Vertical Grid Nesting For Improved Surface Layer Resolution In Large-Eddy Simulation

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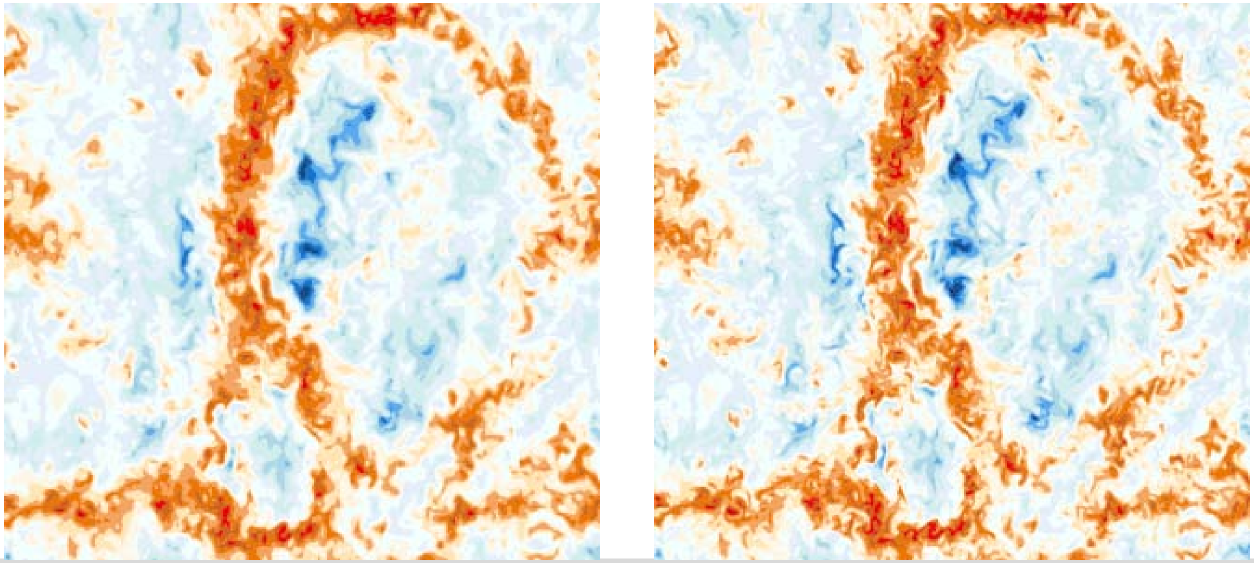
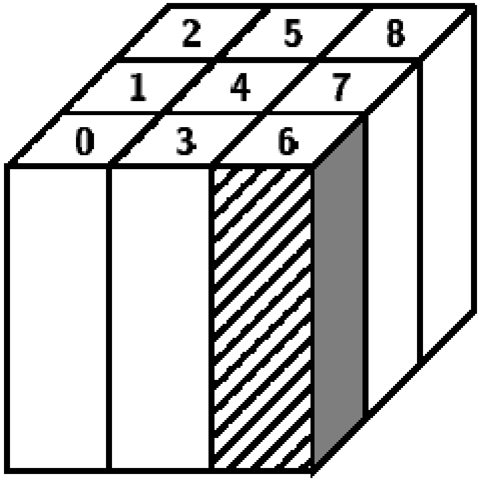


LES: Hardware limitation

- Reynolds numbers of order 10^7 are commonly encountered in the ABL
- Number of grid points required to resolve the energy containing eddies is known to be in the range of $Re^{1.76}$
- Total number of grid points of order 10^{12} are required
- LES of atmospheric flows with high resolution in the surface layer are not feasible yet
- Number of grid points can be reduced using grid nesting approach

PArallelized Large-Eddy Simulation Model (PALM)

- Non-hydrostatic incompressible Boussinesq equations
- SGS turbulence is modeled according to Deardoff (1980)
- Monin-Obukhov similarity is assumed between the surface and the first computational grid point
- Third order three stage Runge-Kutta scheme for time discretization
- 2-D domain decomposition
- Arakawa-C Grid

