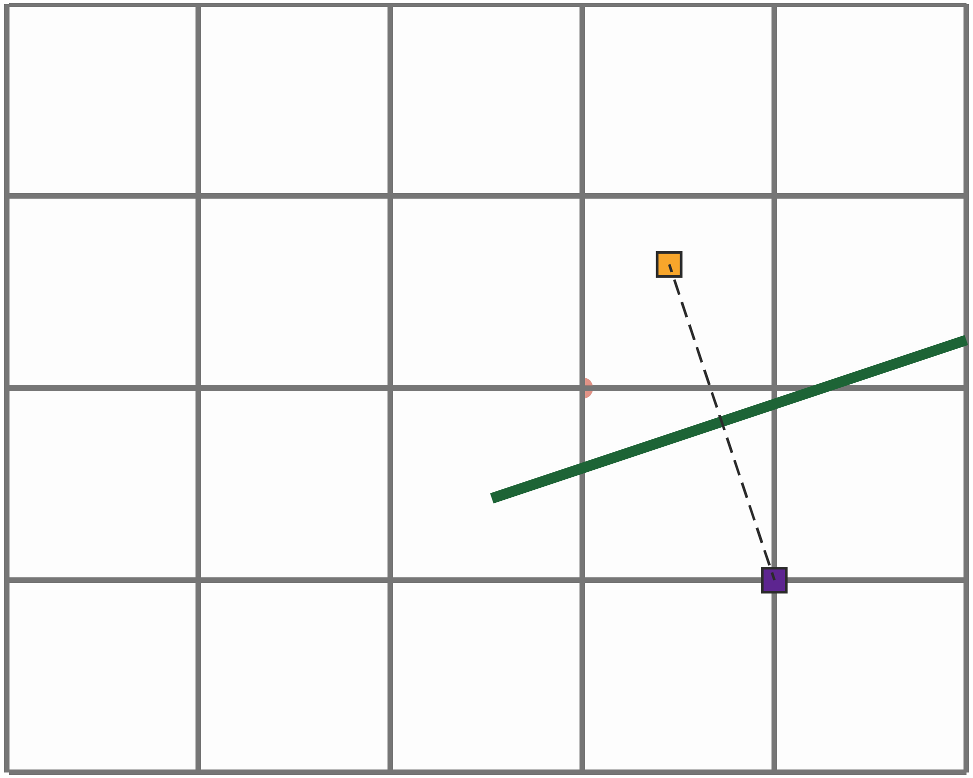

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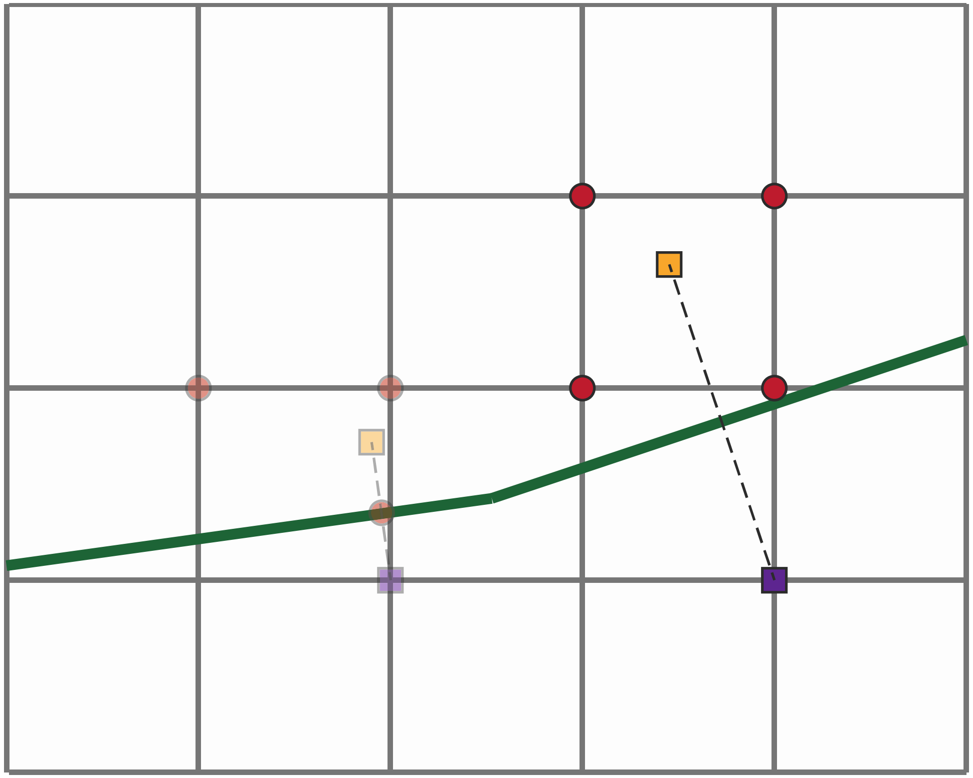

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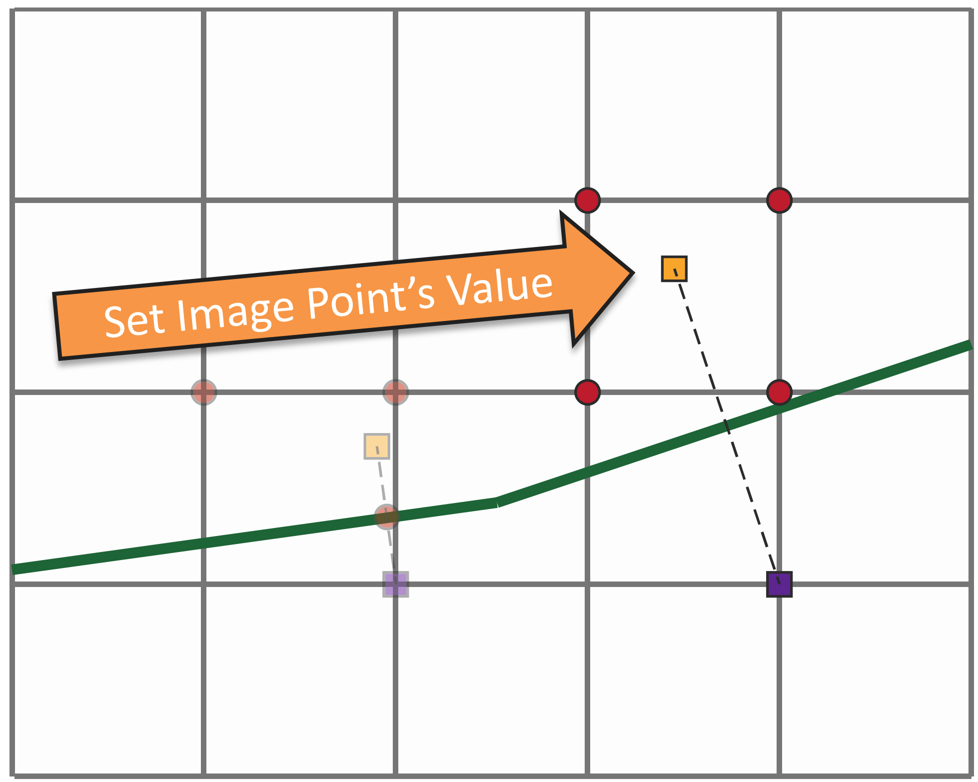

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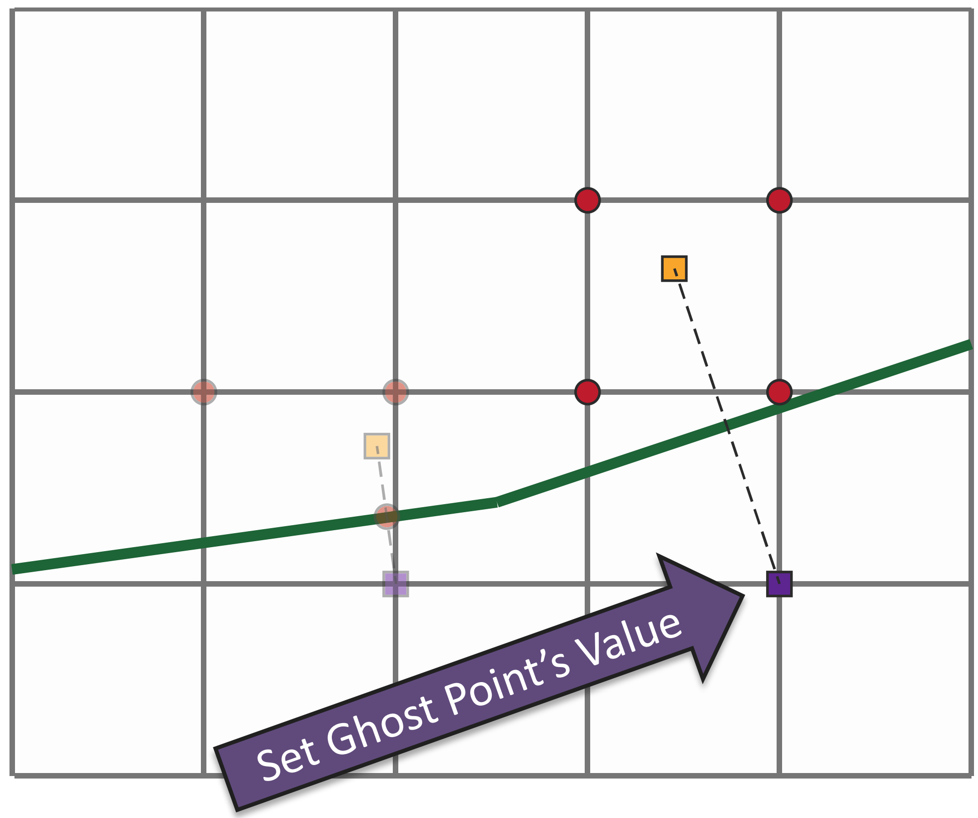

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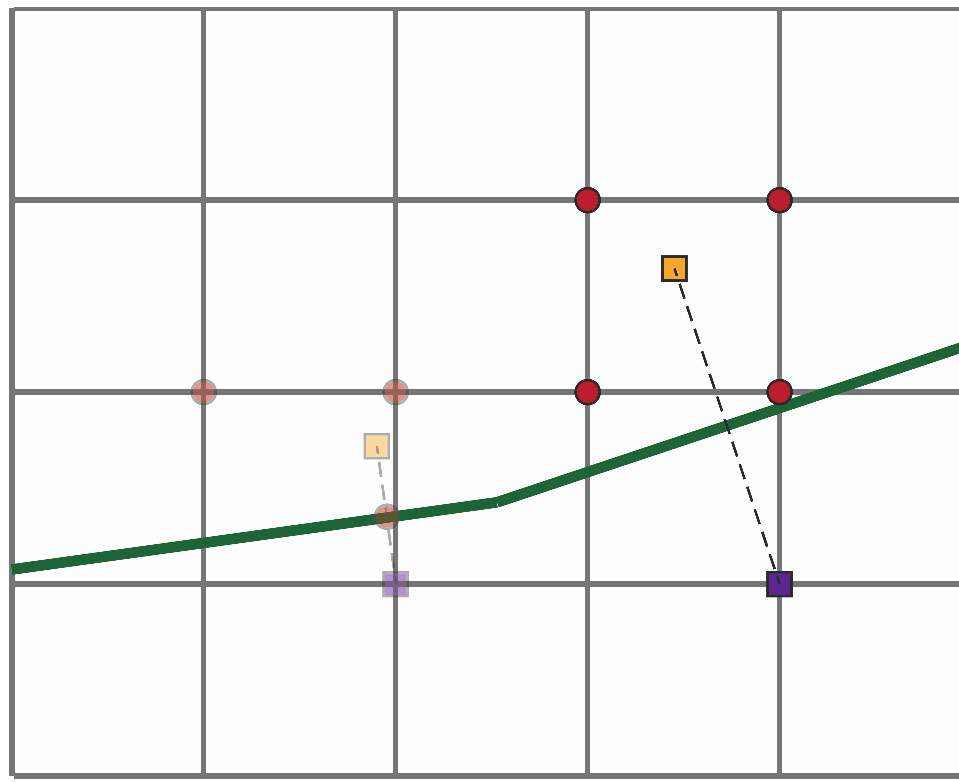
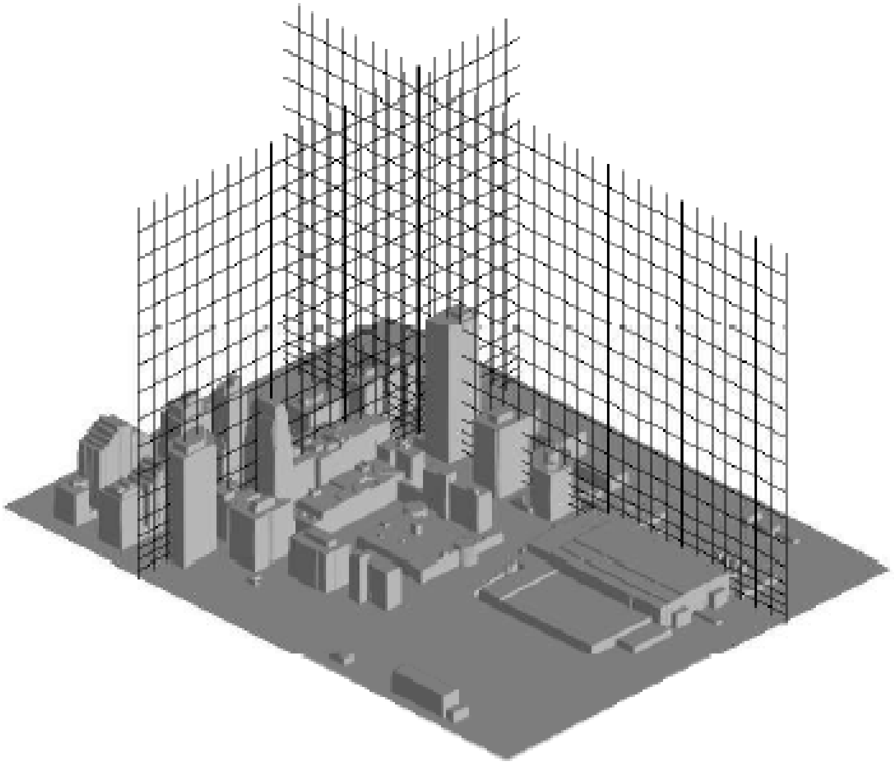


WRF-IBM's Vertical Coordinate

- Pressure-based but not terrain-following.
- No grid skewness due to terrain slopes.



