Improving the Immersed Boundary Method in WRF for Complex Mountainous Terrain

Implementation of surface scalar and momentum fluxes for WRF-IBM

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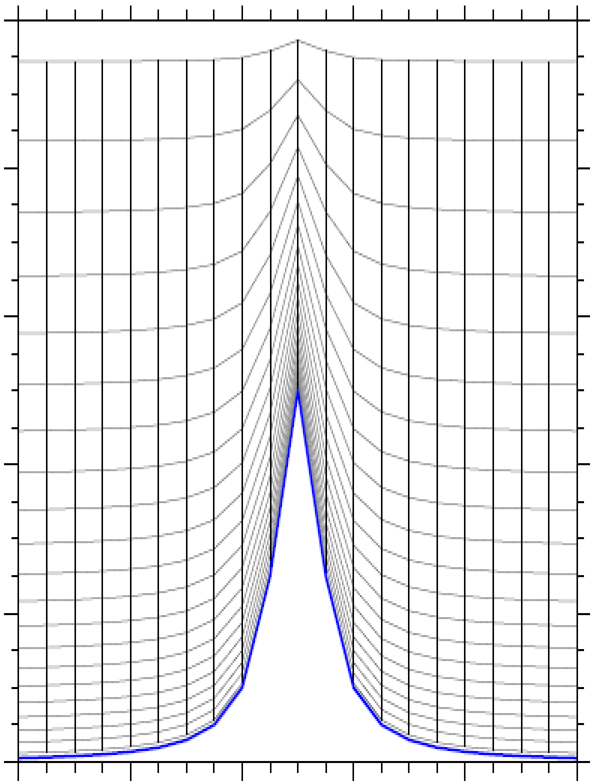
Limitations of WRF

- WRF: Weather Research and Forecasting model
- Terrain following coordinate system
  - Horizontal gradient errors
  - Numerical instability
  - Terrain slope limit
  - Grid aspect ratio limit



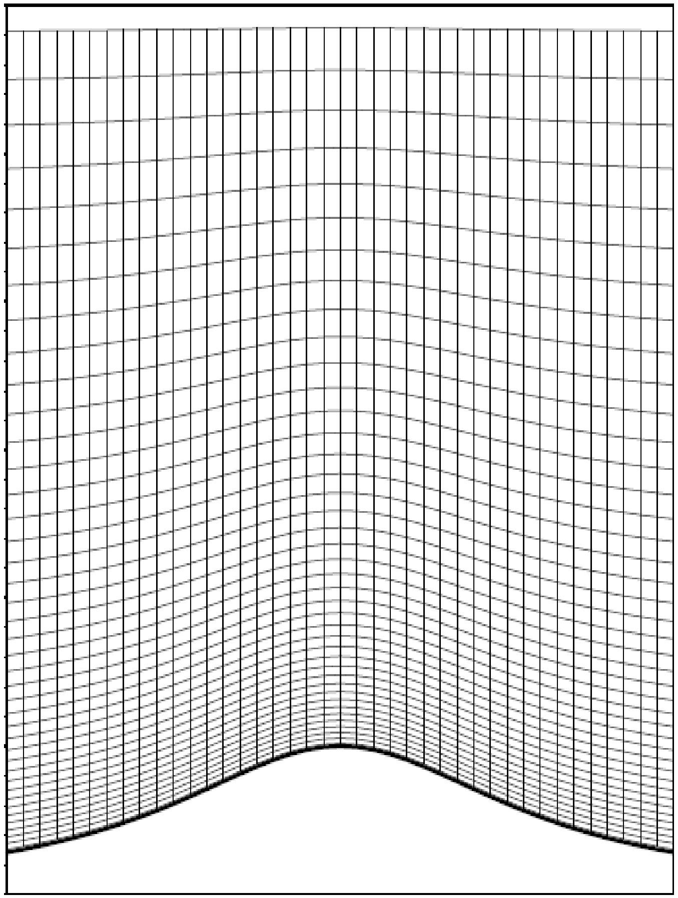
Higher resolution – Steeper slopes

dx = 500m
max slope ~ 20 degrees

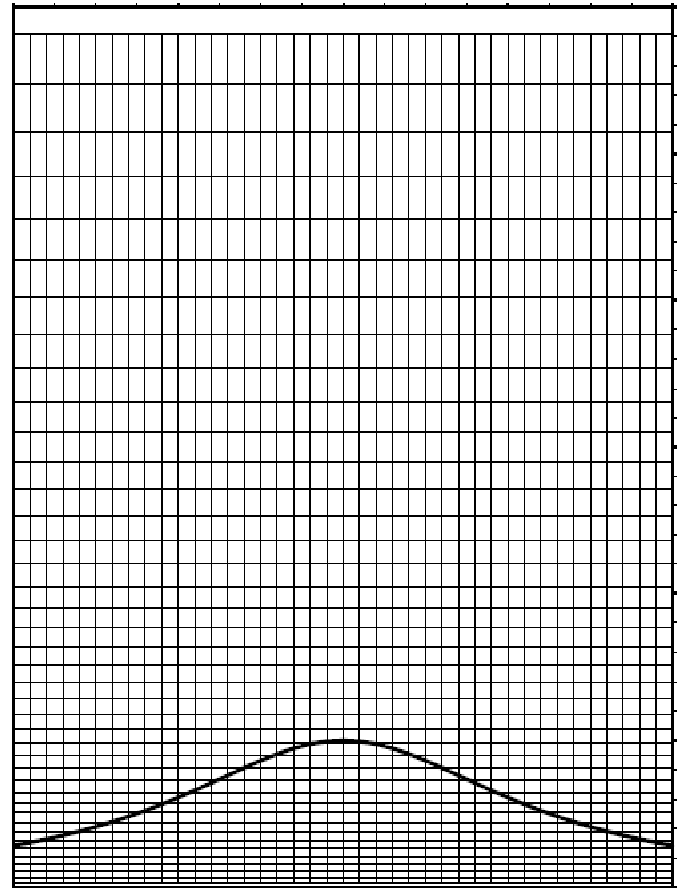
Higher resolution – Steeper slopes

dx = 60m
max slope ~ 70 degrees

Immersed boundary method



Terrain following coordinates



Immersed boundary (WRF-IBM)

WRF implementation of scalar and momentum flux

- Advection diffusion equation for scalar

$$\frac{\partial T}{\partial t} + V \cdot \nabla T = -(\frac{\partial H_1}{\partial x} + \frac{\partial H_2}{\partial y} + \frac{\partial H_3}{\partial z}) + F_T$$

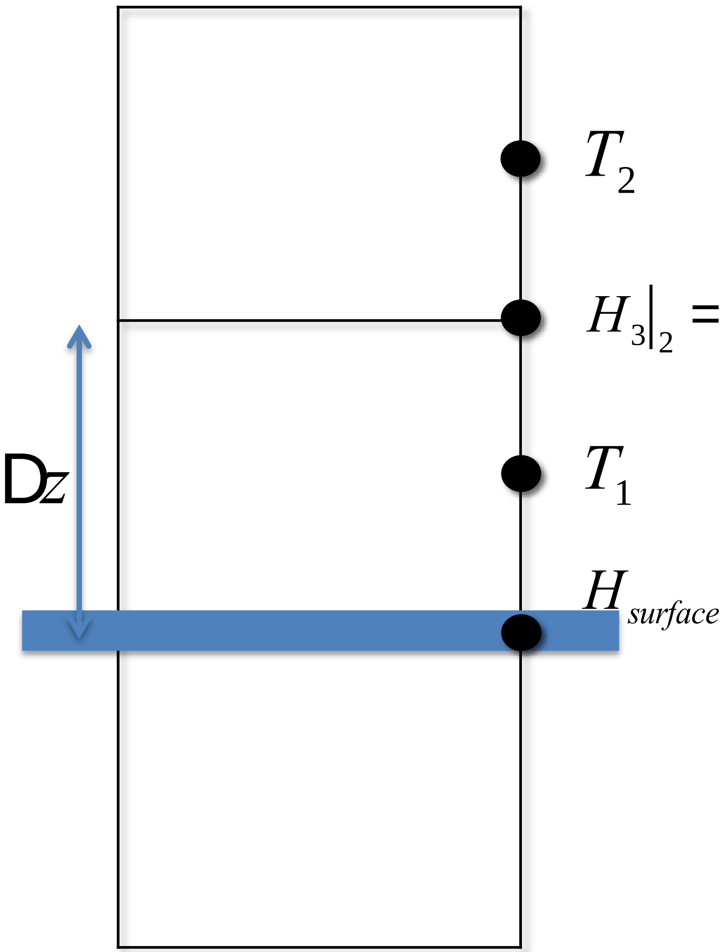
- Momentum equation in U direction

$$\frac{\P U}{\P t} + U\frac{\P U}{\P x} + V\frac{\P U}{\P y} + W\frac{\P U}{\P z} = - \frac{1}{r}\frac{\P P}{\P x} - (\frac{\P t_{11}}{\P x} + \frac{\P t_{12}}{\P y} + \frac{\P t_{13}}{\P z})$$