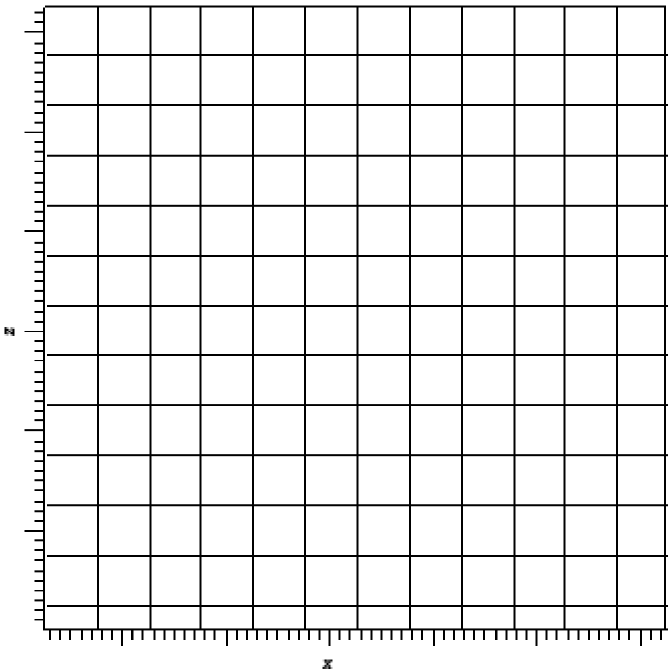


S. Raasch and M. Schröter, Meteorologische Zeitschrift, 2001

Nested Grid Approach

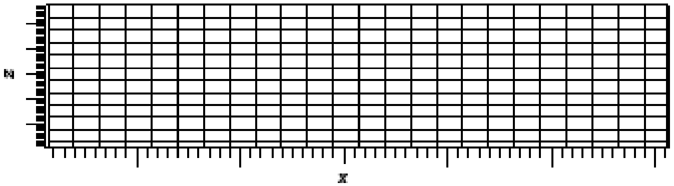
- Horizontal grid nesting is common in numerical weather prediction models
- Vertical grid nesting studies: Sullivan et al. 1996 and PALM Group - University of Hannover, 2003

Coarse Grid



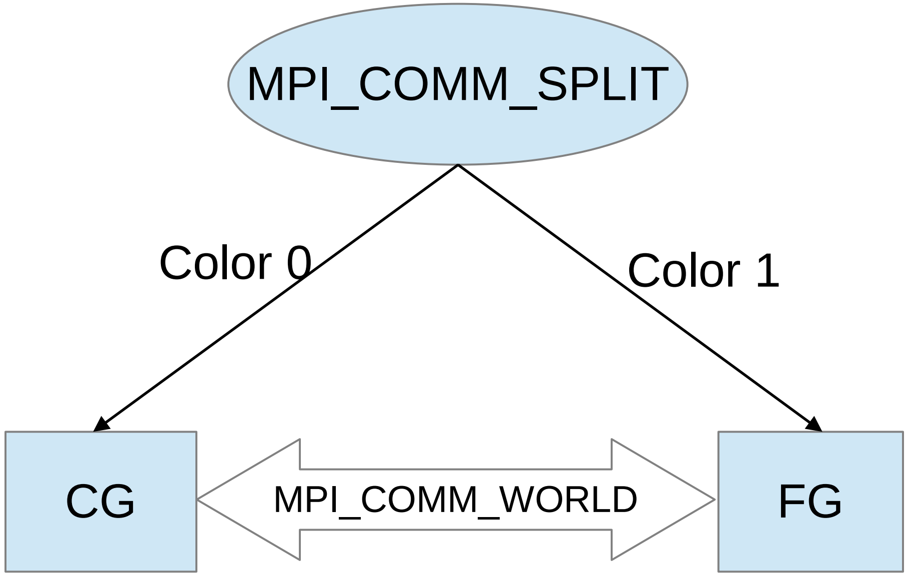
- Equal horizontal extent
- Cyclic lateral Boundary Conditions (BC)
- Integer nesting ratio

Fine Grid



MPI Coupling Strategy

- MPI-1 standards adopted (no processor spawning)
- MPI_COMM_SPLIT to distribute the available processor cores between Fine Grid (FG) and Coarse Grid (CG) groups.