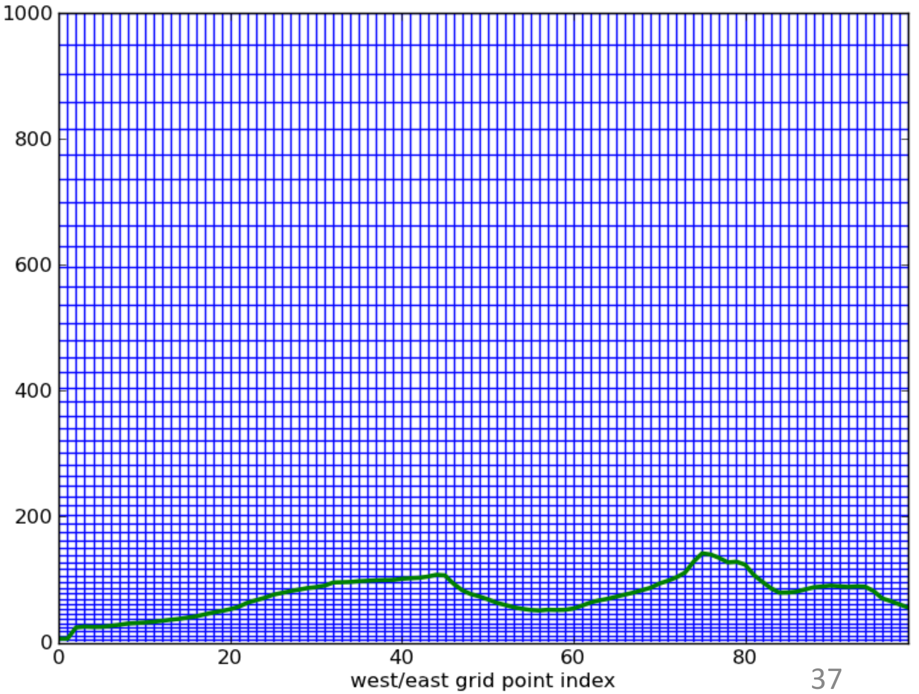
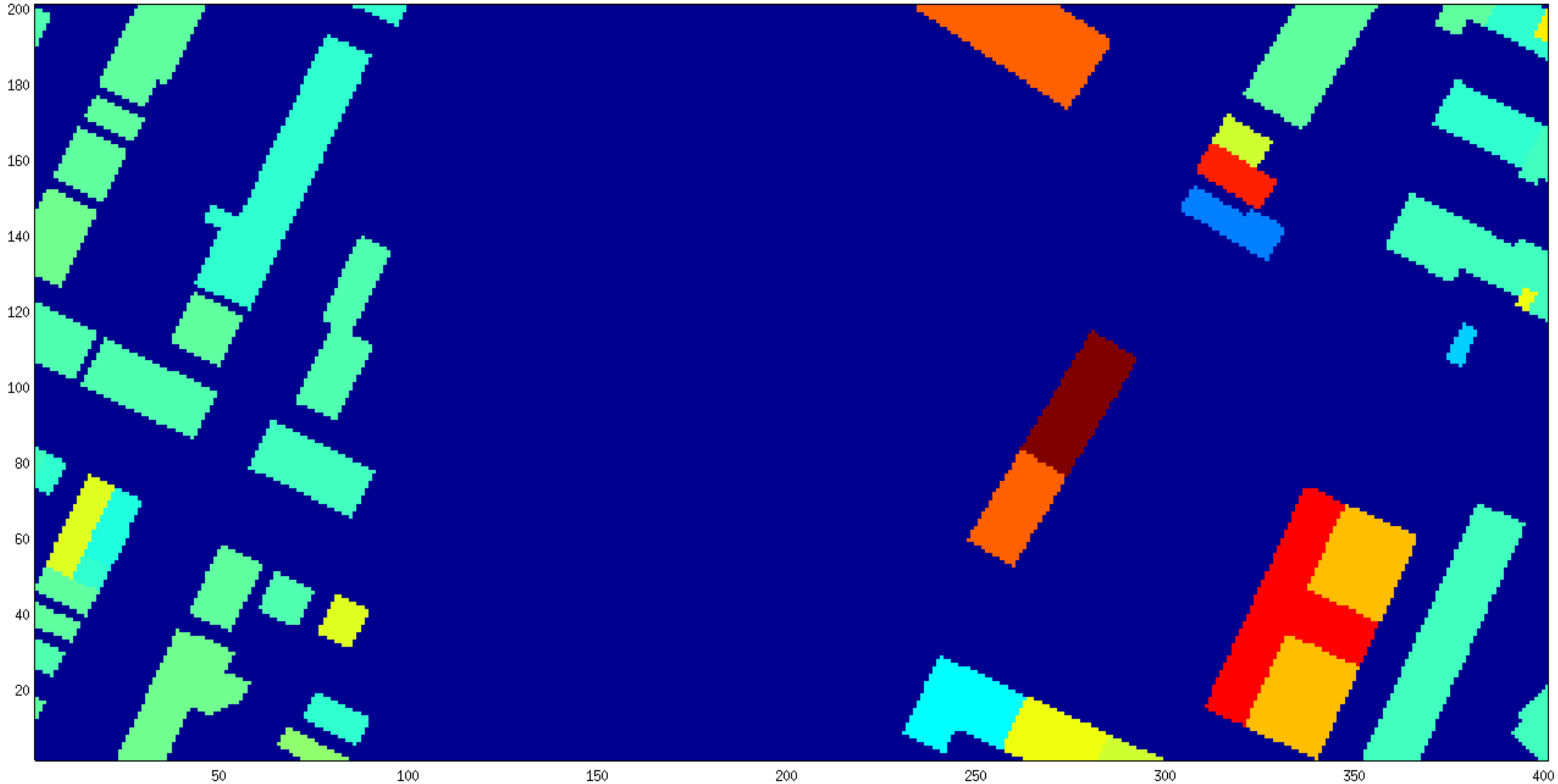


Image courtesy of Katherine Lundquist

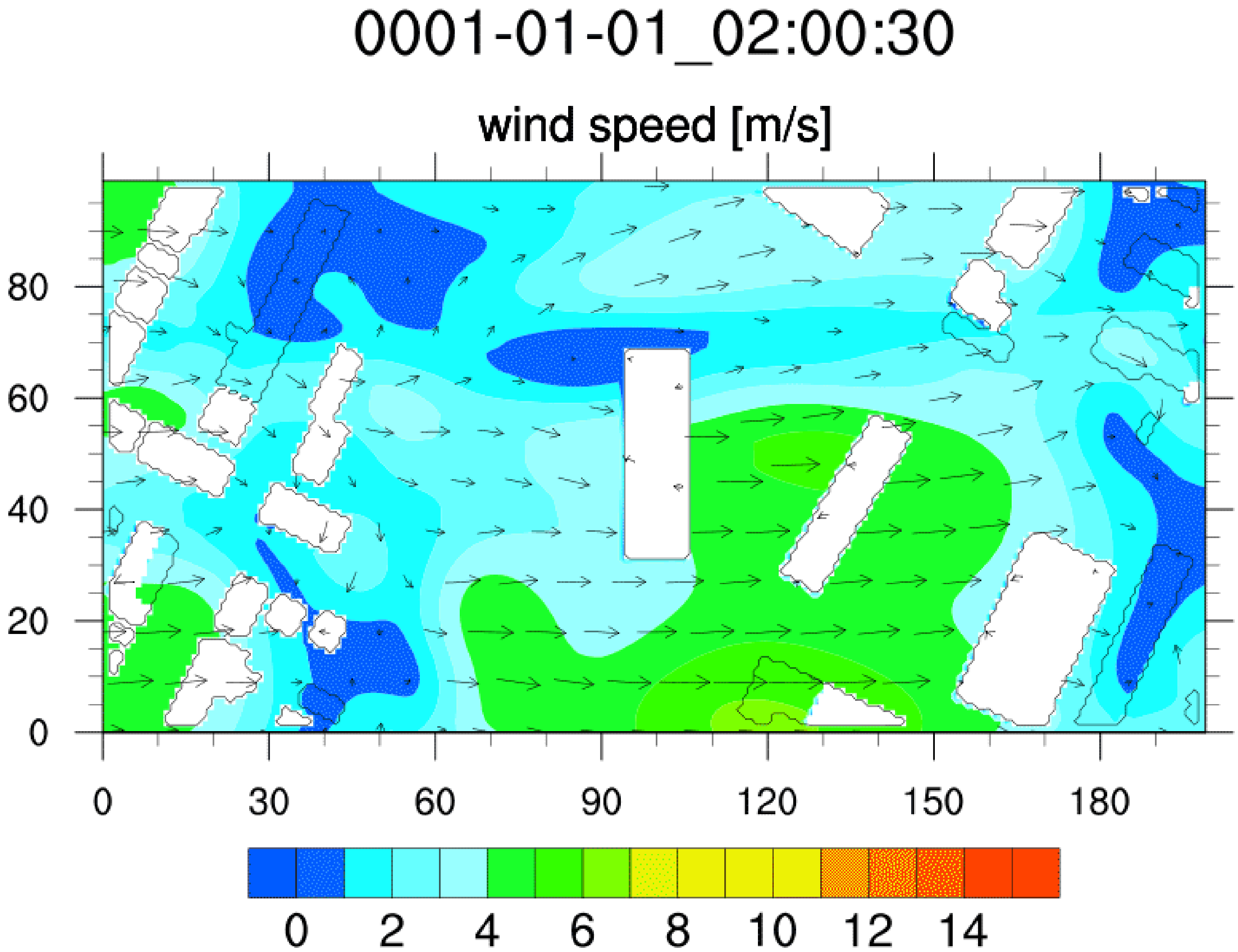
WRF-IBM Setup

- Inverse Distance Weighting interpolation scheme
- Smagorinsky turbulence closure
- No-slip bottom boundary
- Two nested domains with the parent being flat and the nested domain containing buildings
- Periodic lateral boundary conditions on the parent domain
- Rigid, no-flux, top boundary
- Initialized with an idealized sounding
- Line source of emissions with zero initial concentration everywhere