- Requires gradient in H_3 and t_{13}

WRF implementation of scalar flux

$$\frac{\partial T_1}{\partial t} = \ldots. - \frac{\partial H_3}{\partial z} = \ldots - \frac{H_3\big|_2 - H_{surface}}{\Delta z}$$

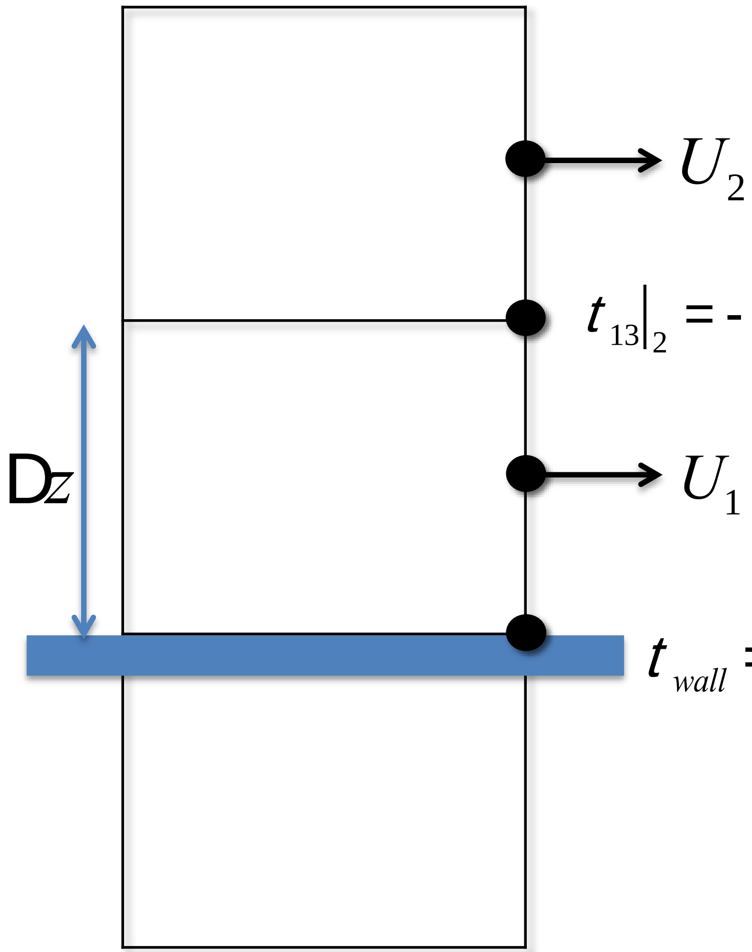


$$H_3\big|_2 = - k_T \frac{\partial T}{\partial z} = - k_T \frac{T_2 - T_1}{\Delta z}$$

WRF implementation of momentum flux

Log Law

$$\frac{\partial U}{\partial t} = -\frac{\partial \tau_{13}}{\partial z} = -\frac{\tau_{13}\big|_2 - \tau_{wall}}{\Delta z} \ldots$$

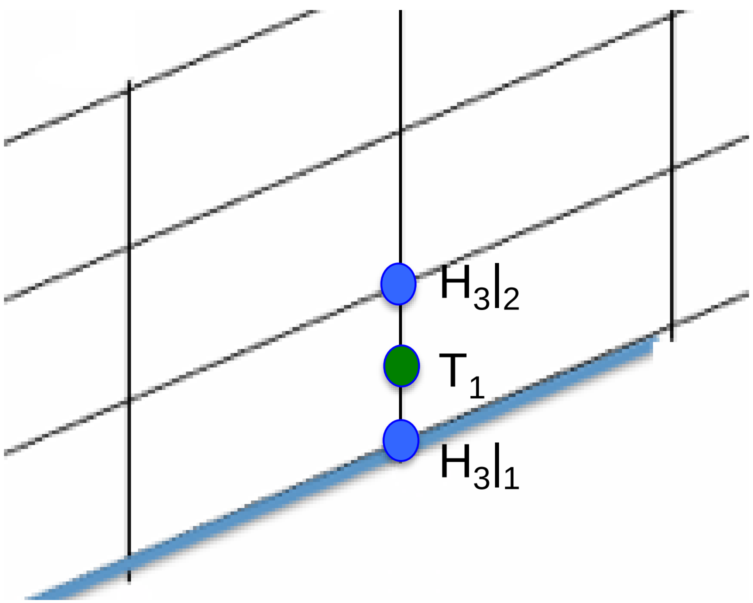


$$\tau_{13}\big|_2 = -\nu_T \frac{\partial U}{\partial z} = -\nu_T \frac{U_2 - U_1}{\Delta z}$$

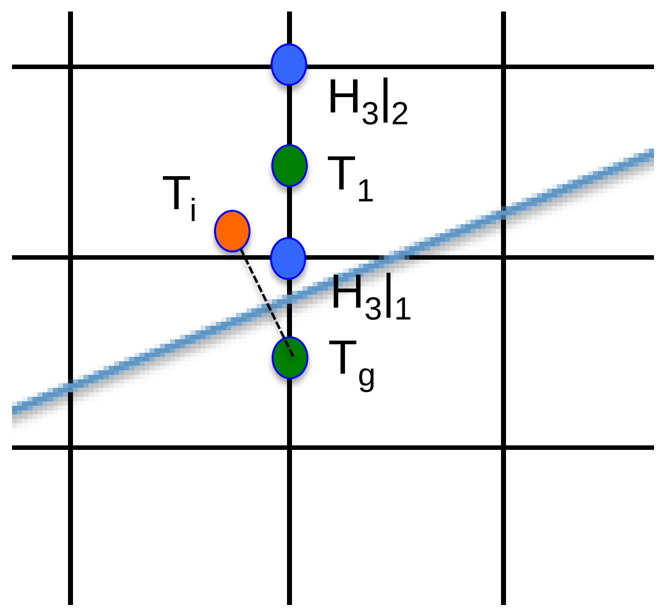
$$\tau_{wall} = -u_*^2 = C_d \left|U_1\right| U_1$$

Difficulty of WRF-IBM scalar flux implementation

- Potential temperature is updated as: $\dfrac{\partial T_1}{\partial t} = \ldots - \dfrac{H_3|_2 - H_3|_1}{\Delta z}$
- Correct $H_3/_1$ is required
- WRF: $H_3|_1 = H_{surface}$ WRF-IBM: $H_3|_1 = -k_{T(atH_{3|1})} \dfrac{(T_1 - T_g)}{\Delta z}$
- Correct T_g and $k_{T(atH_{3|1})}$ is required for WRF-IBM