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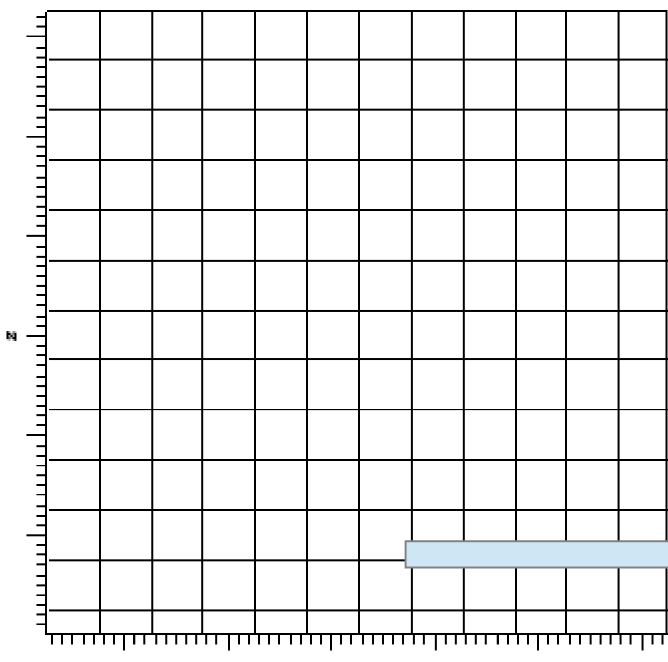
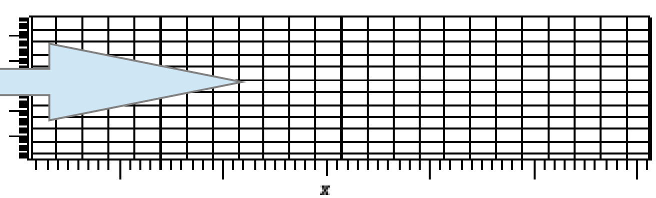
Interpolation

- Initialize the Fine Grid (prognostic variables & surface fluxes)
- To set top Boundary Conditions for the Fine Grid.
  - Dirichlet: Horizontal velocities and potential temperature
- Scheme: Clark and Farley (1984)

$$
\begin{aligned}
\phi_k &= E^k_{i-1}\Phi_{i-1} + E^k_i\Phi_i + E^k_{i+1}\Phi_{i+1} \\
E^k_{i-1} &= \frac{\epsilon_k(\epsilon_k - 1)}{2} + \alpha \\
E^k_i &= (1 - \epsilon^2_k) - 2\alpha \\
E^k_{i+1} &= \frac{\epsilon_k(\epsilon_k + 1)}{2} + \alpha \\
\epsilon_k &= \frac{(2k-1)\Delta x - \Delta X}{2\Delta X} \qquad k = 1, \ldots, n \\
\alpha &= \frac{\left(\frac{\Delta x}{\Delta X}\right)^2 - 1}{24}.
\end{aligned}
$$