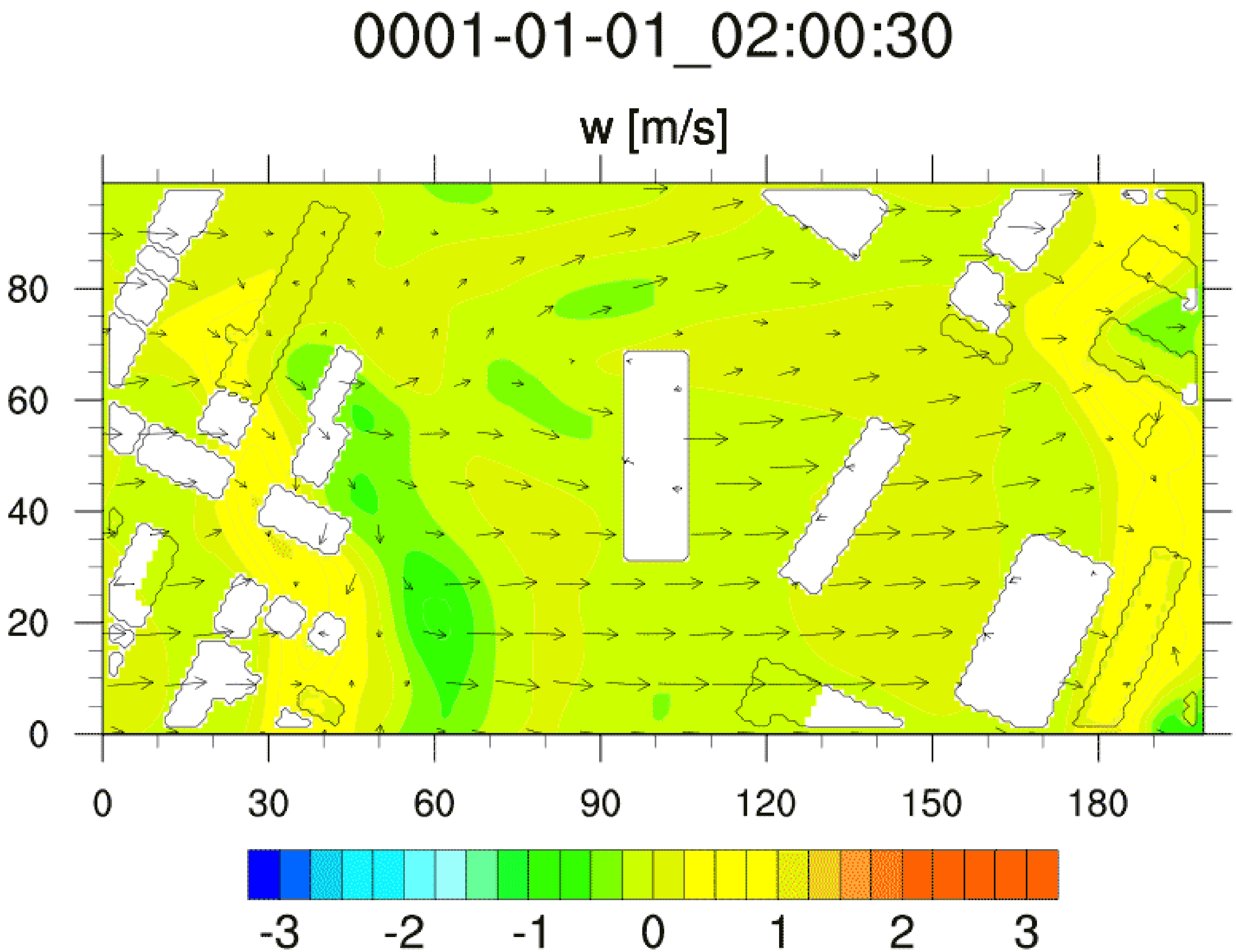
Picking the Grid Resolution



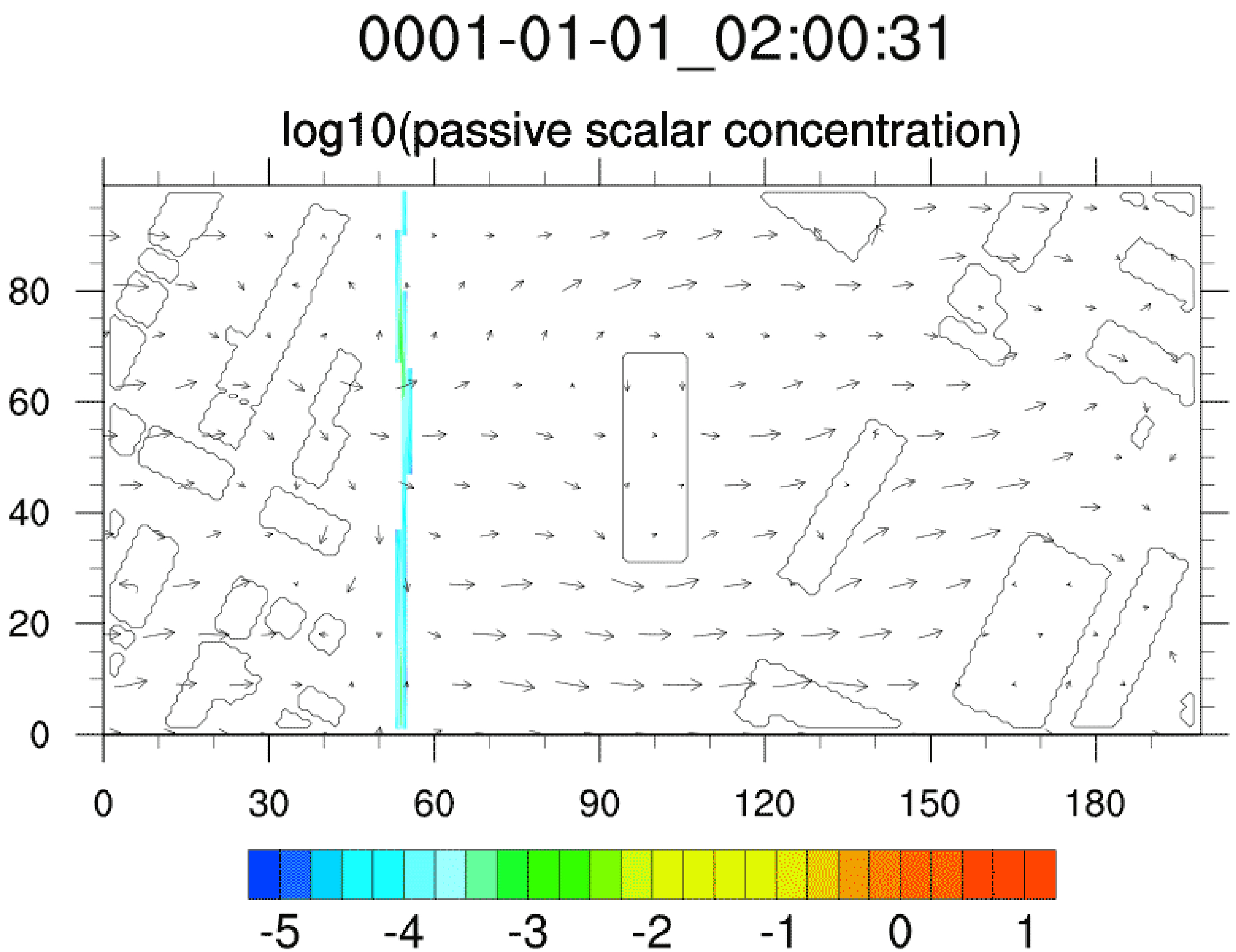
Wind Speed at 2m AGL



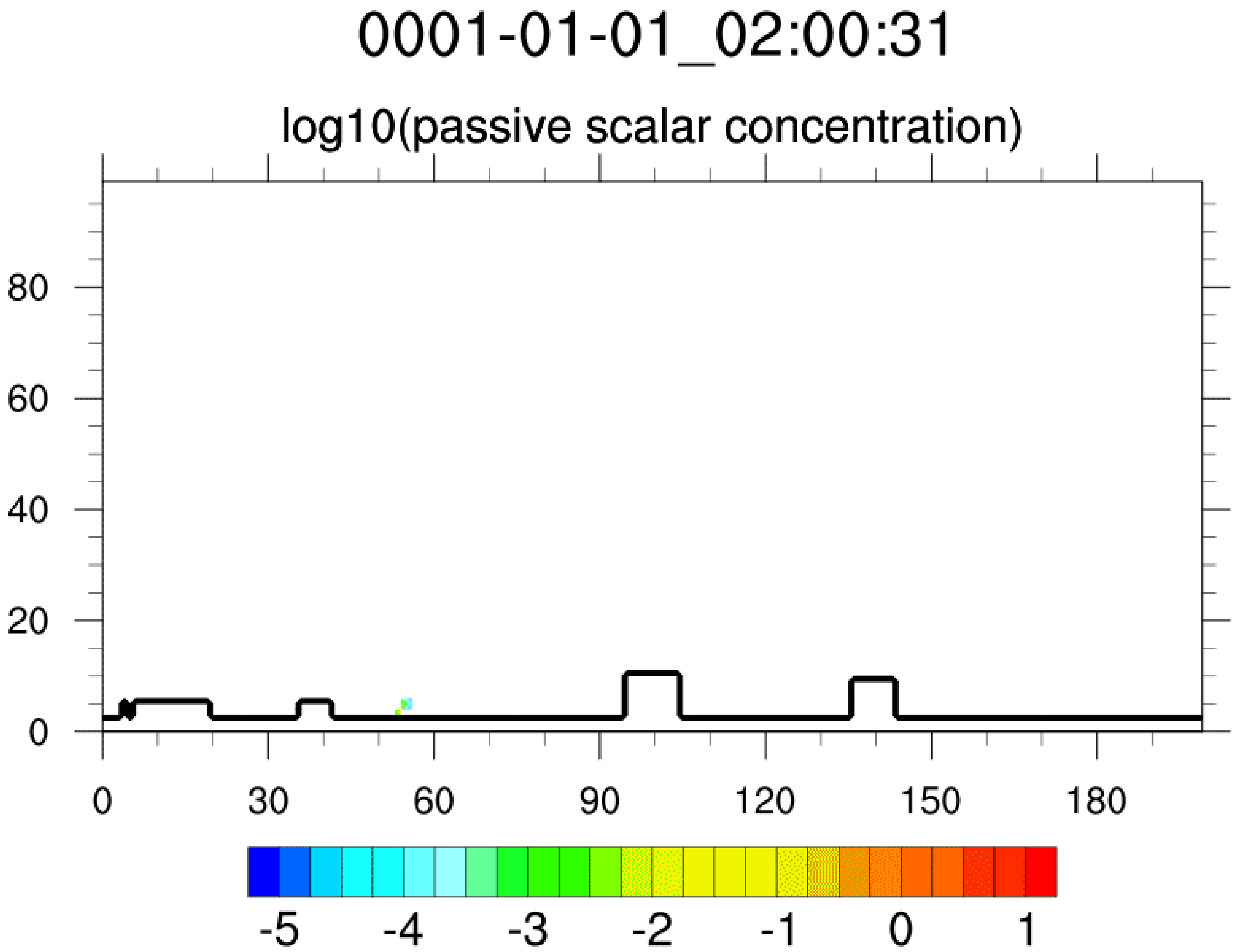
Vertical Velocity at 2m AGL



Passive Tracer at 2m AGL



East-West Slice of Passive Tracer



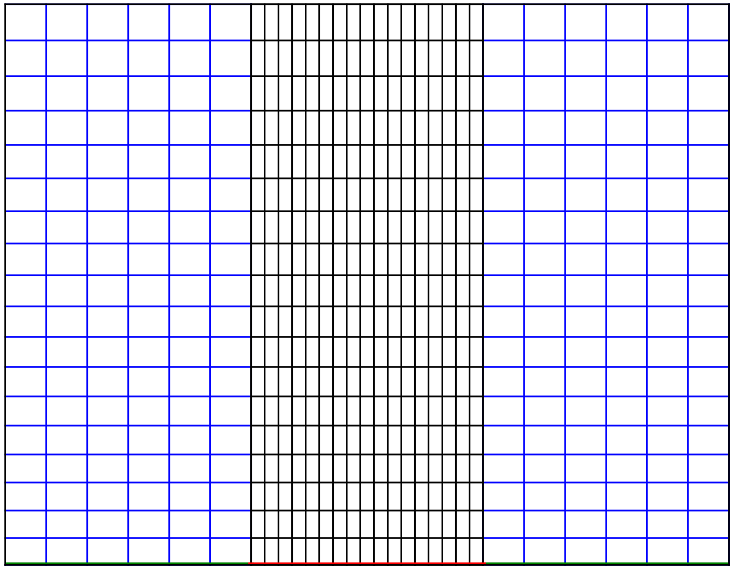
Vertical Grid Nesting in WRF

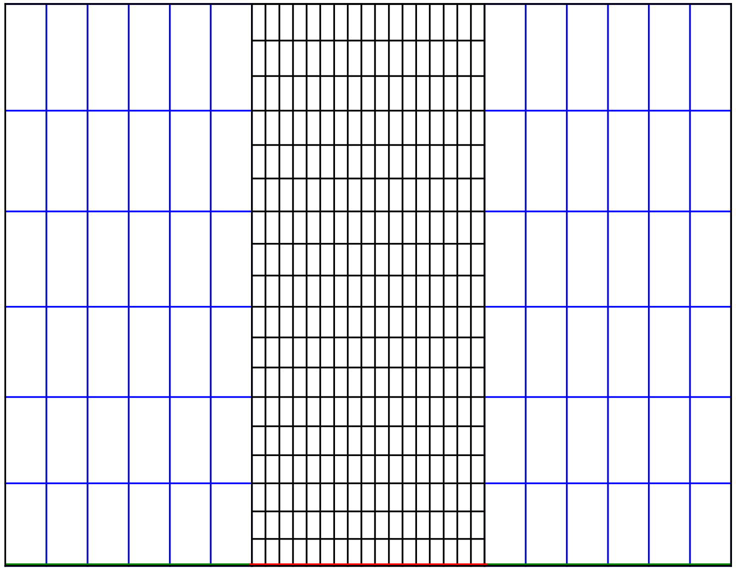
- WRF requires all concurrently nested domains to use the same number and placement of vertical grid levels.
- Vertical grid nesting…
  - allows for additional vertical levels in a nested domain.
  - prevents an excessive number of vertical levels on the parent domain.
  - provides control over the grid aspect ratio of each domain
    - Vital if nesting in a LES model.

Existing Vertical Grid Nesting in WRF

- Concurrent simulation
  - All domains must have identical vertical levels

- Sequentially run simulations with "ndown" (1)
  - Nest boundary conditions update at the frequency of parent grid history
- Uses integer refinement of parent vertical levels





(1) Moustaoui, M., A. Mahalov, J. Dudhia, and D. Gill, 2009: Nesting in wrf with vertical grid refinement and implicit relaxation. WRF Users' Workshop 2009, Boulder, CO, National Center for Atmospheric Research.

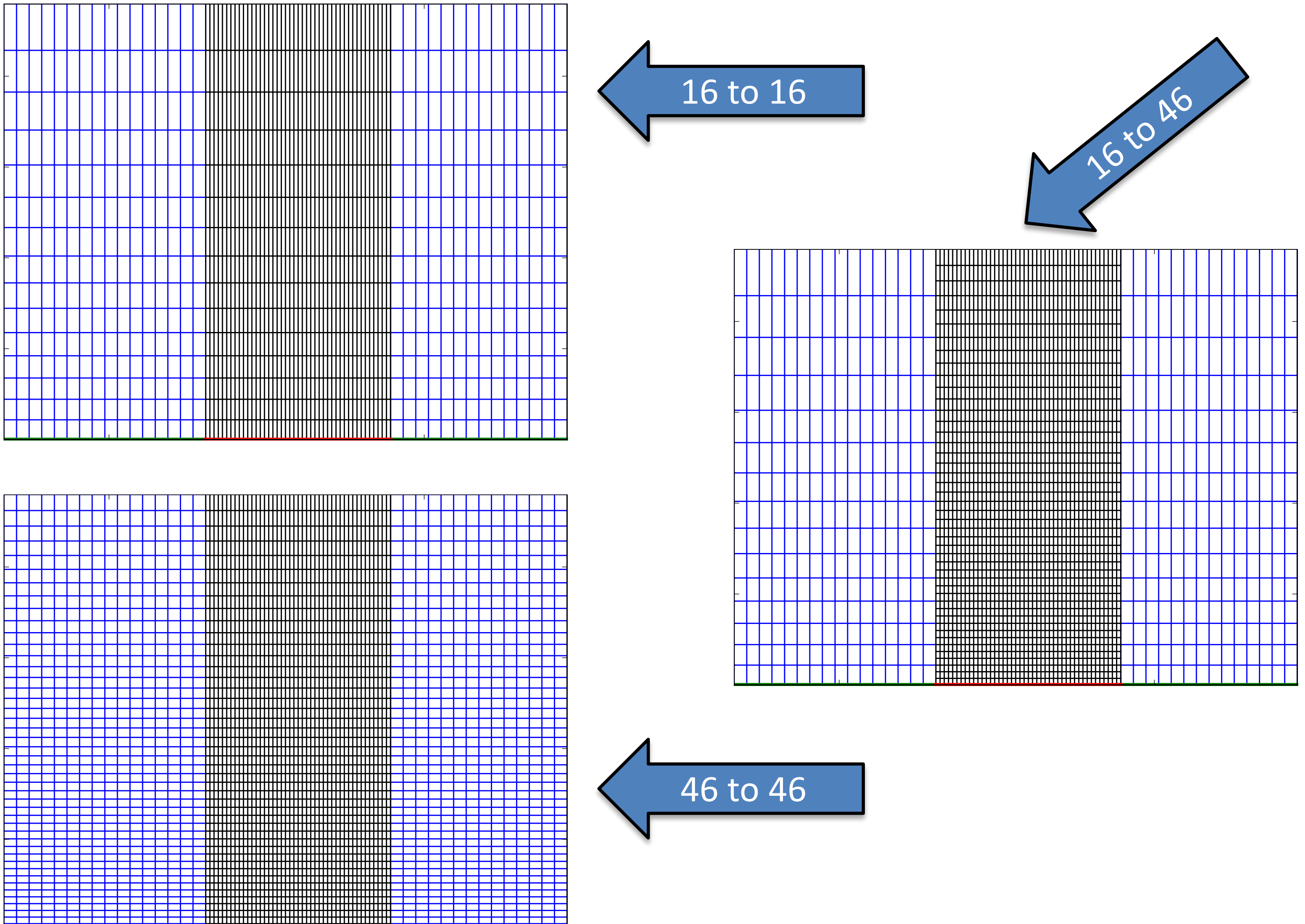
Concurrent Vertical Grid Nesting

- Utilizes the interpolation scheme from ndown
  - Cubic Hermite interpolation
    - Matches value at known points and first derivative
  - Can use an arbitrary number of vertical levels for nested domain compared to parent domain
- Included in the public release of WRFv3.6.1
  - Still in development and currently undocumented
- Enabled by one new variable in namelist.input