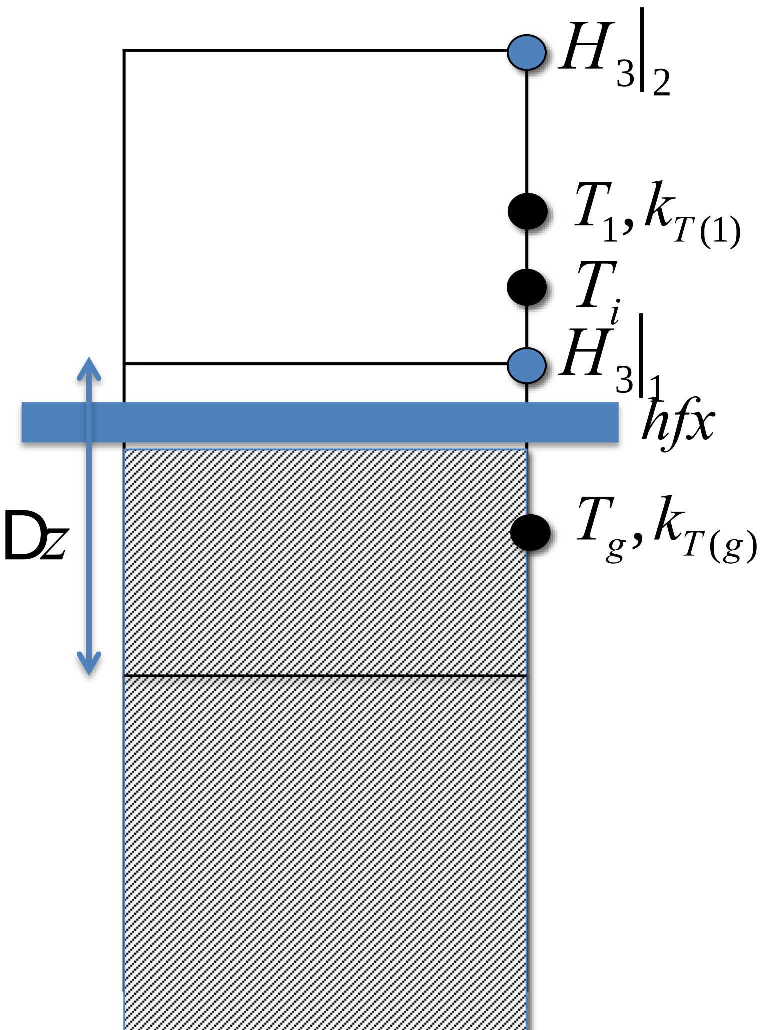


WRF



WRF-IBM

IBM implementation of heat flux



$$\frac{\partial T_1}{\partial t} = -\frac{\partial H_3}{\partial z} = -\frac{H_3|_2 - H_3|_1}{\Delta z} \ldots$$

Need correct $H_3|_1$

$$H_3|_1 = -k_{T(atH_{3|1})} \frac{T_1 - T_g}{\Delta z}$$

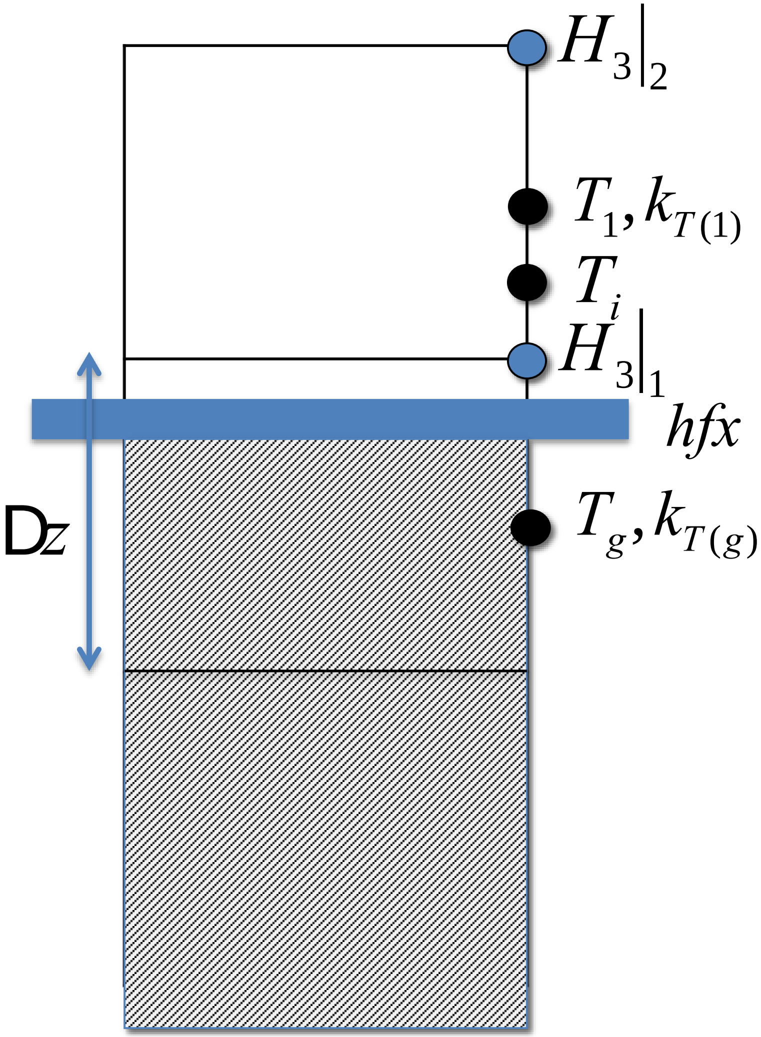
Need correct T_g and $k_{T(atH_{3|1})}$

$$hfx = -k_{T(wall)} \frac{T_i - T_g}{\Delta z}$$

$$T_g = T_i + \frac{hfx}{k_{T(wall)}} \Delta z$$

Need correct $k_{T(wall)}$ and $k_{T(atH_{3|1})}$

IBM implementation of heat flux



Need correct $k_{T(wall)}$

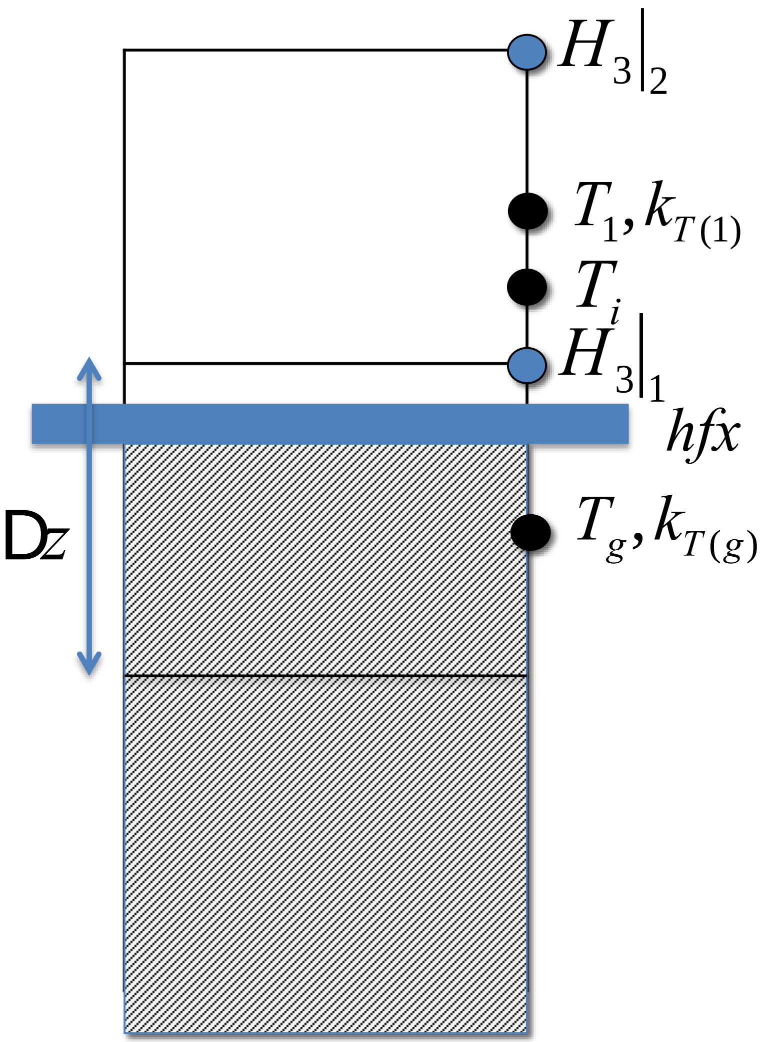
Method : Prandtl's mixing length

- More realistic simulation
- Can couple with turbulence closure

$$\nu_{T(wall)} = u_* kz$$

$$k_{T(wall)} = \frac{\nu_{T(wall)}}{\Pr}$$

IBM implementation of heat flux



Need correct $k_{T(atH_{3|1})}$

Method : Prandtl's mixing length

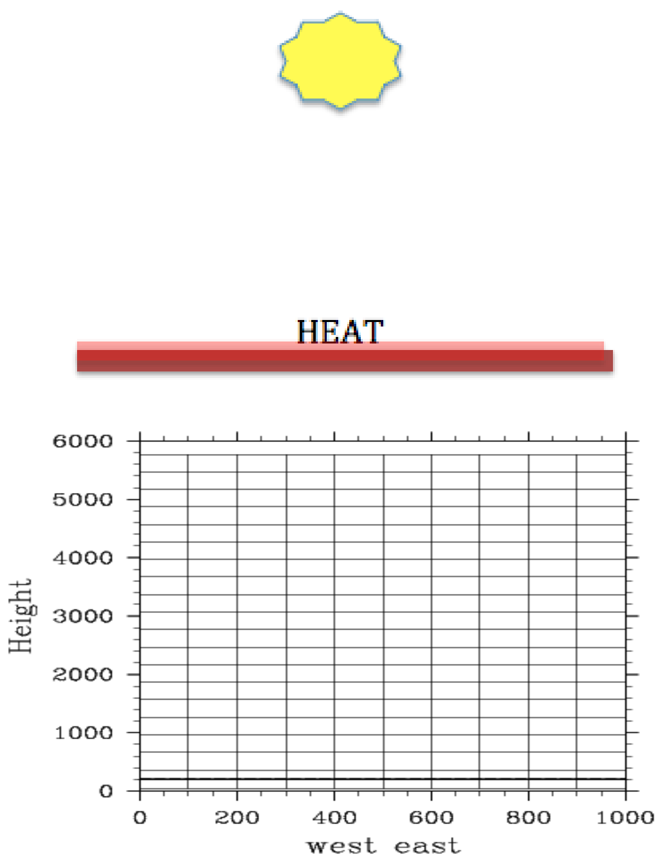
- More realistic simulation
- Can couple with turbulence closure