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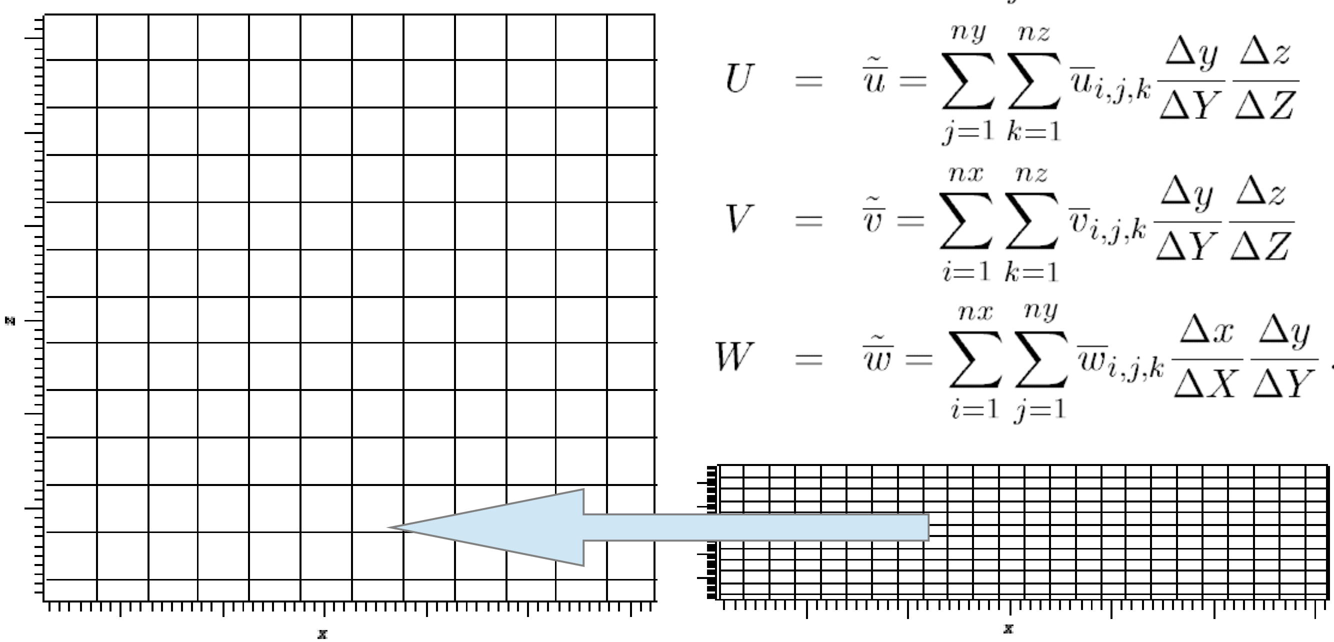
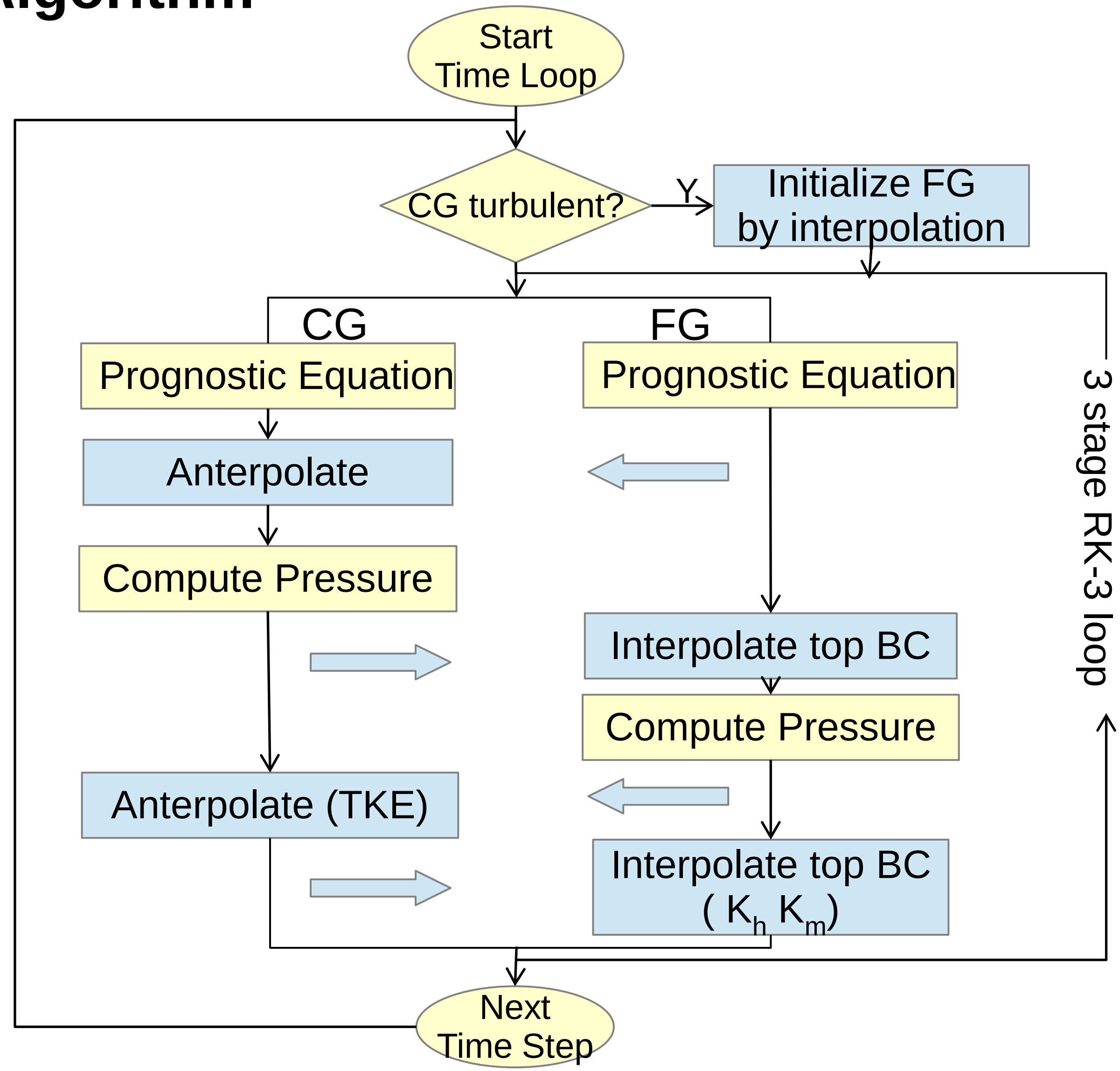
Anterpolation