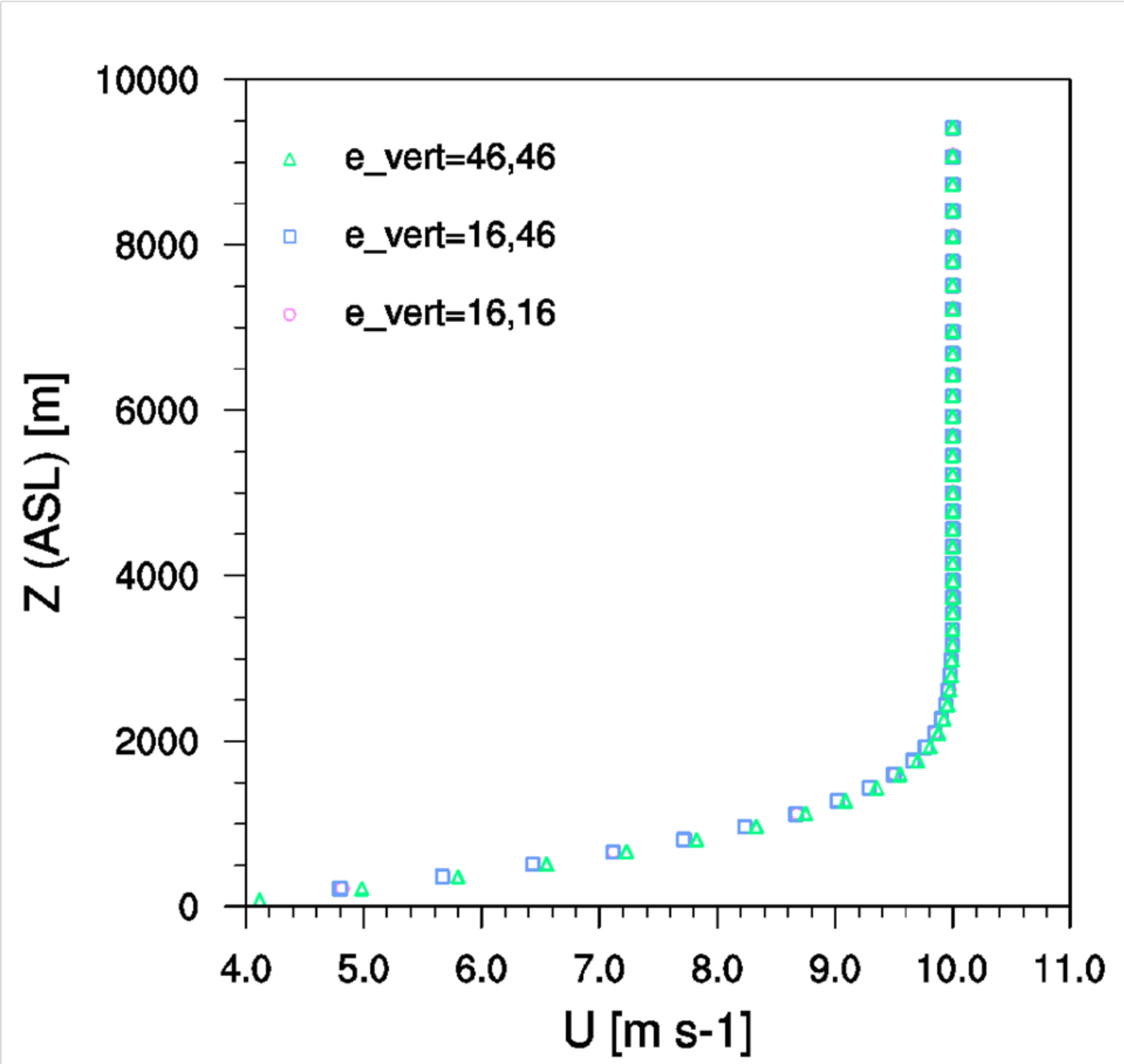
Validation of Vertical Grid Nesting

- Flat plate
- Periodic lateral boundary conditions
- No atmospheric physics
- Initialized with idealized sounding
  - 10 m s^{-1} wind speed at all heights
  - Dry and neutral temperature profile
- Forced by maintaining initial conditions in top 3000 meters of domain

With & Without Vertical Grid Nesting



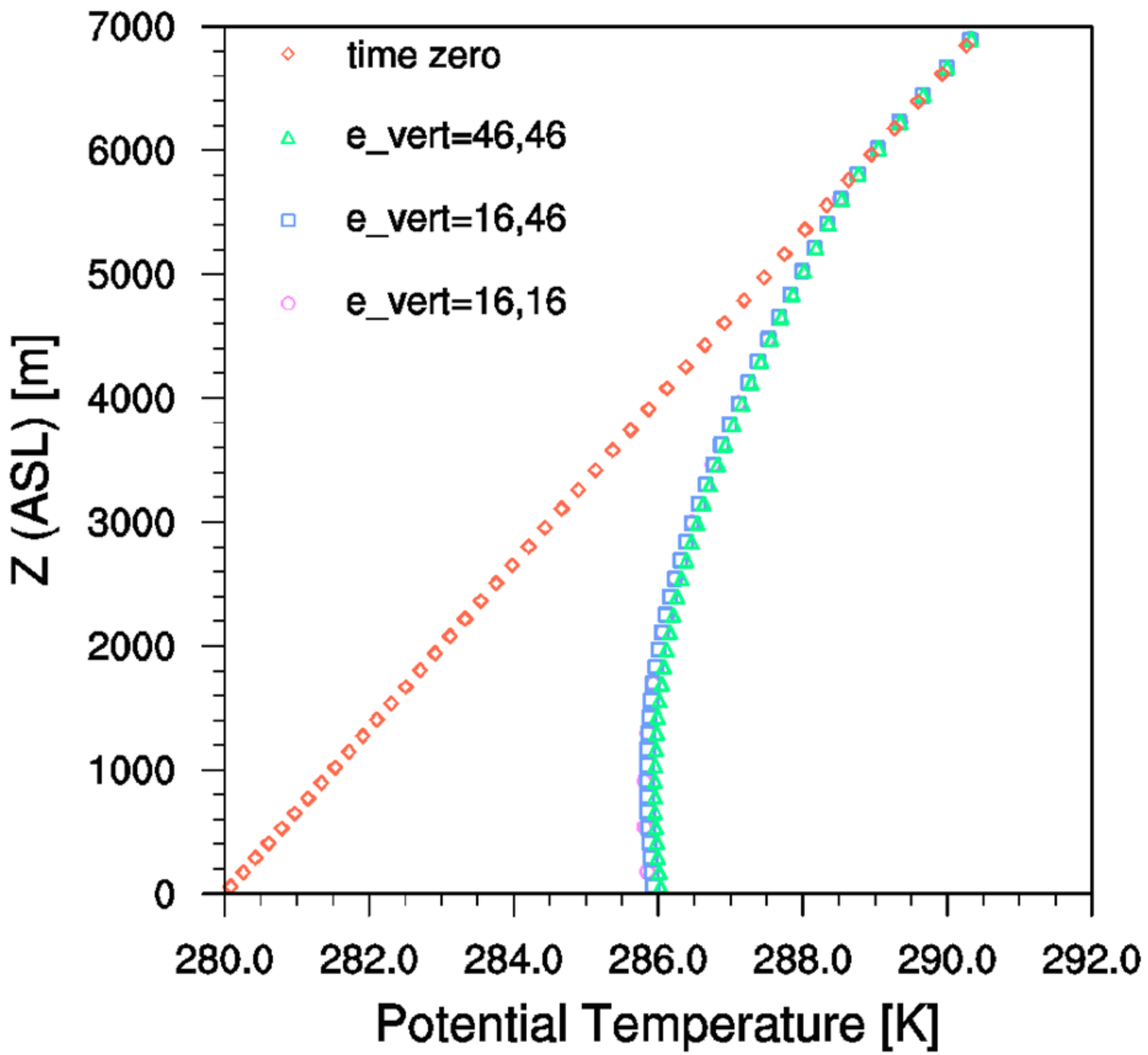
Flow Over A Flat Plate



Vertical Nesting with Atmospheric Physics

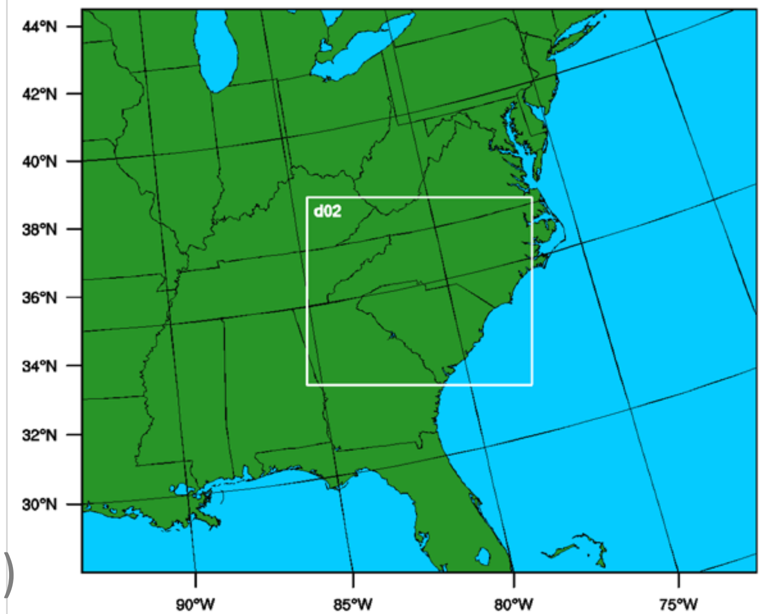
- Flat plate with uniform land surface and soil properties
- Initialized with a stable, dry, quiescent idealized sounding
- Periodic lateral boundary conditions
- Parameterizations and sub-models:
  - Longwave radiation (RRTM)
  - Shortwave radiation (Dudhia)
  - Land surface model (Noah)
  - Surface layer (Monin-Obukhov)
- Difficulties with radiation schemes
  - We are currently evaluating which schemes are working properly with our modifications and enabling the use of several popular schemes with vertical nesting

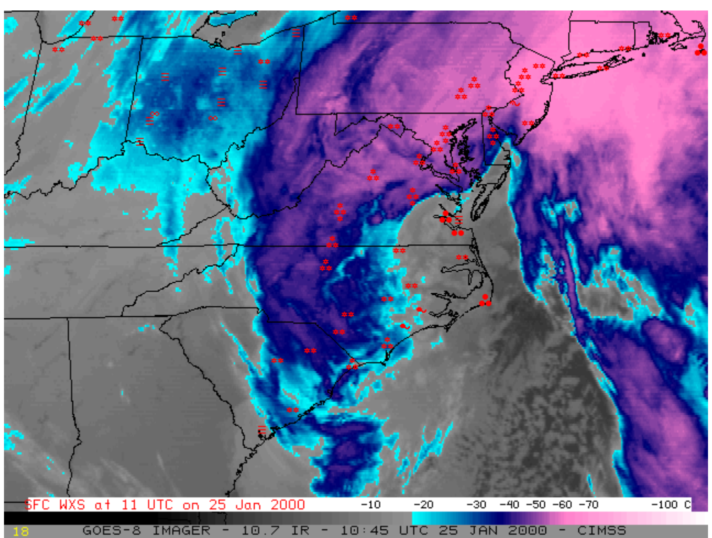
Heating of a Flat Plate

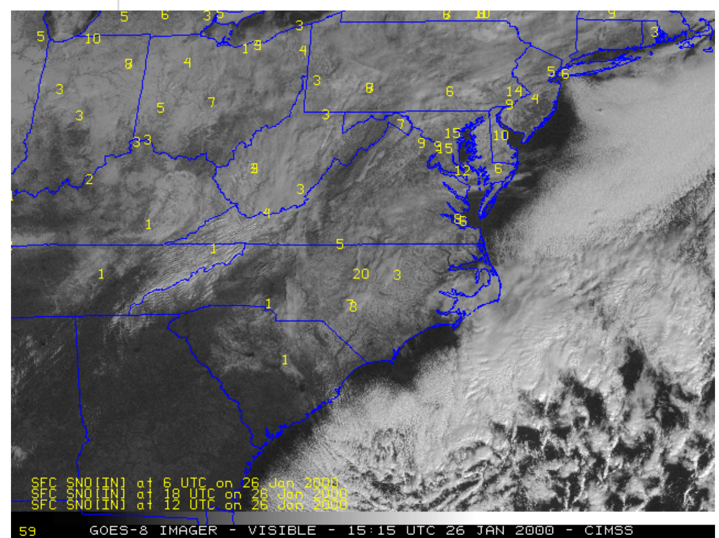


WRF Meso-Scale Test Case

- Parameterizations and sub-models:
  - Microphysics (WSM 3-class)
  - Longwave radiation (RRTM)
  - Shortwave radiation (Dudhia)
  - Land surface model (Thermal diffusion)
  - Surface layer (Monin-Obukhov)
  - Planetary Boundary Layer (YSU)
  - Cumulus Parameterization (Kain-Fritsch)