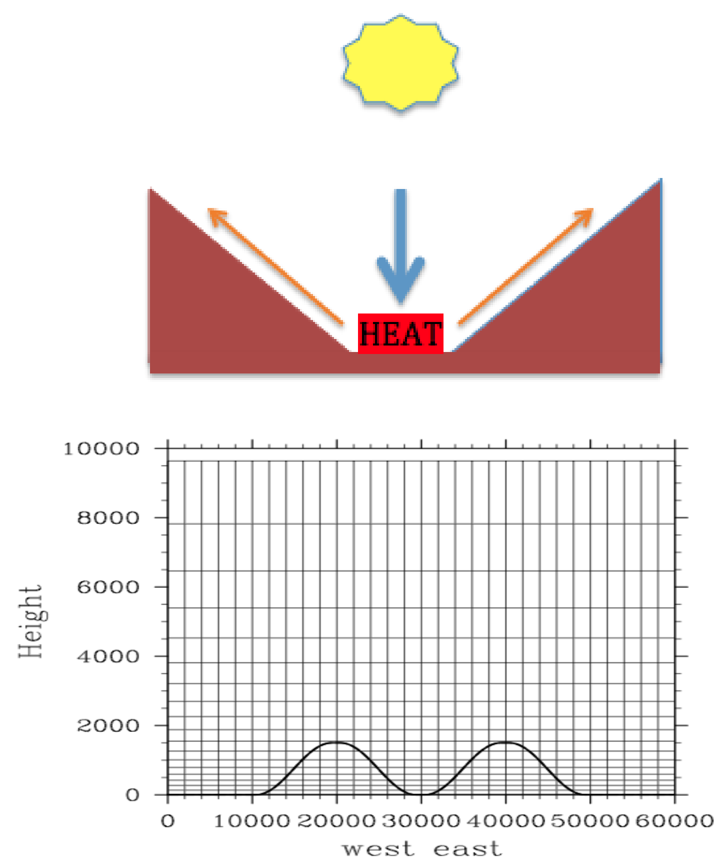
$$\nu_{T(atH_{3|1})} = u_* kz(atH_{3|1})$$

$$k_{T(atH_{3|1})} = \frac{\nu_{T(atH_{3|1})}}{\Pr}$$

Idealized thermal driven flow simulation

- Uncoupled simulations with specified surface heating
- Coupled simulations using atmospheric parameterizations





Idealized validation cases summary

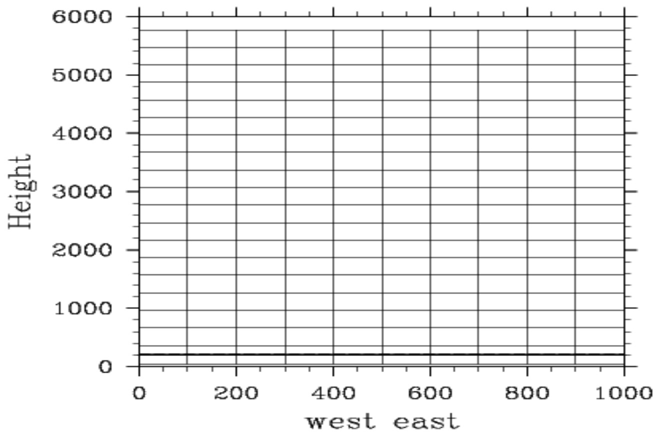
		Flat plate(a) /Idealized valley(b)
Case 1	Uncoupled	Prandtl's mixing length $k_{T(wall)} = \frac{u_* kz}{\Pr}$ $k_{T(atH_{3|1})} = \frac{u_* kz(atH_{3|1})}{\Pr}$
Case 2	Coupled	

- Can couple with different turbulence closure
- Matches perfectly for flat plate
- Idealized valley simulation is still under work

Cases 1a and 2a - Flat plate setup

Domain Set-Up

- (X,Y,Z) = (1, 1, 6)km
- $\Delta X = \Delta Y = 100$ m, $\Delta Z \sim 100$ m



Initialization

- (U,V,W) = (1,0,0)
- Neutral mixed layer and capping inversion at top

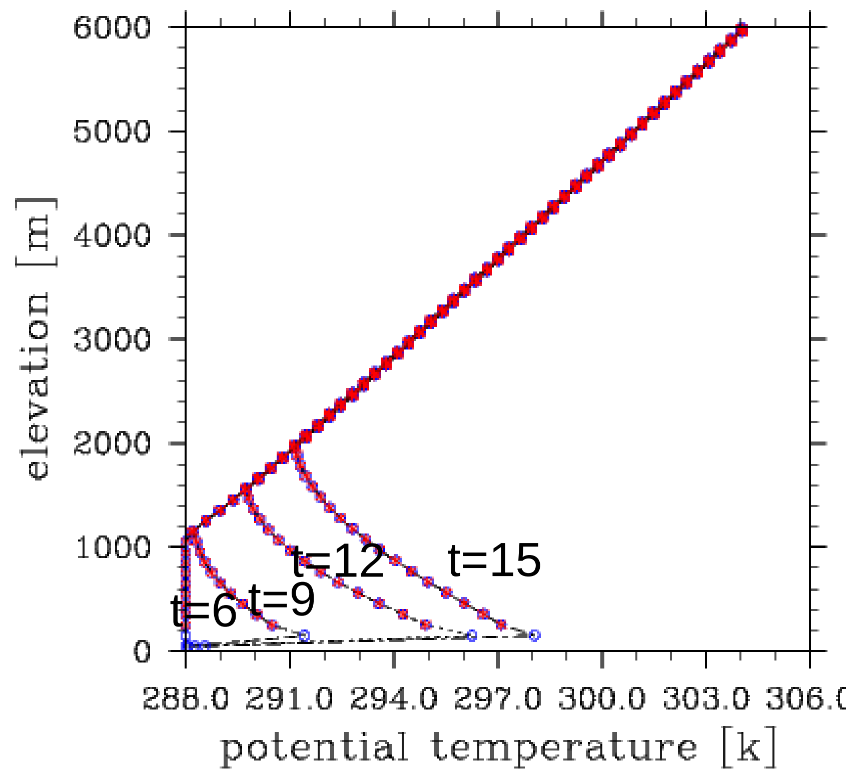
Simulation

- 6:00 to 18:00 UTC
- Uncoupled and Coupled (RRTM Longwave Radiation/MM5 Shortwave Radiation/MM5 Surface Layer Model/NOAH Land Surface Model)
- Smagorinsky closure
- Free slip bottom boundary condition