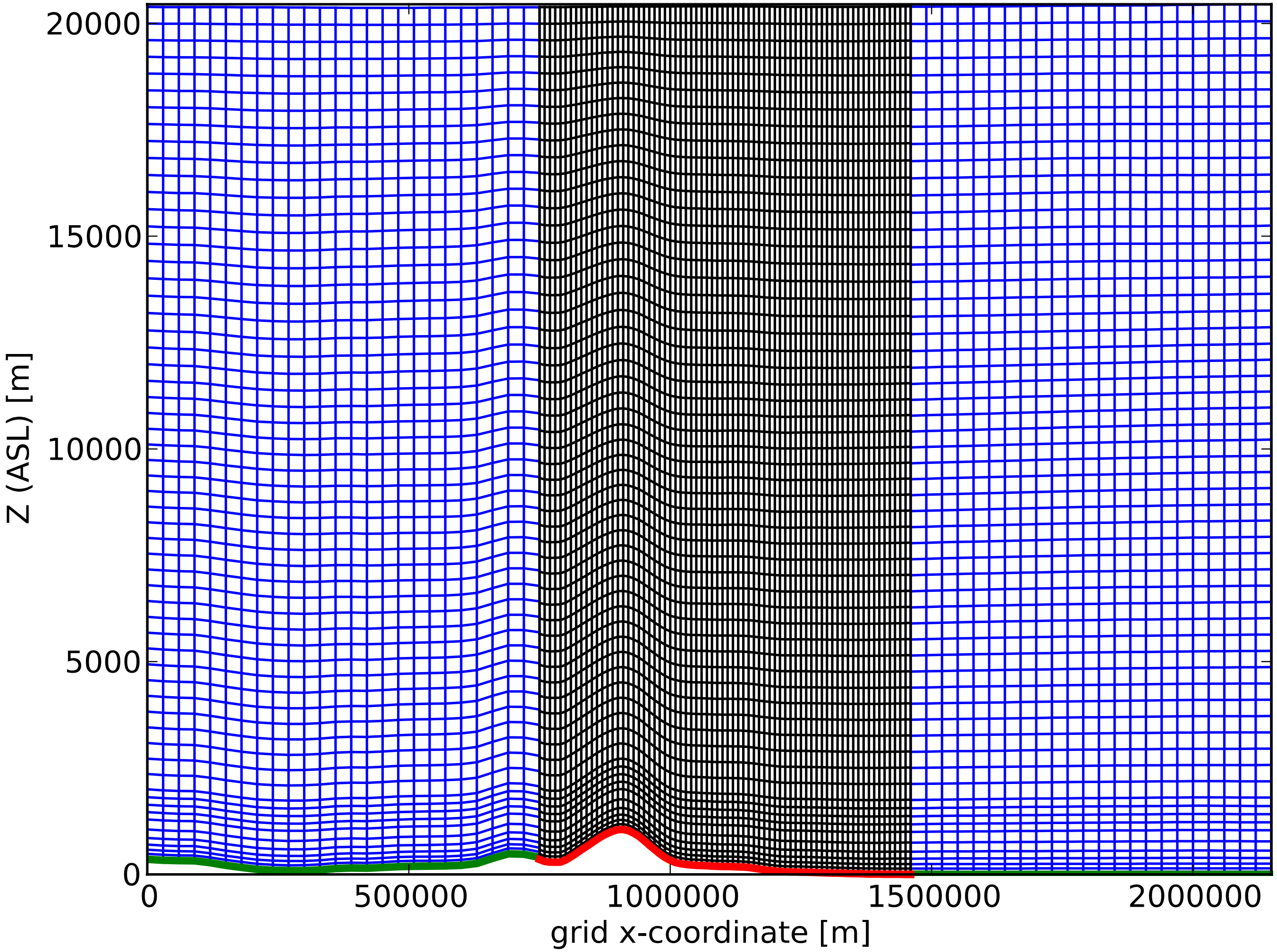






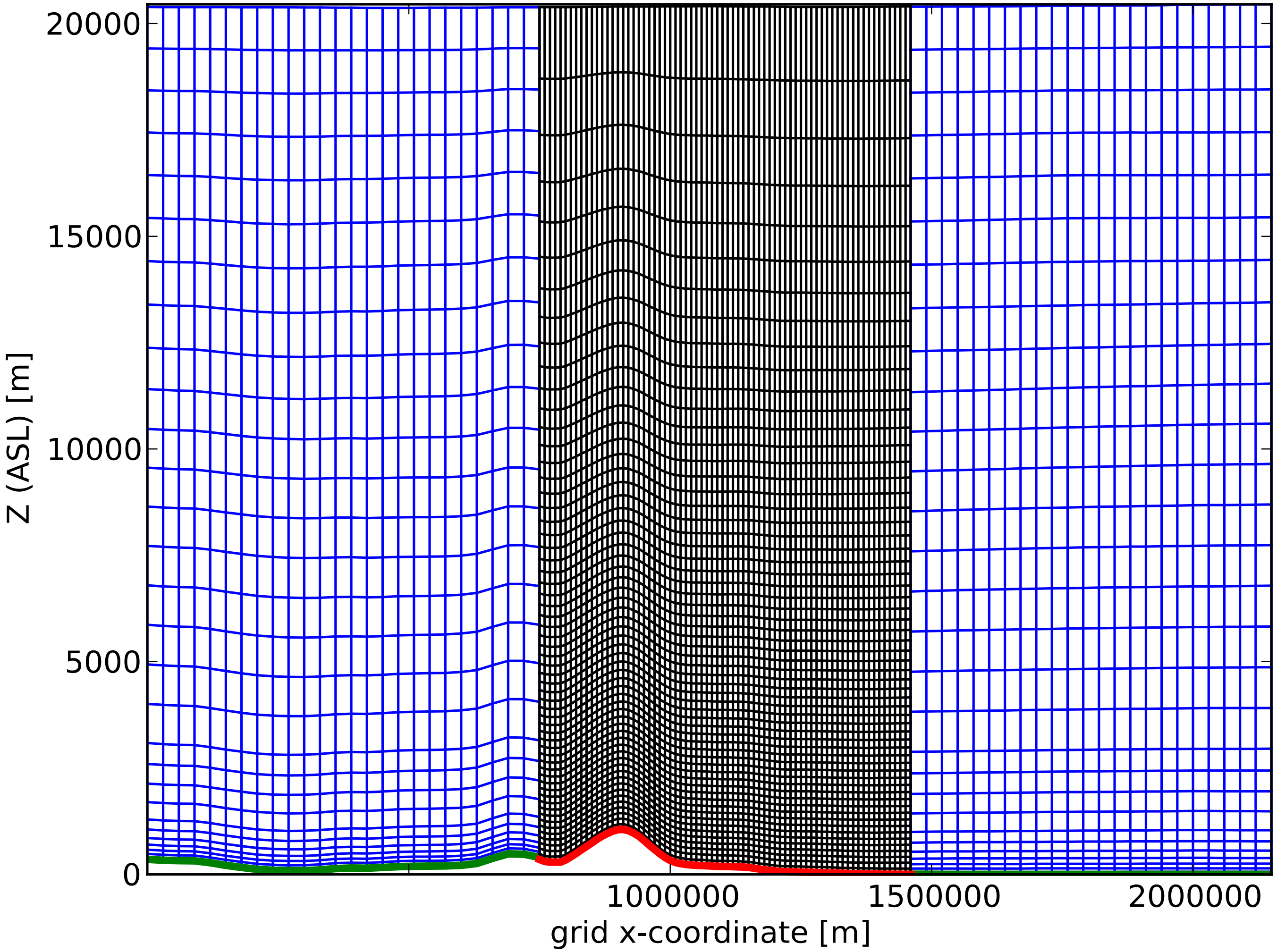
Without Vertical Grid Nesting

Vertical Levels
Parent: 60
Nest: 60



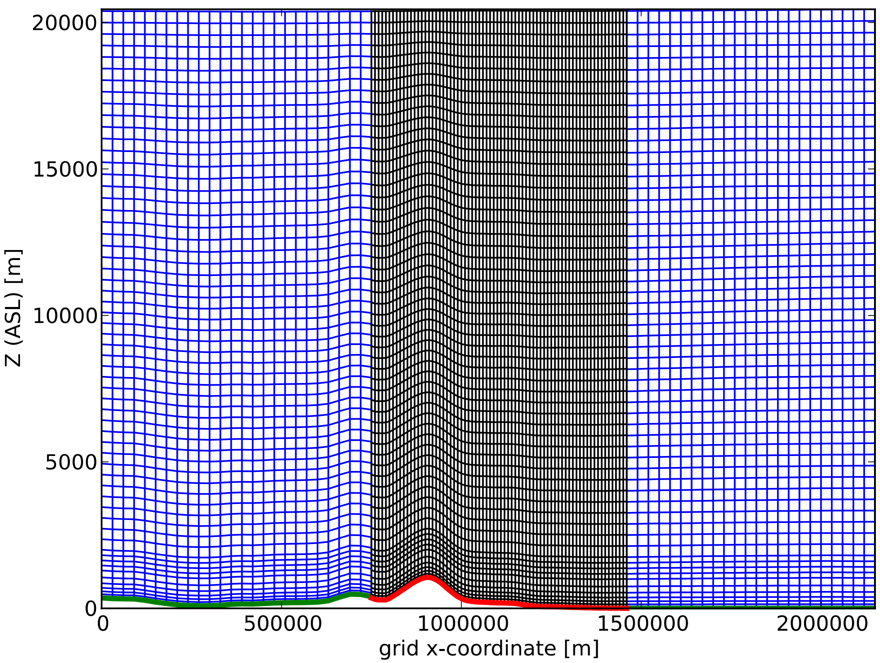
With Vertical Grid Nesting

Vertical Levels
Parent: 30
Nest: 60

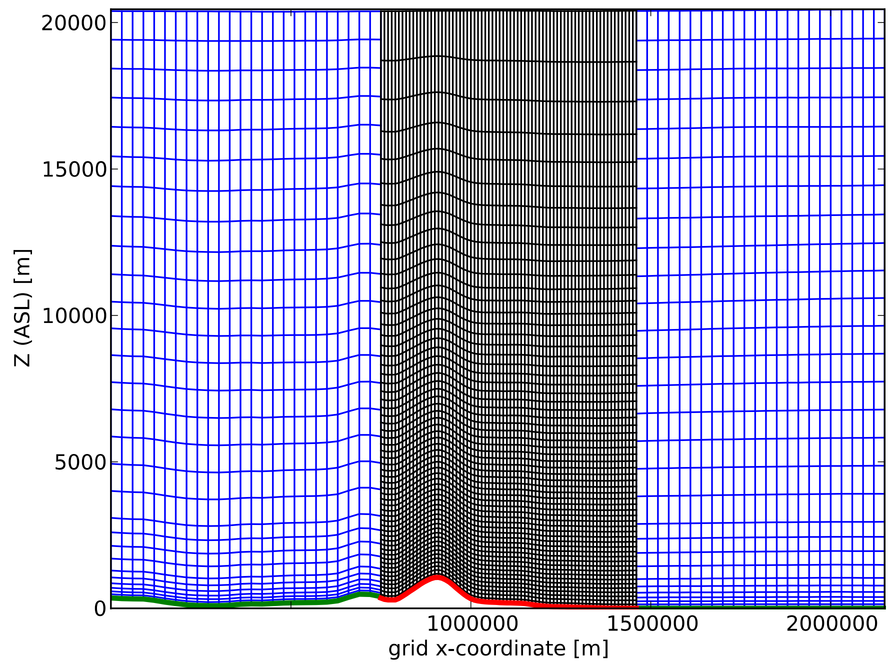


With and Without Vertical Grid Nesting

Vertical Levels
Parent: 60
Nest: 60



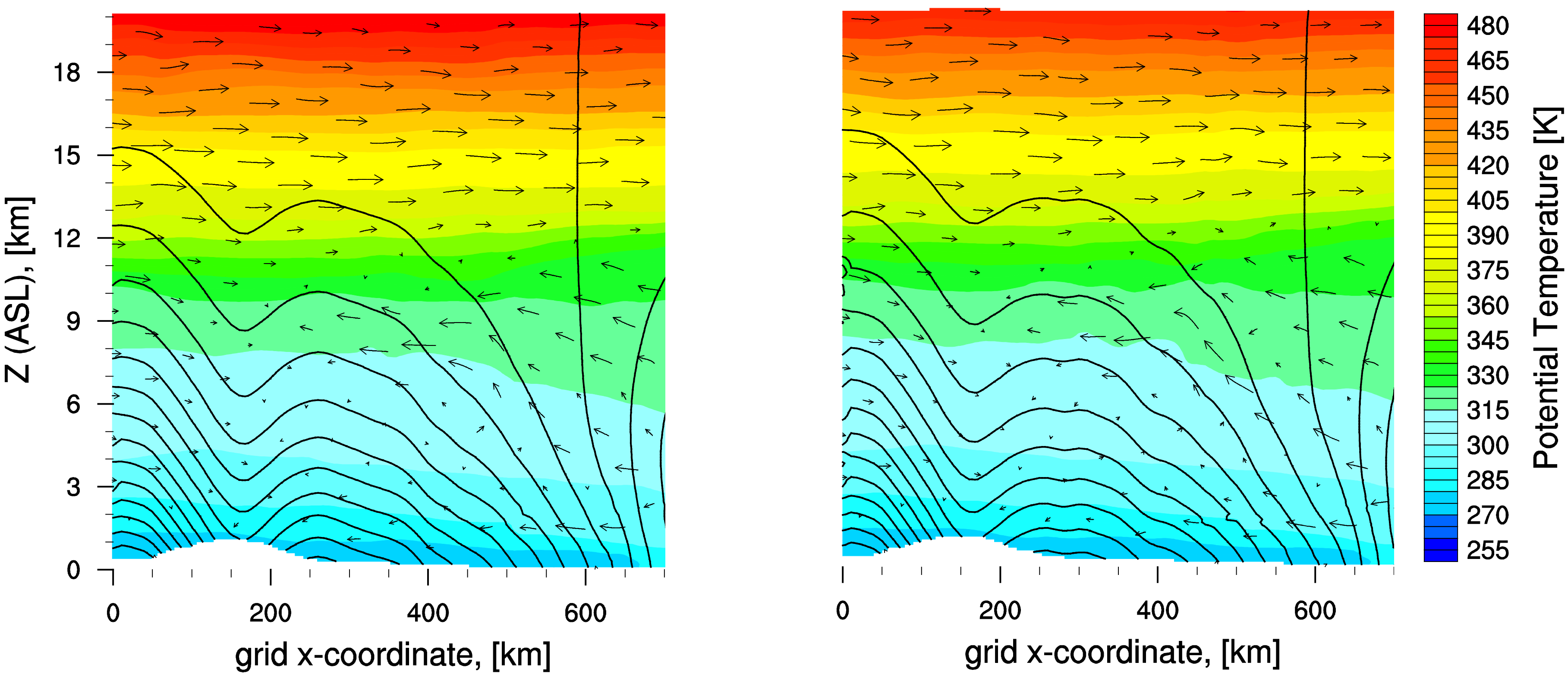
Vertical Levels
Parent: 30
Nest: 60



East-West Slice of Potential Temperature
(from the nested domain)

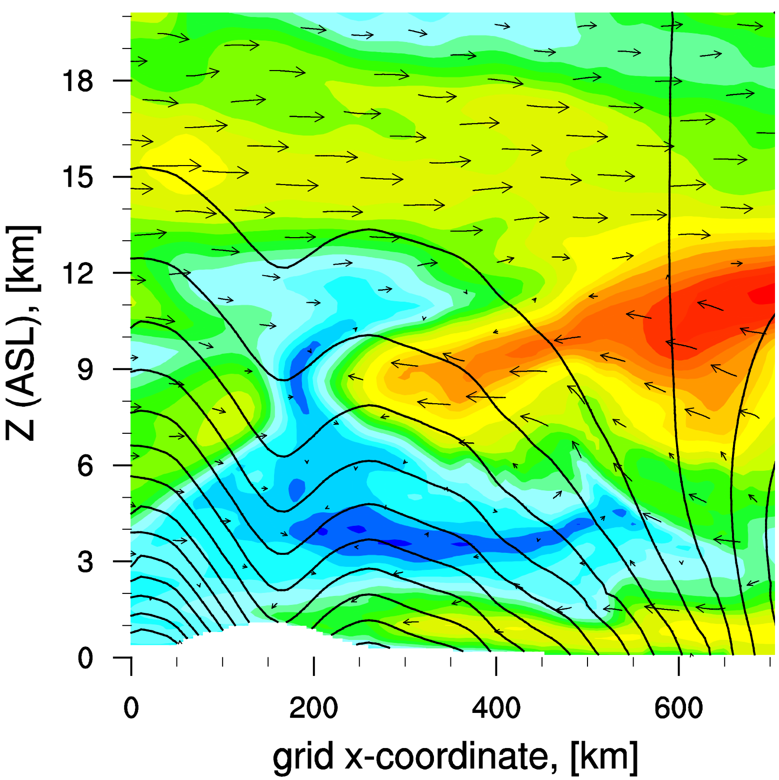
Vertical Levels
Parent: 60
Nest: 60

Vertical Levels
Parent: 30
Nest: 60

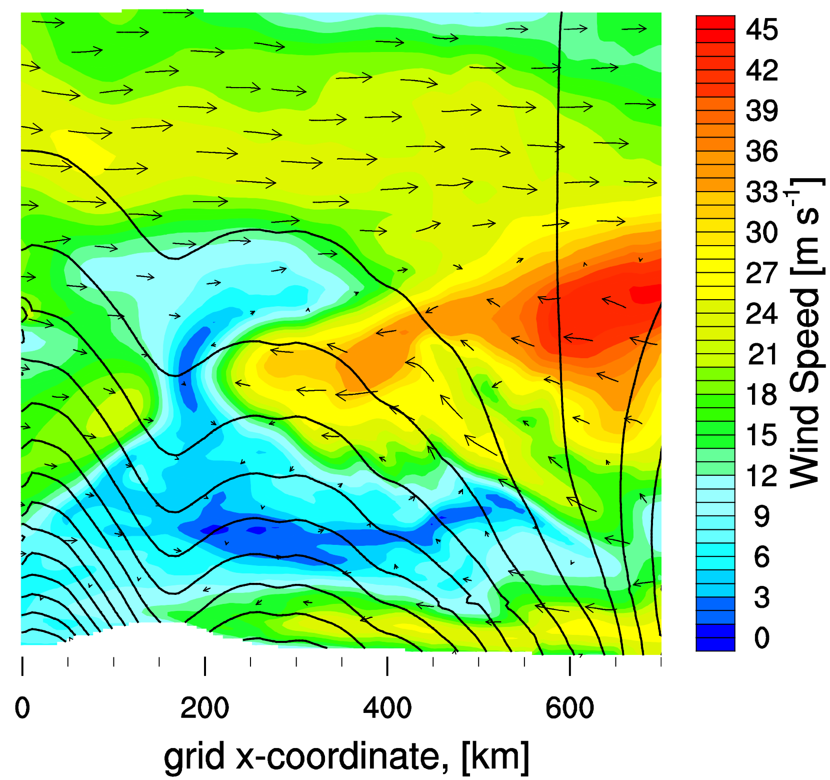


East-West Slice of Wind Speed [m s-1]
(from the nested domain)