Uncoupled Flat plate

potential temperature

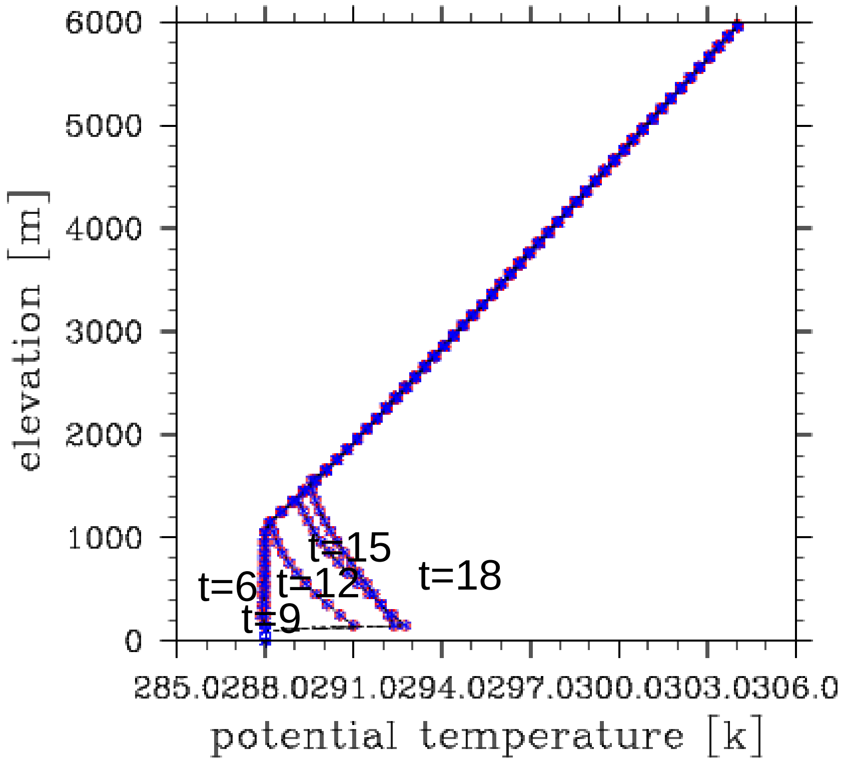
- **WRF-IBM (blue)** and **WRF (red)**



Coupled flat plate

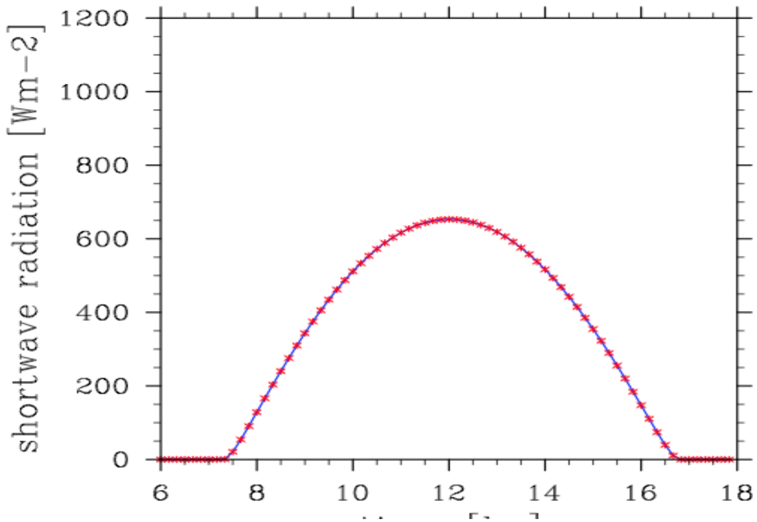
potential temperature

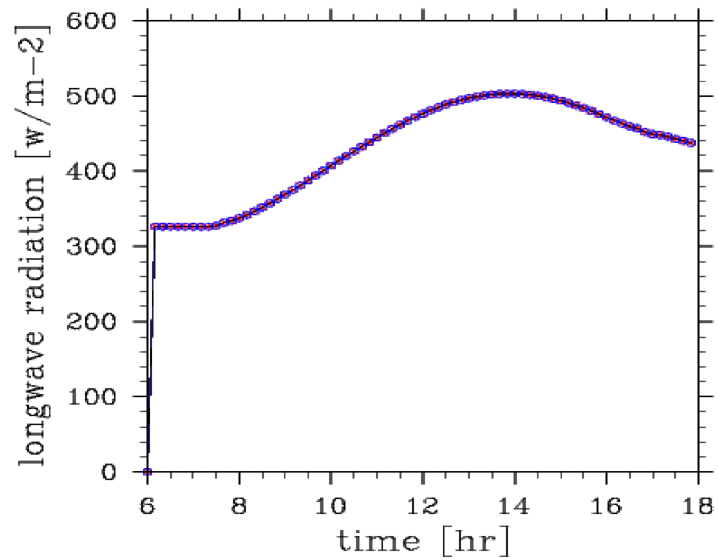
- **WRF-IBM (blue)** and **WRF (red)**

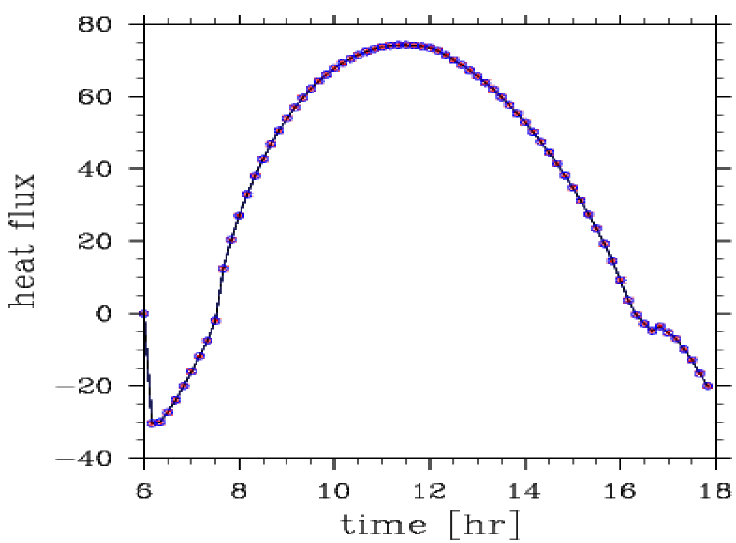


Coupled flat plate

radiation/surface physics







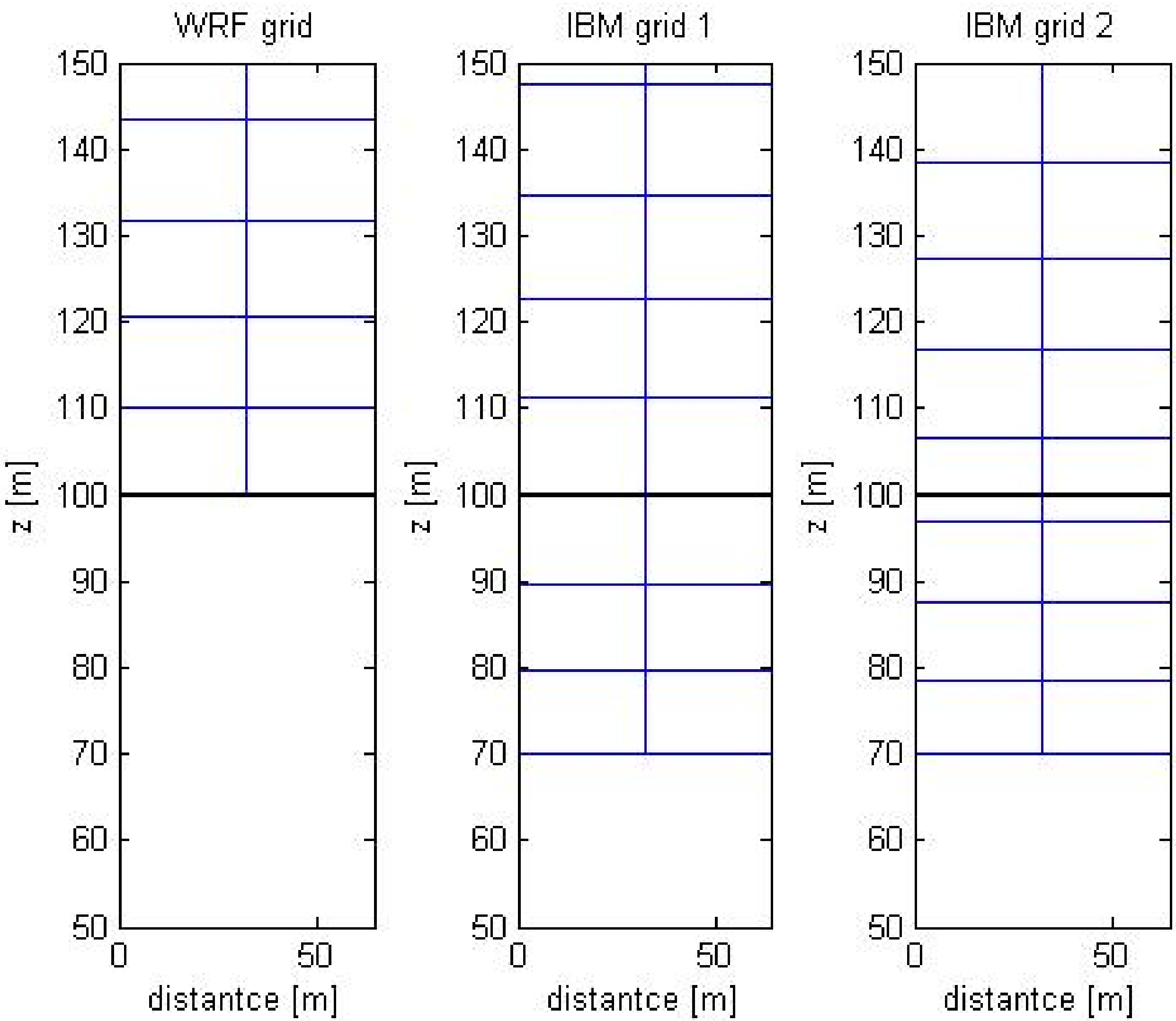
- WRF-IBM (blue) and WRF (red)
- Excellent agreement