Vertical Levels
Parent: 60
Nest: 60

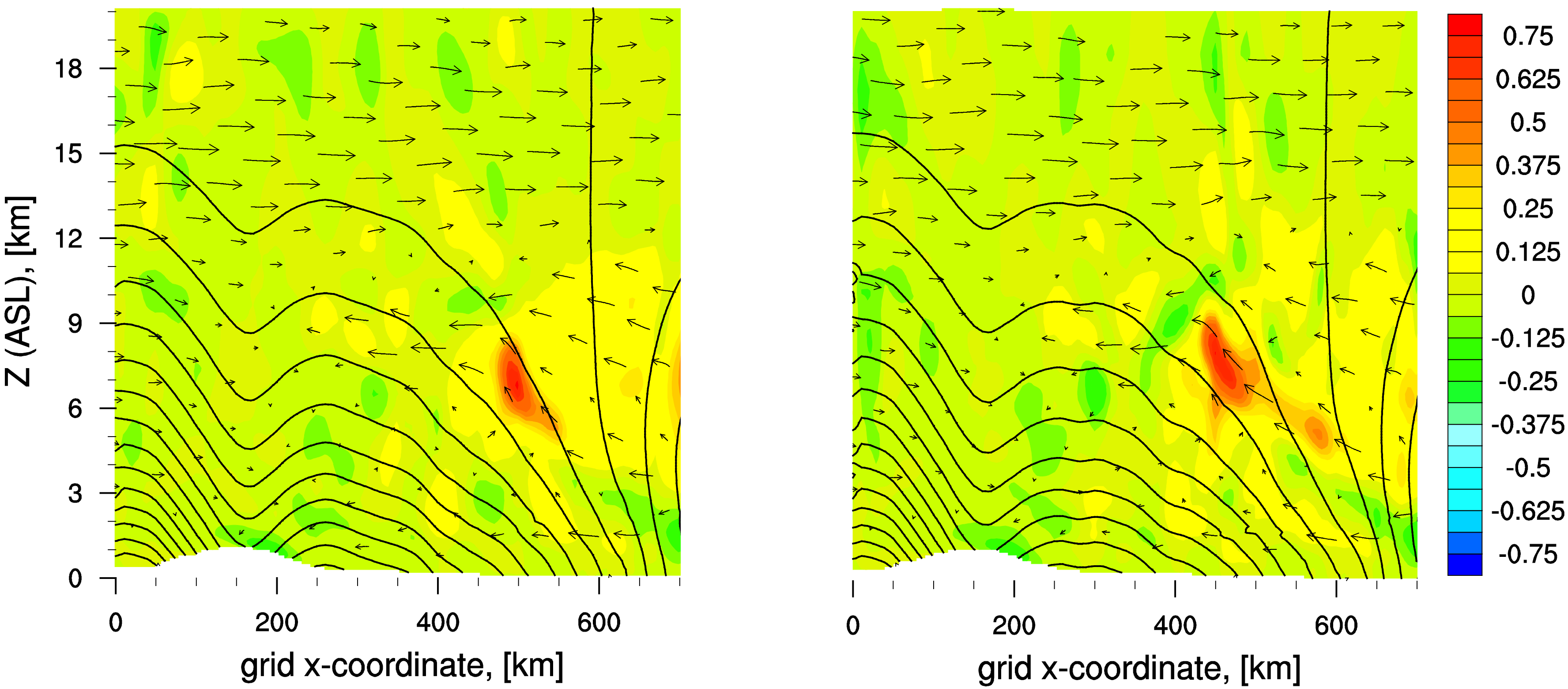


Vertical Levels
Parent: 30
Nest: 60

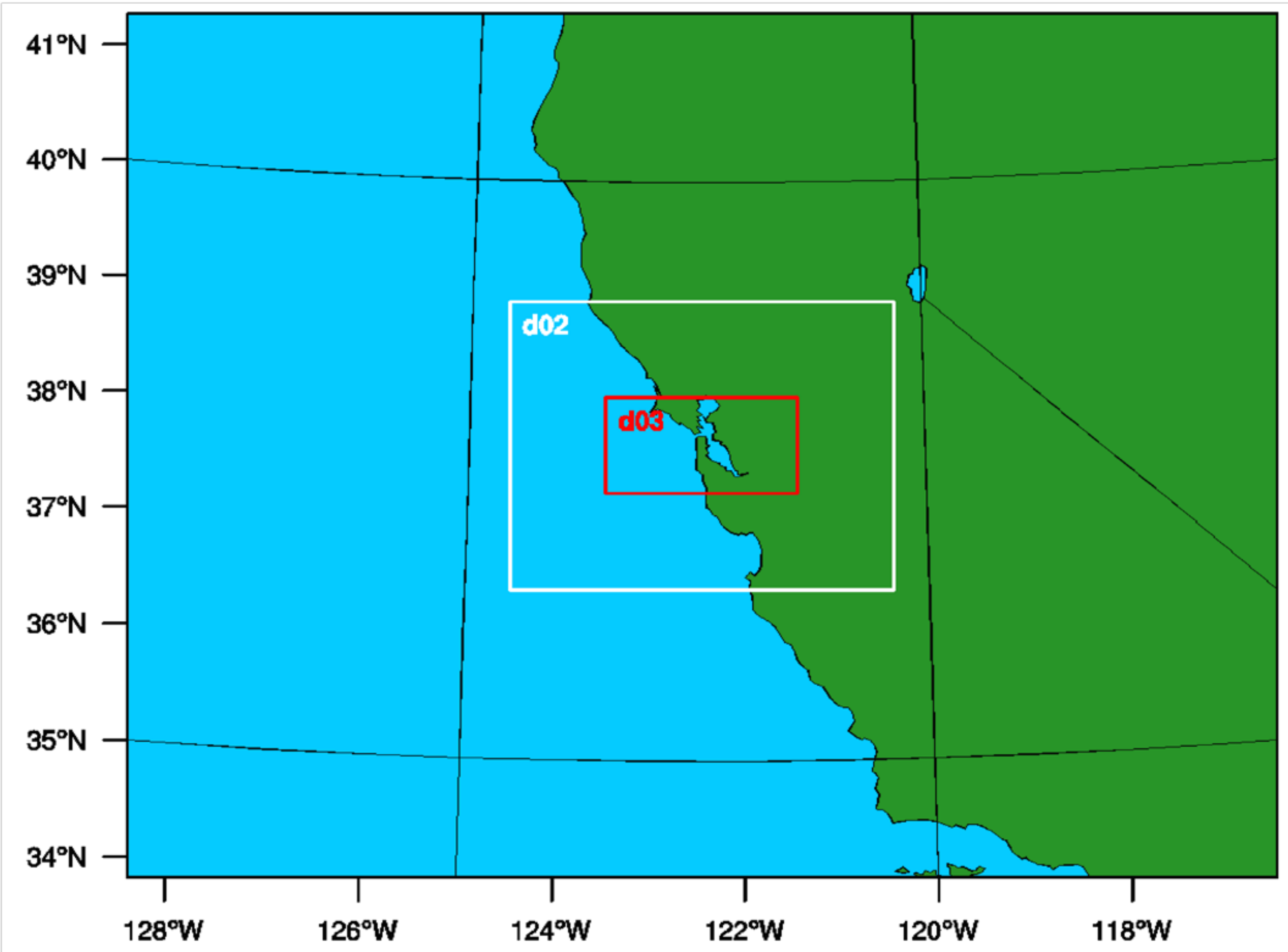


East-West Slice of Vertical Velocity [m s-1]
(from the nested domain)

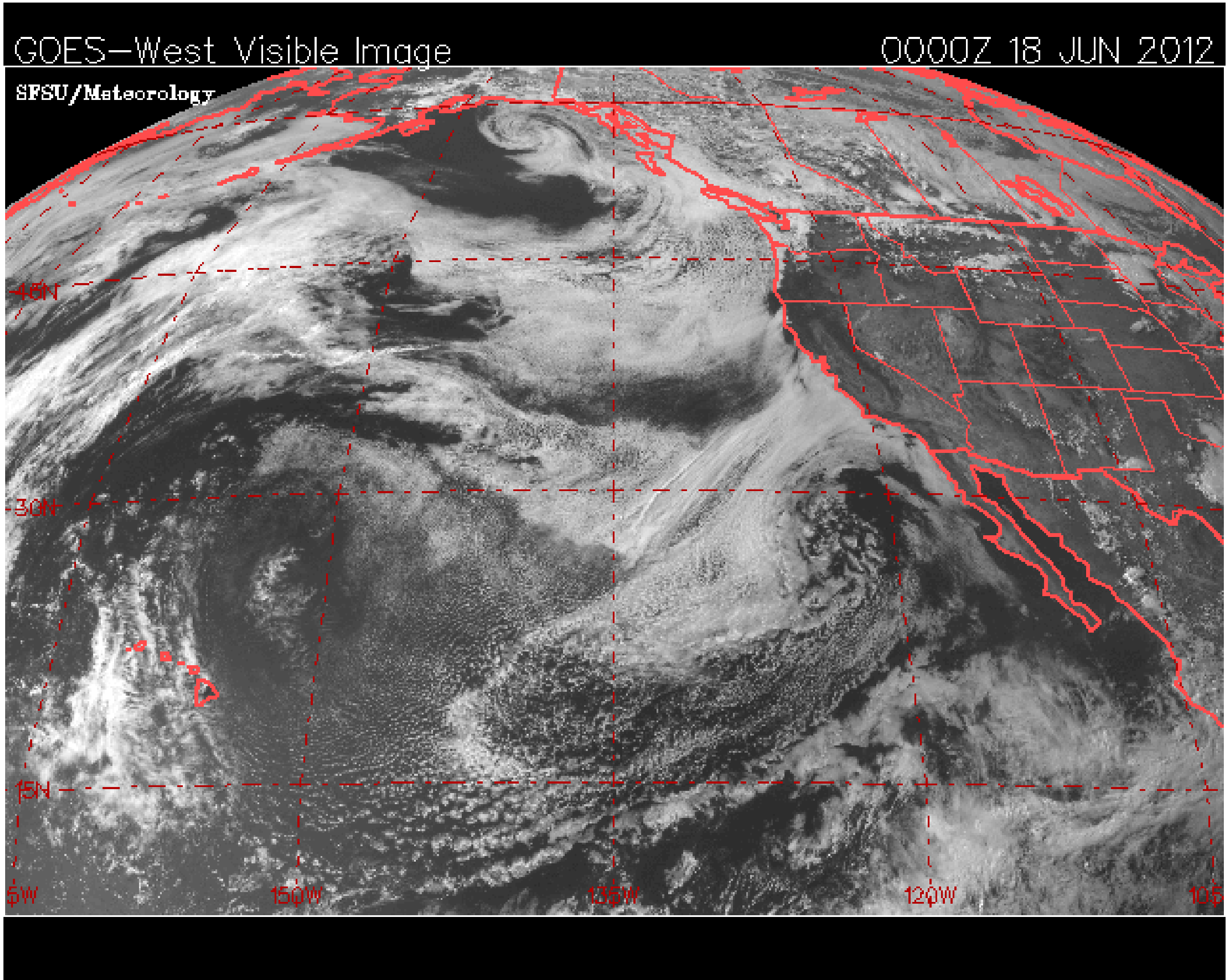
	Vertical Levels		Vertical Levels
Parent:	60	Parent:	30
Nest:	60	Nest:	60



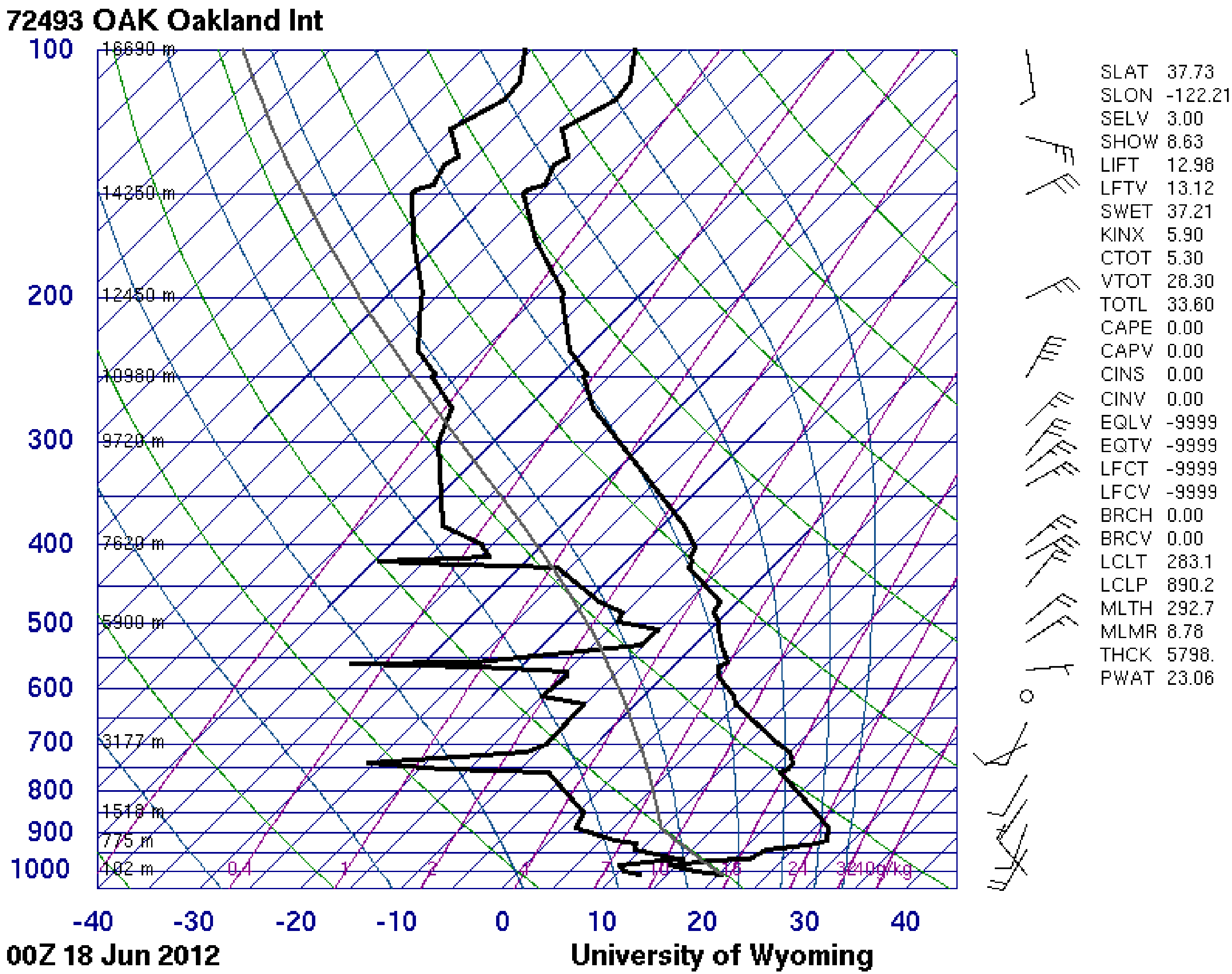
Modeling the Bay Area With Vertical Grid Nesting