Neutral boundary layer setup

- Geostrophically forced flow over a flat plate
- $U_g = 10m/s, V_g = 0m/s$
- $dx = dy = 32m$
- Domain size $\sim$1500m in each direction
- Plate located at 100m
- Log law at bottom boundary
- Smagorinsky turbulence closure
- Turbulence introduced at initialization

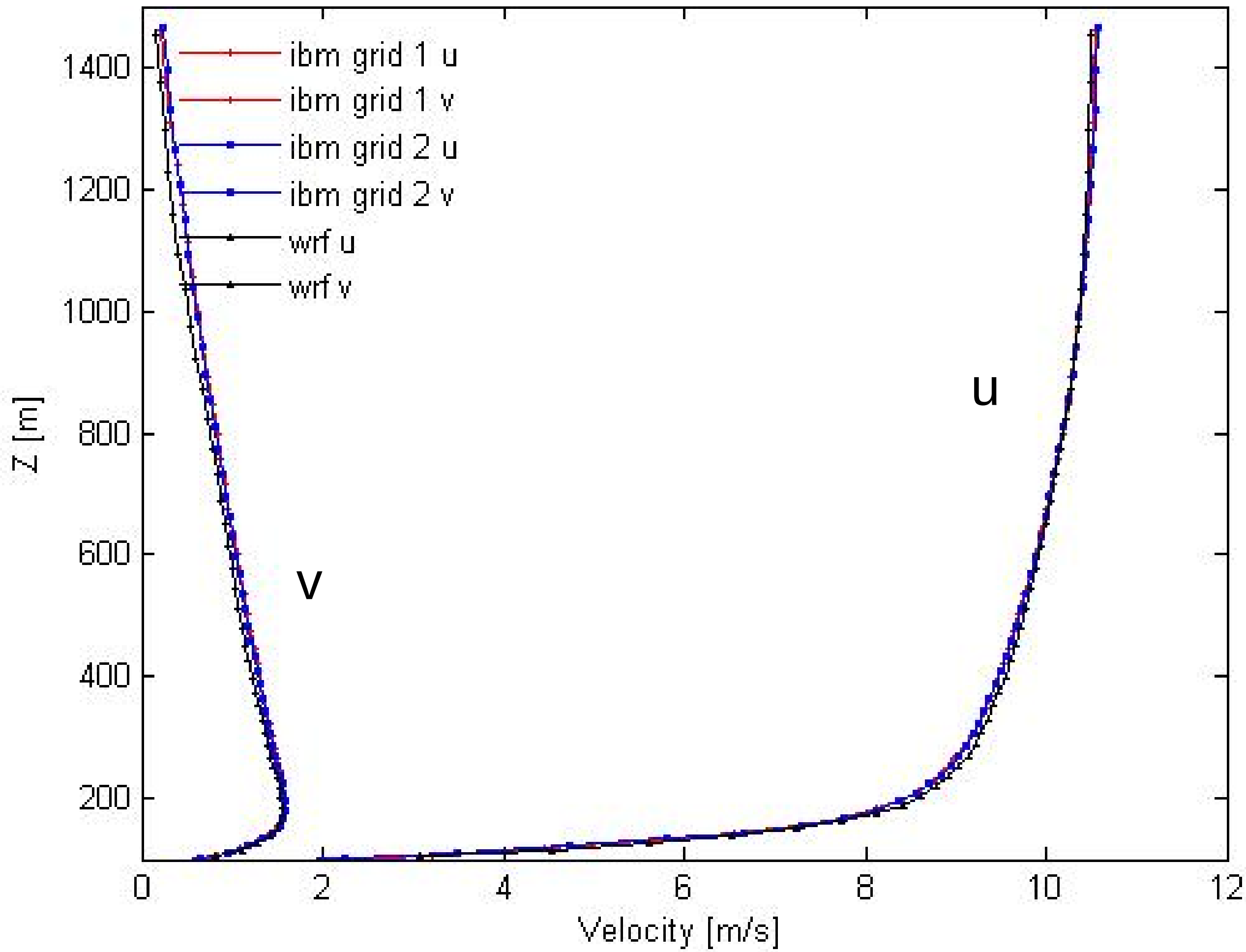
- 2 WRF-IBM cases and 1 WRF case with different vertical levels

Grid setup



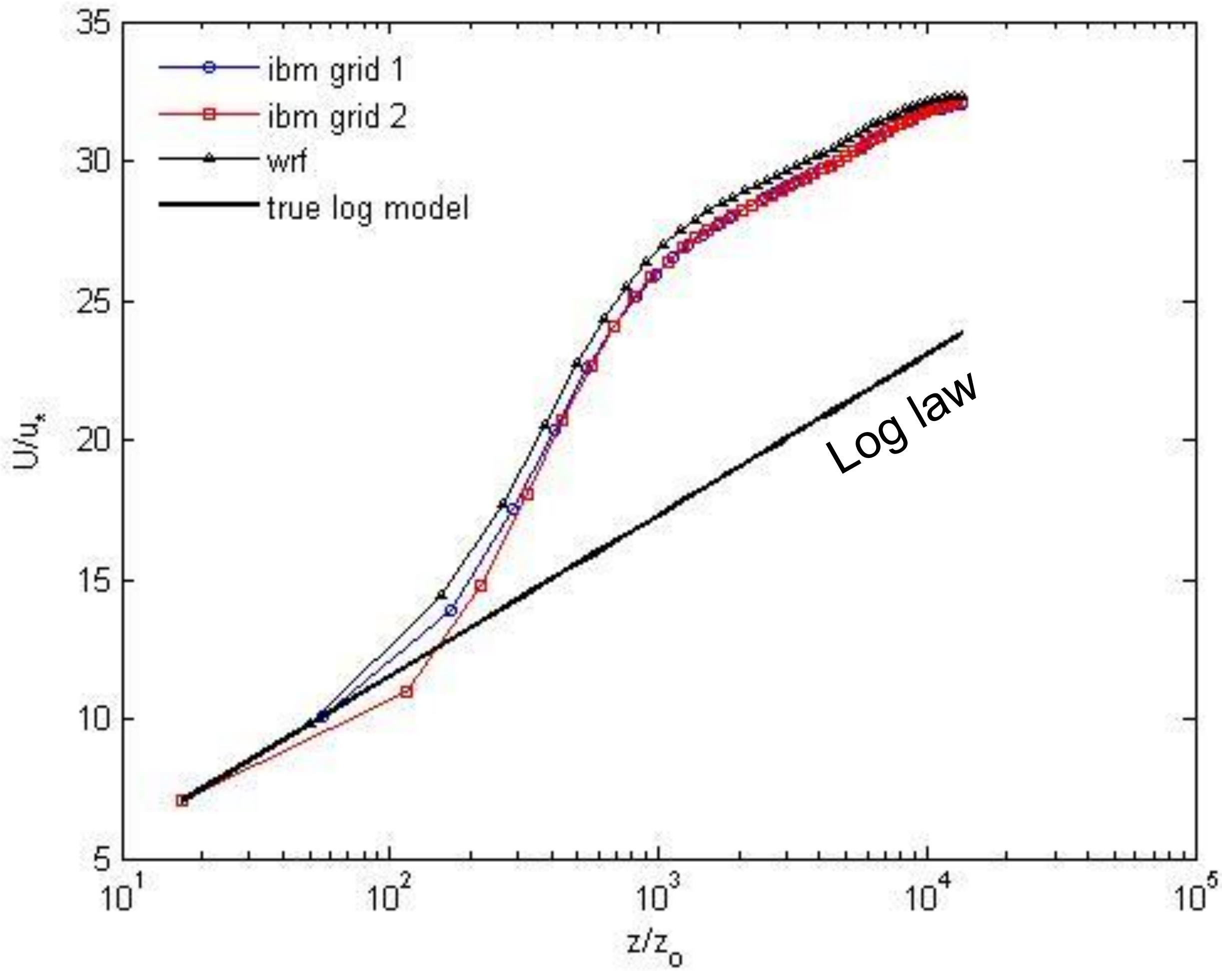
	Zlevel	Z_top
WRF	42	1500
IBM_1	45	1500
IBM_2	50	1500

WRF and WRF-IBM velocity profiles



- IBM-WRF and WRF match

Comparison to log law profile



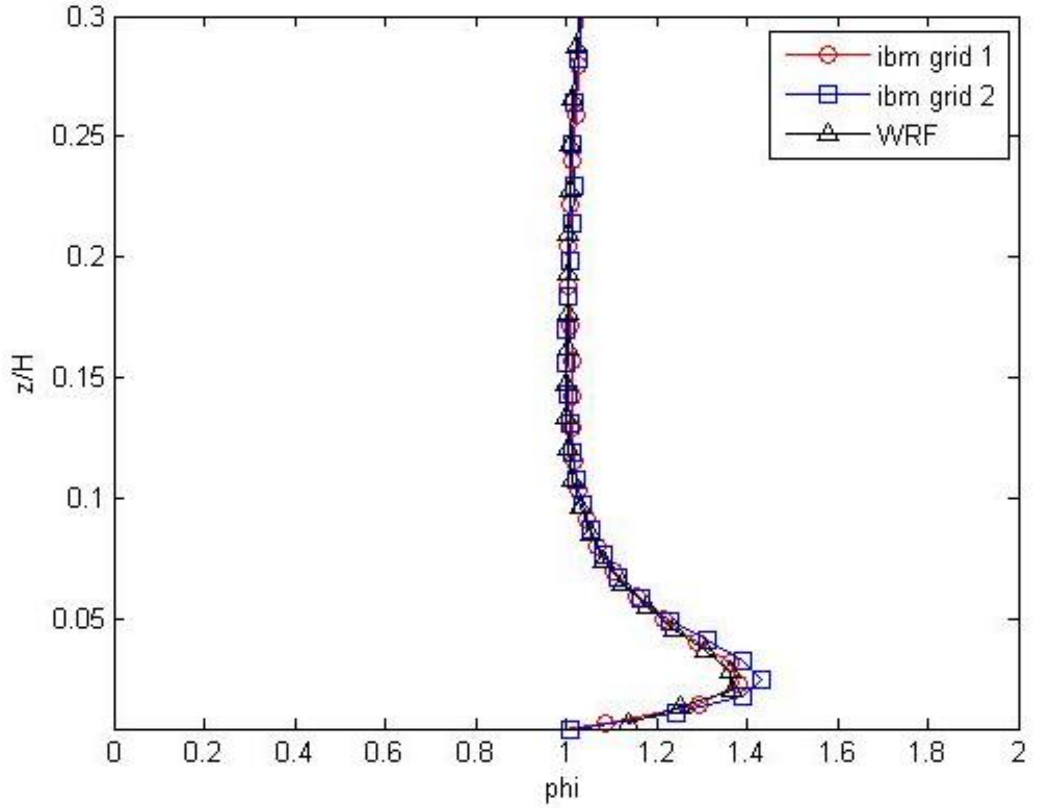
Nondimensional shear profile

- More sensitive measure of log law performance
- Nondimensional velocity gradient

$$F = \frac{kz}{U_*}\sqrt{\left(\frac{\partial U}{\partial z}\right)^2 + \left(\frac{\partial V}{\partial z}\right)^2}$$

- In the logarithmic region of NABL

$$F = 1$$



Ongoing work

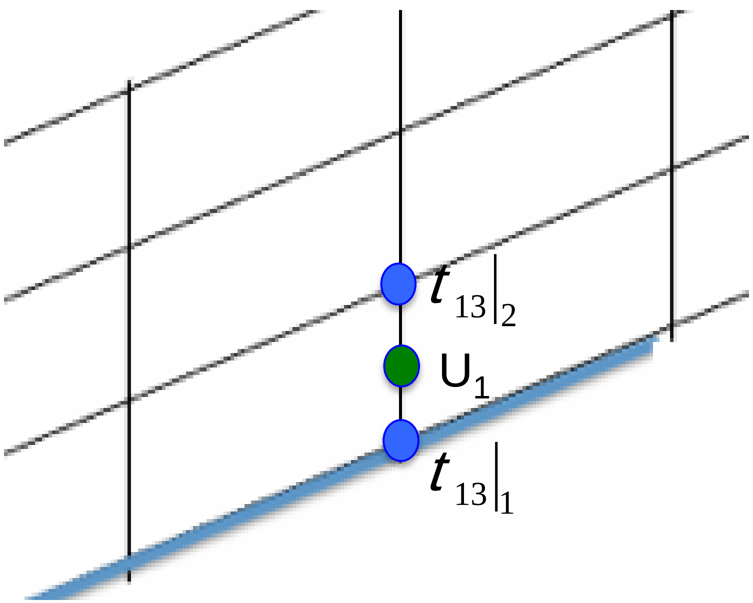
- Ongoing test cases including idealized valley for both surface scalar and momentum fluxes
- More test cases for stable/unstable cases
- Implementation with higher order turbulence closures including TKE 1.5

Conclusions

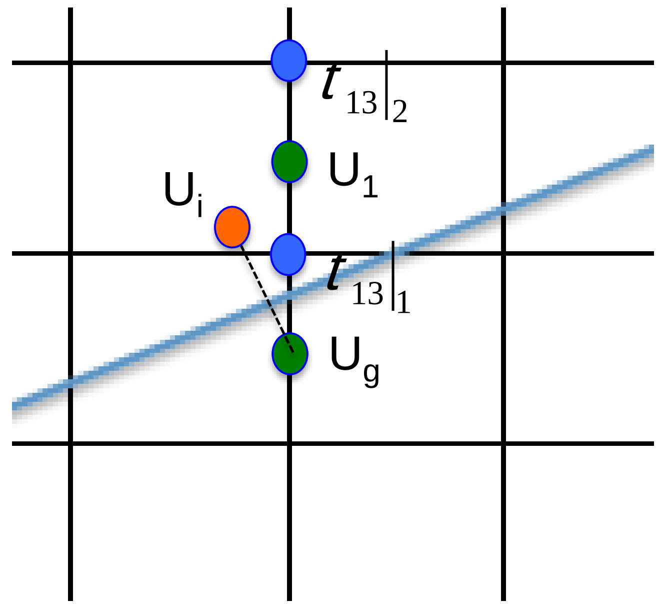
- Verification of the implementation of surface heat flux boundary condition in WRF-IBM
- Verification of the immersed boundary method with log law wall model for neutral boundary layer for momentum
- WRF-IBM agrees well with WRF results.
- Different turbulence models can be coupled with the bottom boundary condition

Difficulty of WRF-IBM momentum implementation

- Potential temperature is updated as: $\dfrac{\partial U}{\partial t} = \ldots - \dfrac{t_{13}|_2 - t_{13}|_1}{\Delta z}$
- Correct $t_{13}|_1$ is required
- WRF: $t_{13}|_1 = t_{wall} = C_d |U_1| U_1$ WRF-IBM: $t_{13}|_1 = - v_{T(att_{13|1})} \dfrac{(U_1 - U_g)}{\Delta z}$
- Correct U_g and $v_{T(att_{3|1})}$ is required for WRF-IBM