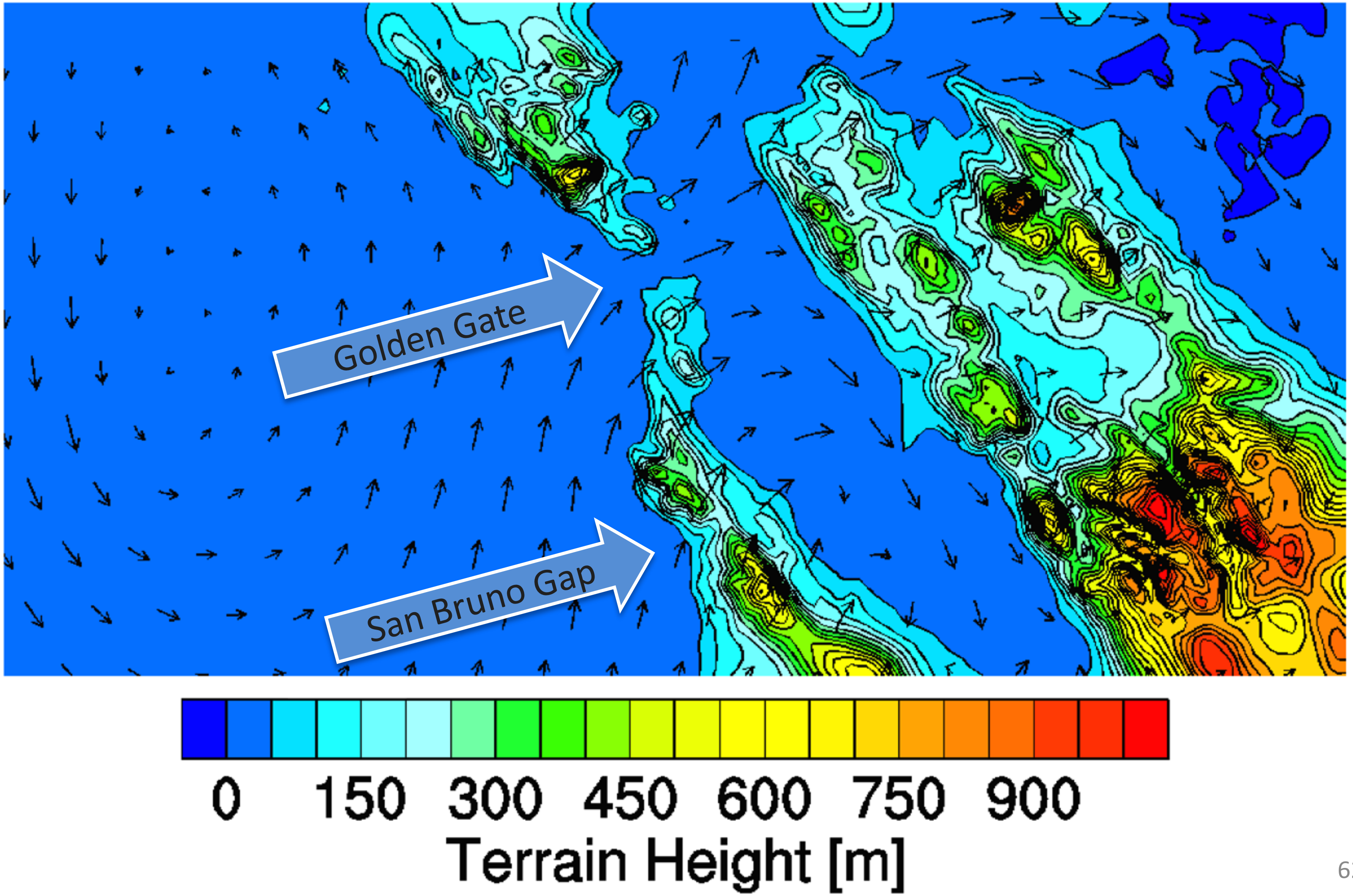
Western US, June 18th 2012



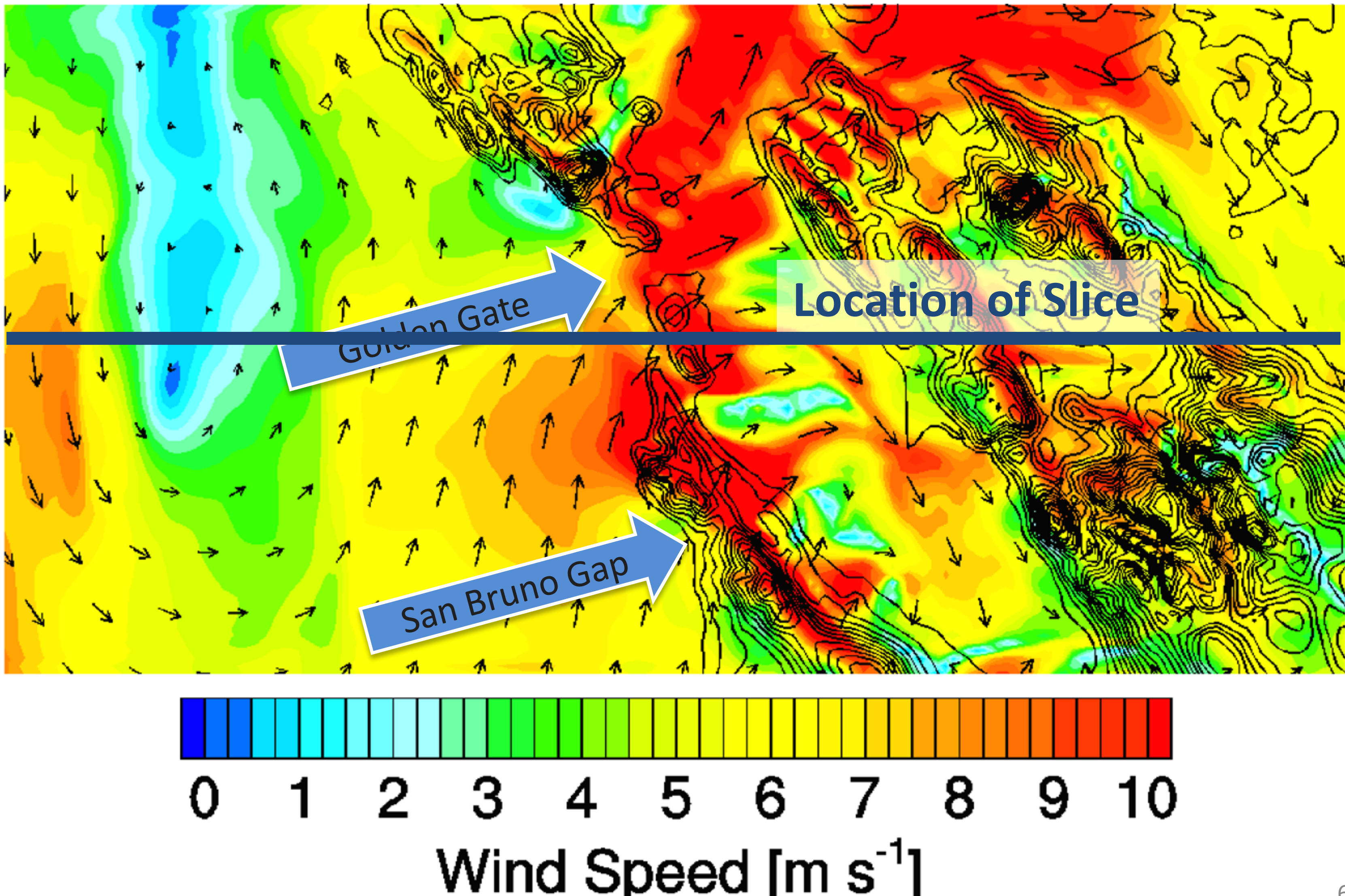
Oakland Radiosonde



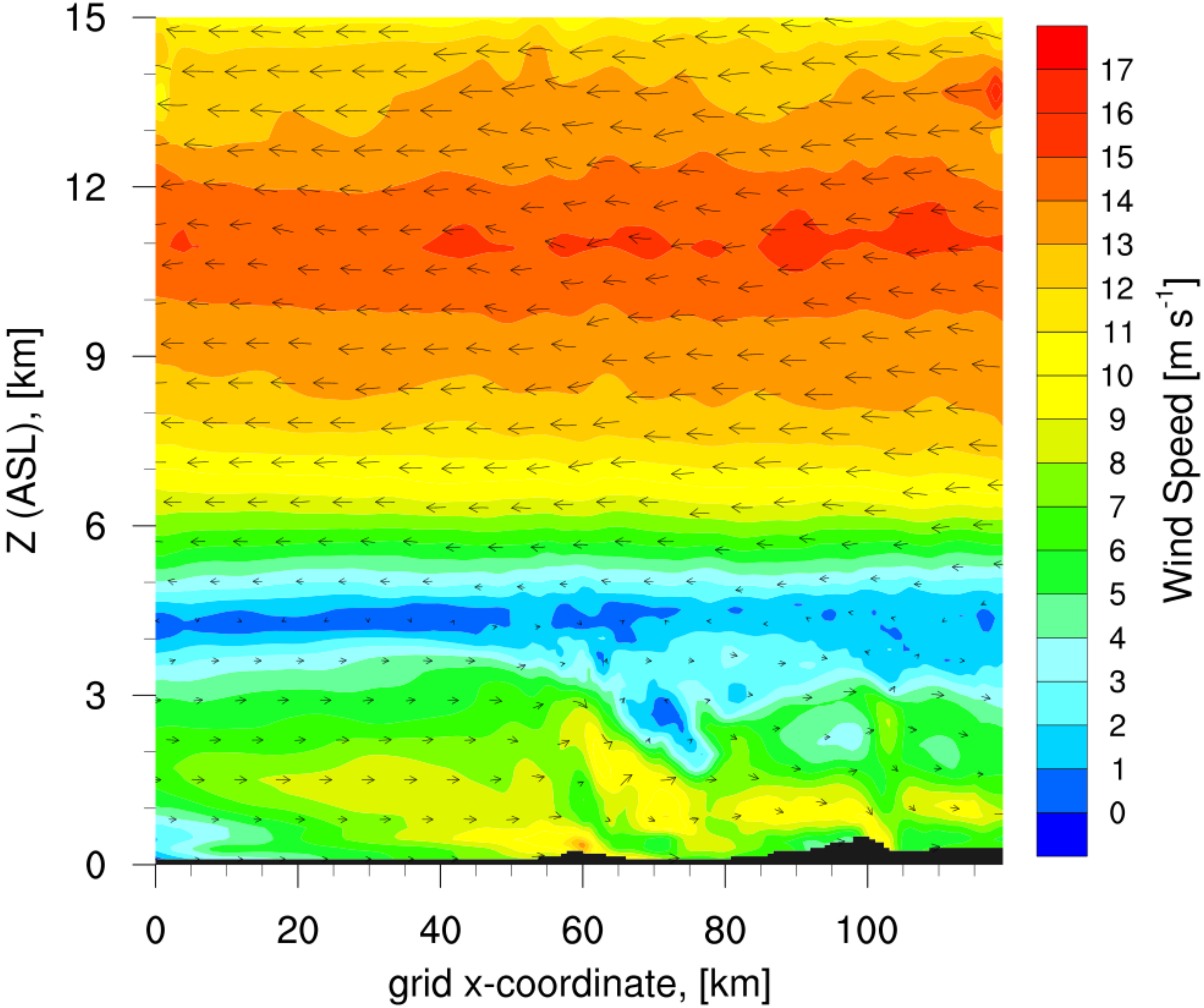
Terrain Height & Wind Vectors from Lowest Model Level



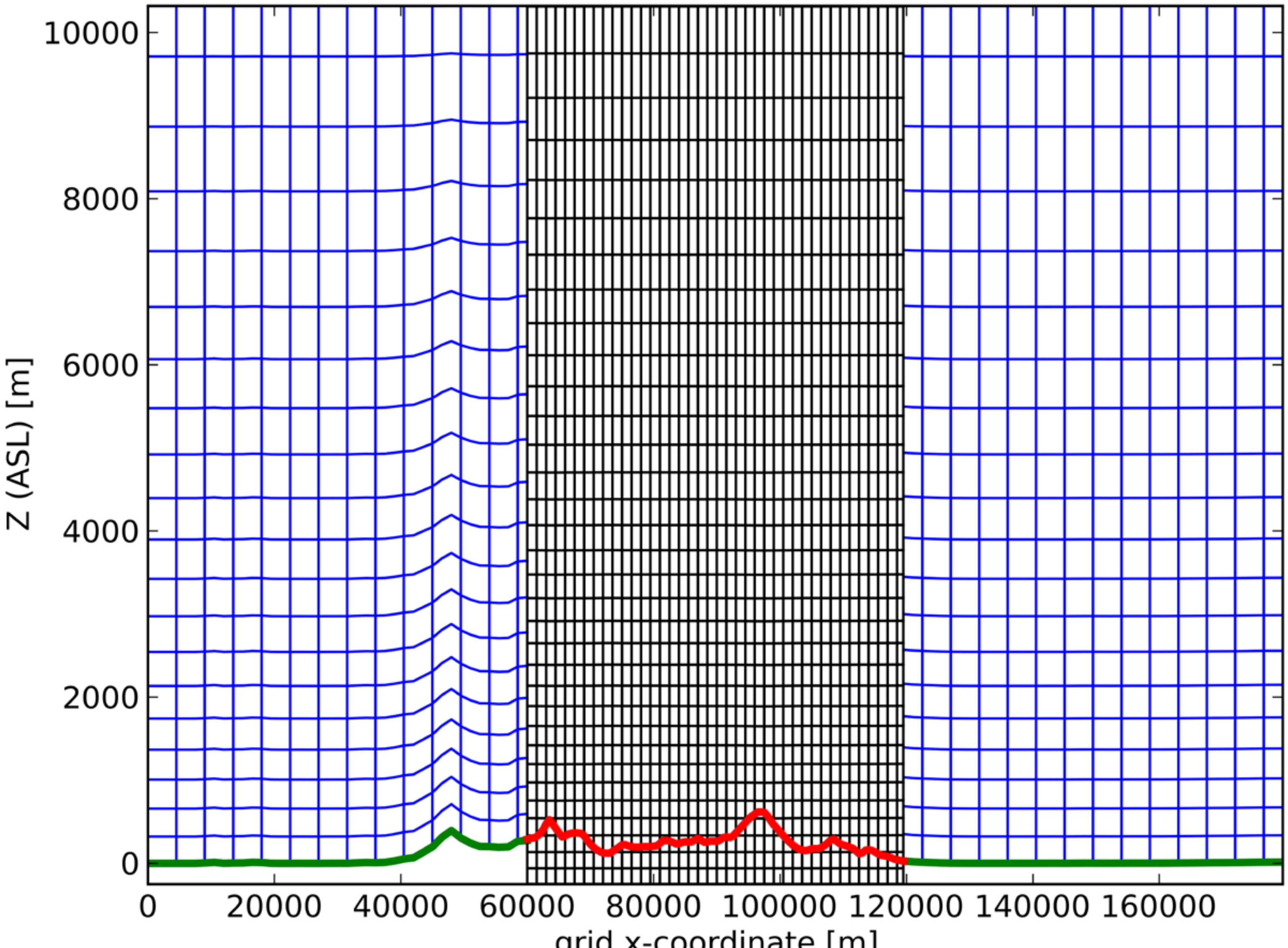
Wind Speed at Lowest Model Level



East-West Slice of Wind Speed



Current Work: WRF to WRF-IBM Nesting



Current Work: WRF to WRF-IBM Nesting

- Vertical grid nesting is necessary to force a WRF-IBM child domain that is nested within a WRF parent domain.
- WRF's solver is passed variables that are "coupled" with the dry air mass in the column.
- The parent and nest have different values for the dry air mass in the column because the domains have different bottoms.