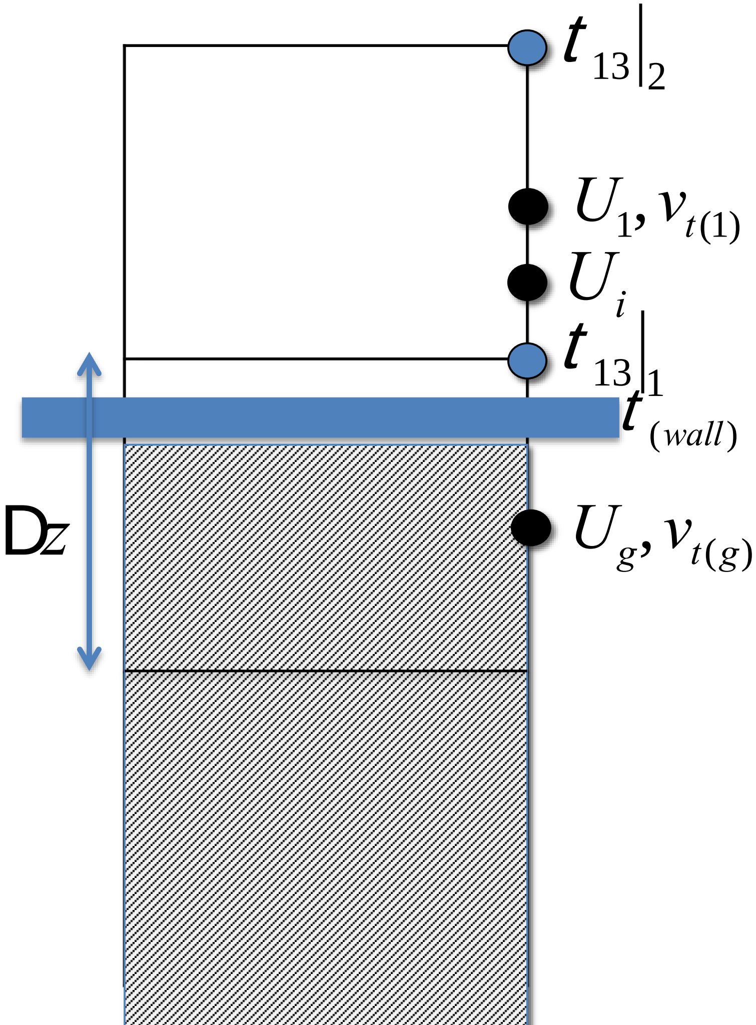
WRF



WRF-IBM

IBM implementation of momentum flux

Log Law



$$\frac{\partial U_1}{\partial t} = \ldots - \frac{\partial t_{13}}{\partial z} = \ldots - \frac{t_{13}\big|_2 - t_{13}\big|_1}{Dz}$$

Need correct $t_{13}\big|_1$

$$t_{13}\big|_1 = -v_{t(att_{13|1})}\frac{U_1 - U_g}{Dz}$$

Need correct U_g and $v_{t(att_{13|1})}$

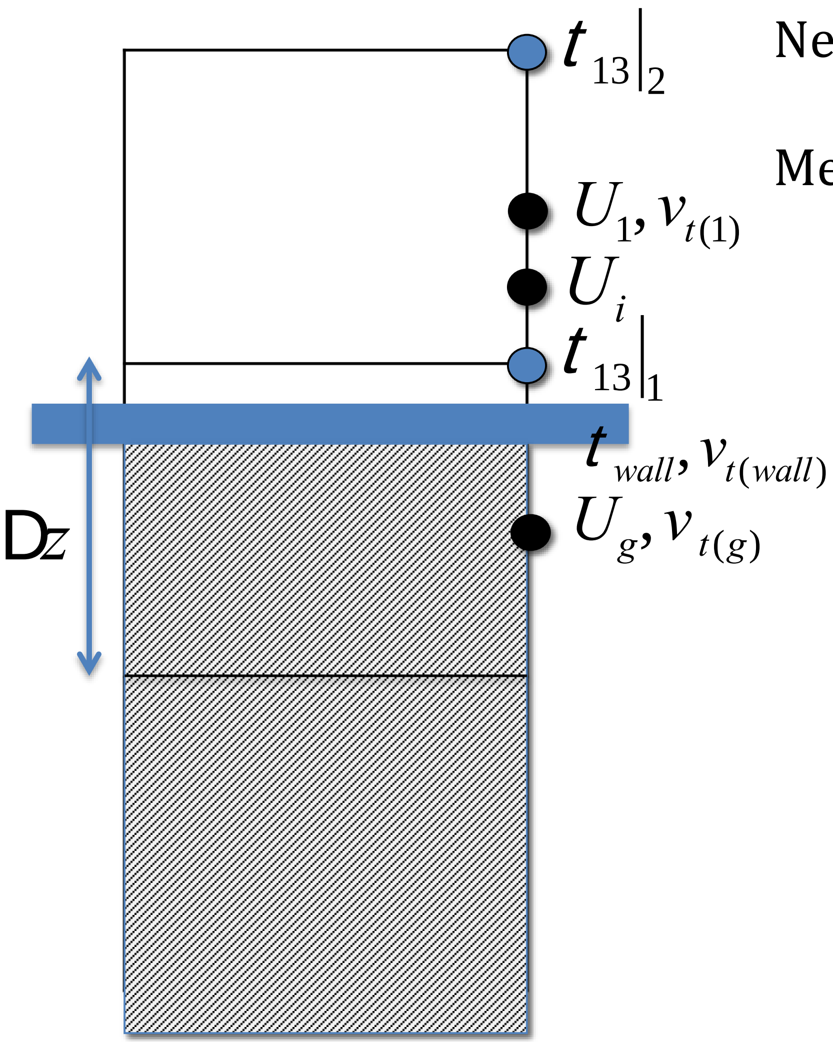
$$t_{wall} = -v_{t(wall)}\frac{U_i - U_g}{Dz}$$

$$U_g = U_i + \frac{t_{wall}}{v_{t(wall)}}Dz \qquad t_{wall} = C_d\left|U_i\right|U_i$$

Need correct $v_{t(wall)}$ and $v_{t(att_{B|1})}$

IBM implementation of momentum flux

Log Law



Need correct $v_{t(wall)}$

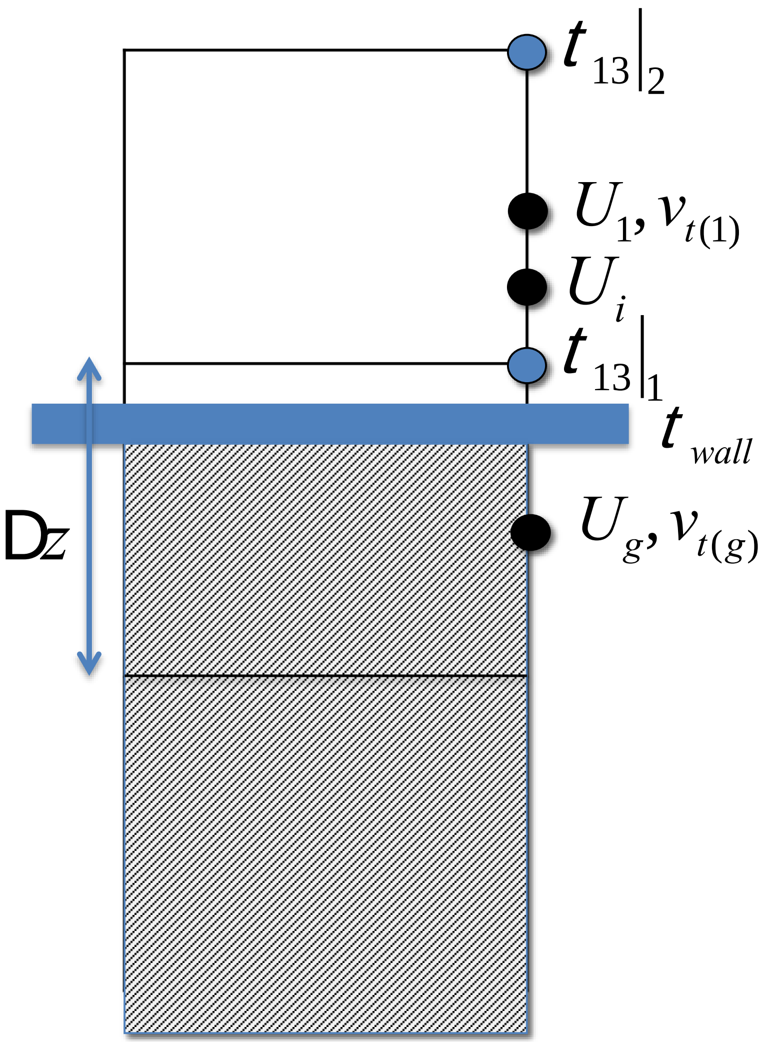
Method : Prandtl's mixing length

- More realistic simulation
- Can couple with turbulence closure

$$v_{t(wall)} = u_* kz$$

IBM implementation of momentum flux

Log law



Need correct $v_{t(atH_{3|1})}$

Method : Prandtl's mixing length

- More realistic simulation
- Can couple with turbulence closure

$$v_{T(atH_{3|1})} = u_* kz(at\,t_{13|1})$$