Current Work: WRF to WRF-IBM Nesting

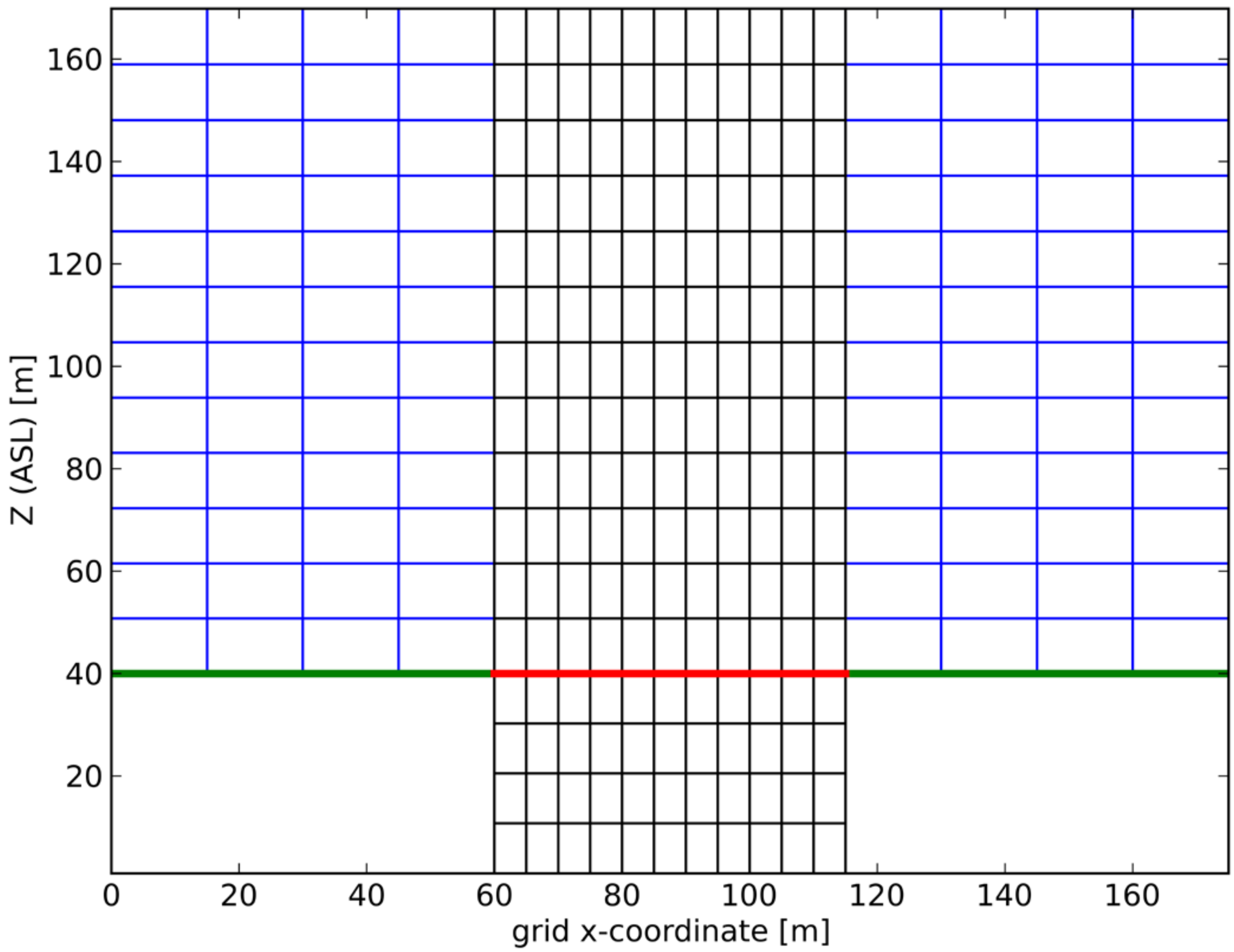
WRF to WRF nesting

- Couple parent domain with μ_{parent}
- Couple nested domain with μ_{nest}
- Vertically interpolate coupled parent on to the nest
- Horizontally interpolate results on to the nest
- Save results to nested domain
- Uncouple parent domain with μ_{parent}
- Uncouple nested domain with μ_{nest}

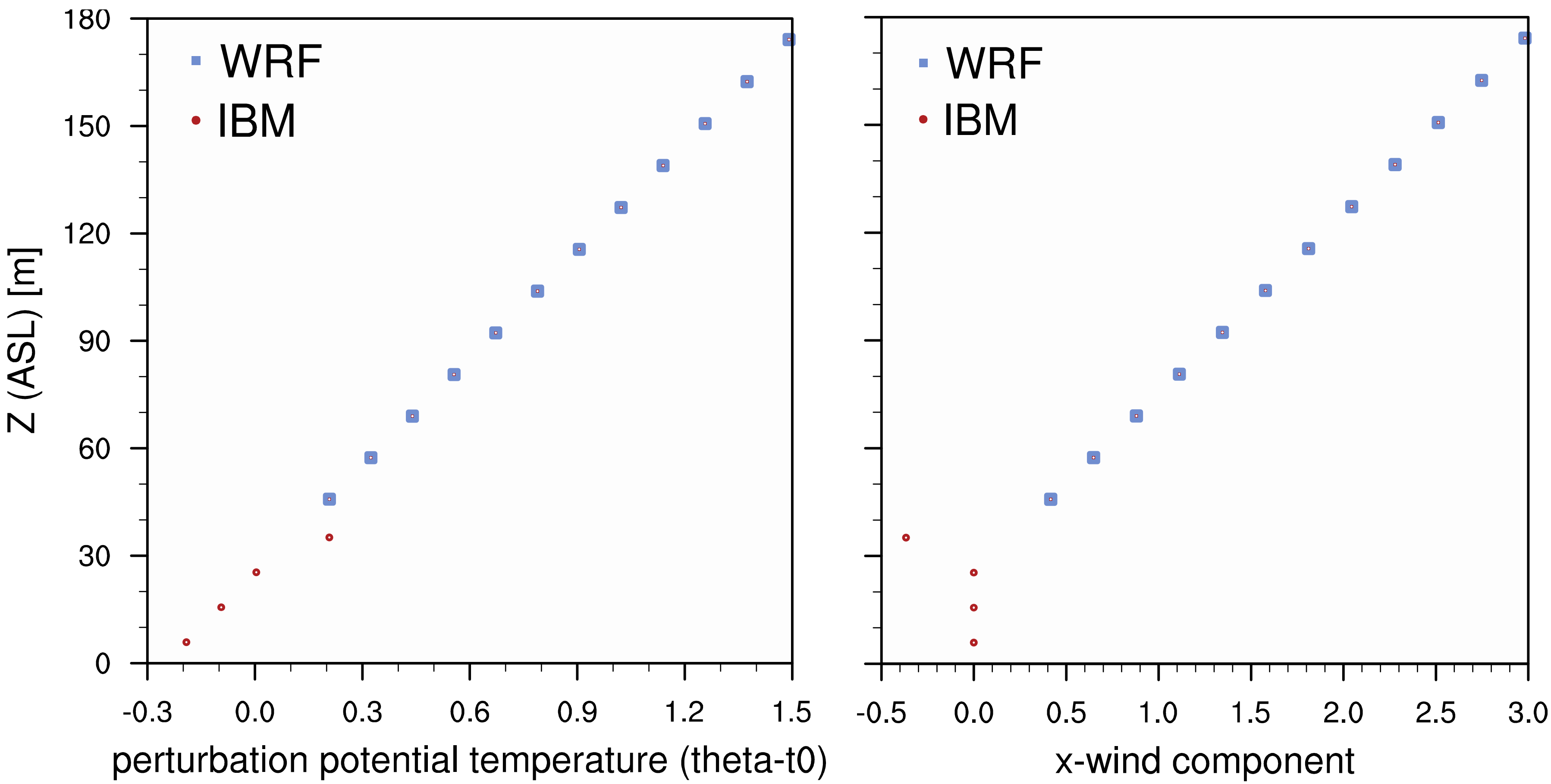
WRF to WRF-IBM nesting

- Vertically interpolate parent on to the nest
- Horizontally interpolate results on to the nest
- Couple results with μ_{nest}
- Save results to nested domain

Current Work: WRF to WRF-IBM Nesting



Current Work: WRF to WRF-IBM Nesting



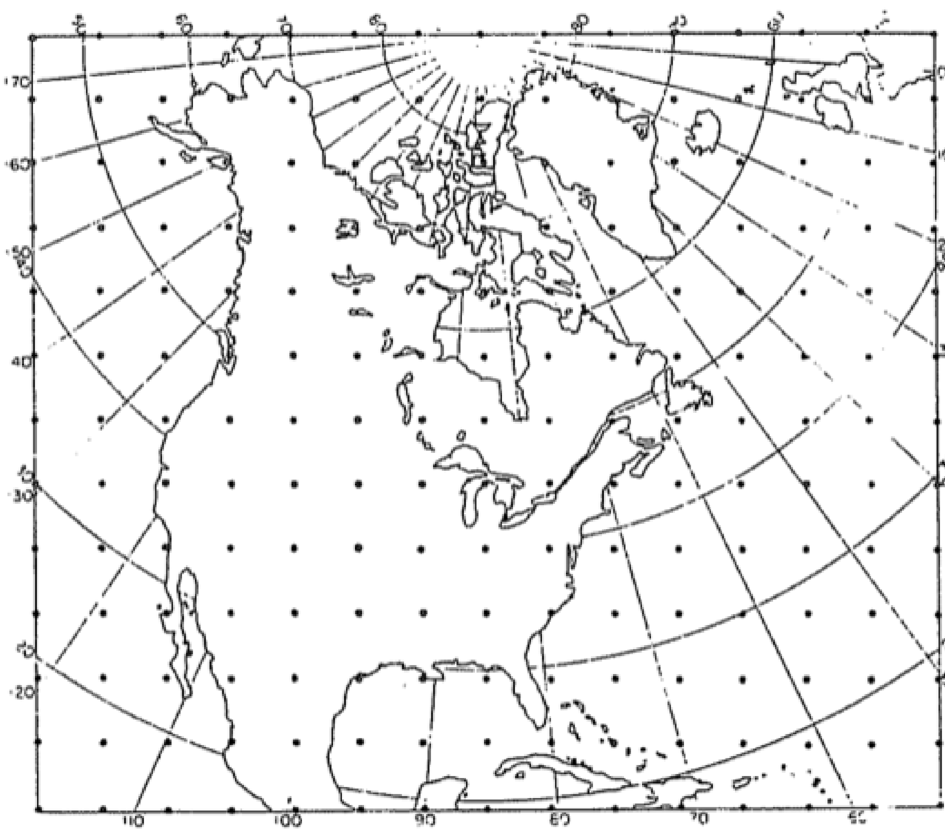
Thank you for your attention

- Neighborhood-scale air quality modeling
- Introduction to multi-scale modeling
- Weather Research and Forecasting (WRF) model
- The immersed boundary method and WRF
- Vertical grid nesting in WRF
- WRF to WRF-IBM grid nesting (in development)
- Thank you to Lawrence Livermore National Laboratory, Jeff Mirocha, Megan Daniels, and EFMH at UC Berkeley

Dave Wiersema, wiersema@berkeley.edu

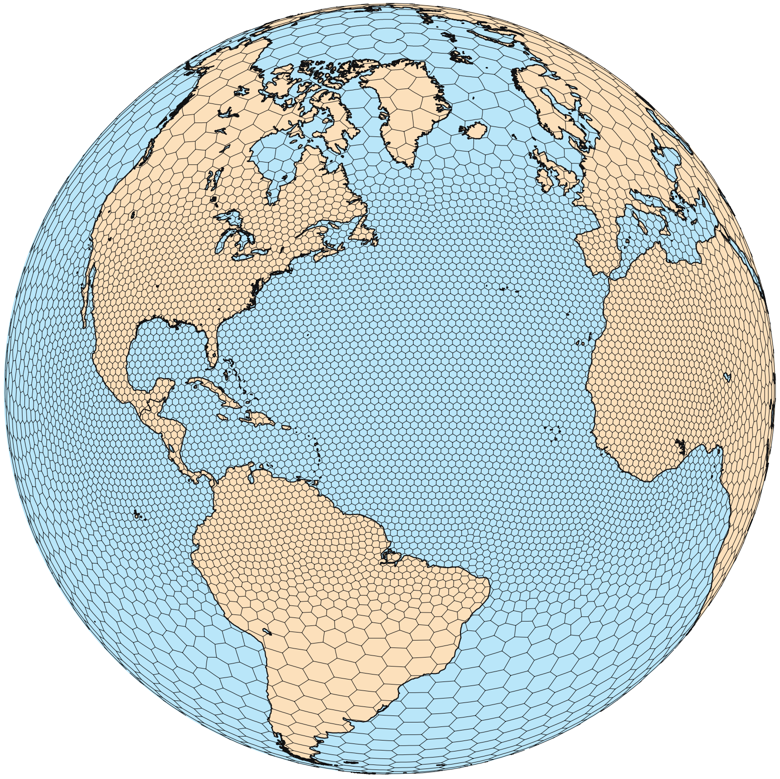
Johnny von Neumann's Simulations

- J. G. Charney, R. Fjörtoft, J. von Neumann, 1950: Numerical Integration of the Barotropic Vorticity Equation. Tellus, Volume-2 Issue-4, 237-254, doi: 10.1111/j.2153-3490.1950.tb00336.x



Approaches to Downscaling

- Adaptive Mesh Refinement (AMR), used in the Model for Prediction Across Scales (MPAS).



- Increase resolution near regions of interest.
- Saves computational resources by minimizing overall number of cells.