- Weighted averaging of the FG data to the CG in the overlapping region
- TKE Germano identity $E = \tilde{\tilde{e}} + \frac{1}{2}\left(\widetilde{\overline{u_i}\,\overline{u_i}} - \tilde{\overline{u}}_i\tilde{\overline{u}}_i\right)$

$$
\begin{aligned}
\Phi &= \tilde{\bar{\phi}} = \sum_{i=1}^{nx}\sum_{j=1}^{ny}\sum_{k=1}^{nz}\bar{\phi}_{i,j,k}\frac{\Delta x}{\Delta X}\frac{\Delta y}{\Delta Y}\frac{\Delta z}{\Delta Z}\\
U &= \tilde{\bar{u}} = \sum_{j=1}^{ny}\sum_{k=1}^{nz}\bar{u}_{i,j,k}\frac{\Delta y}{\Delta Y}\frac{\Delta z}{\Delta Z}\\
V &= \tilde{\bar{v}} = \sum_{i=1}^{nx}\sum_{k=1}^{nz}\bar{v}_{i,j,k}\frac{\Delta y}{\Delta Y}\frac{\Delta z}{\Delta Z}\\
W &= \tilde{\bar{w}} = \sum_{i=1}^{nx}\sum_{j=1}^{ny}\bar{w}_{i,j,k}\frac{\Delta x}{\Delta X}\frac{\Delta y}{\Delta Y}.
\end{aligned}
$$



Nesting Algorithm



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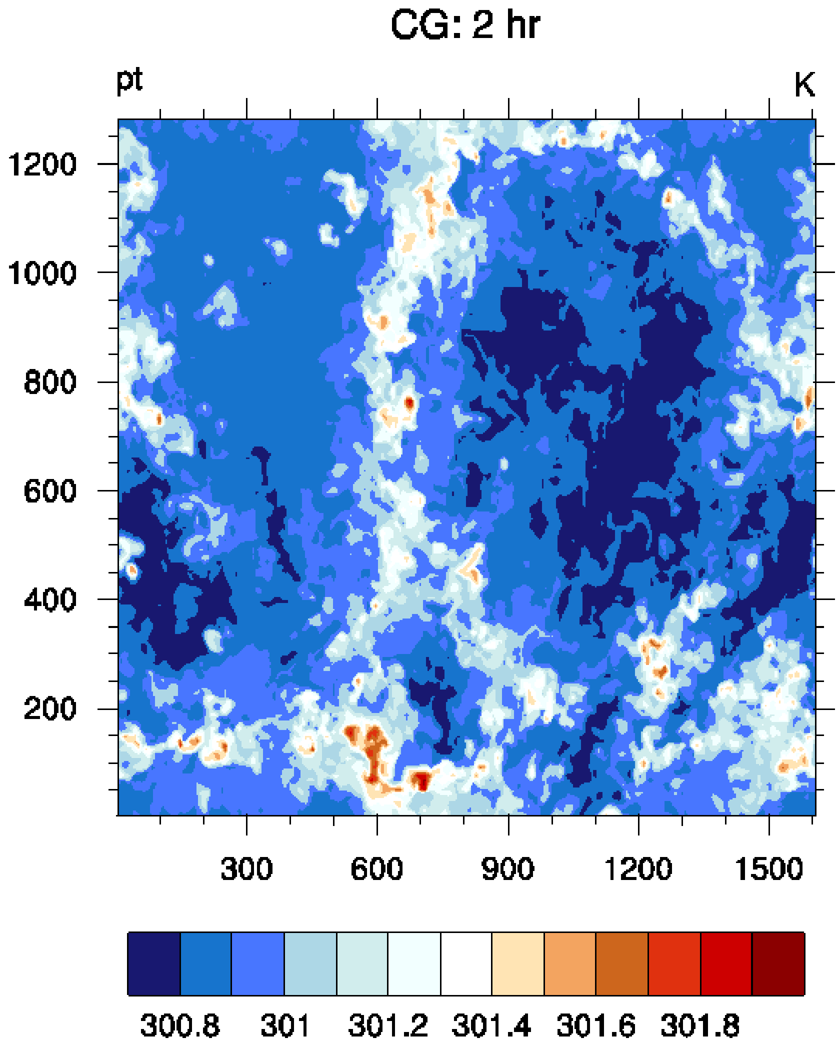
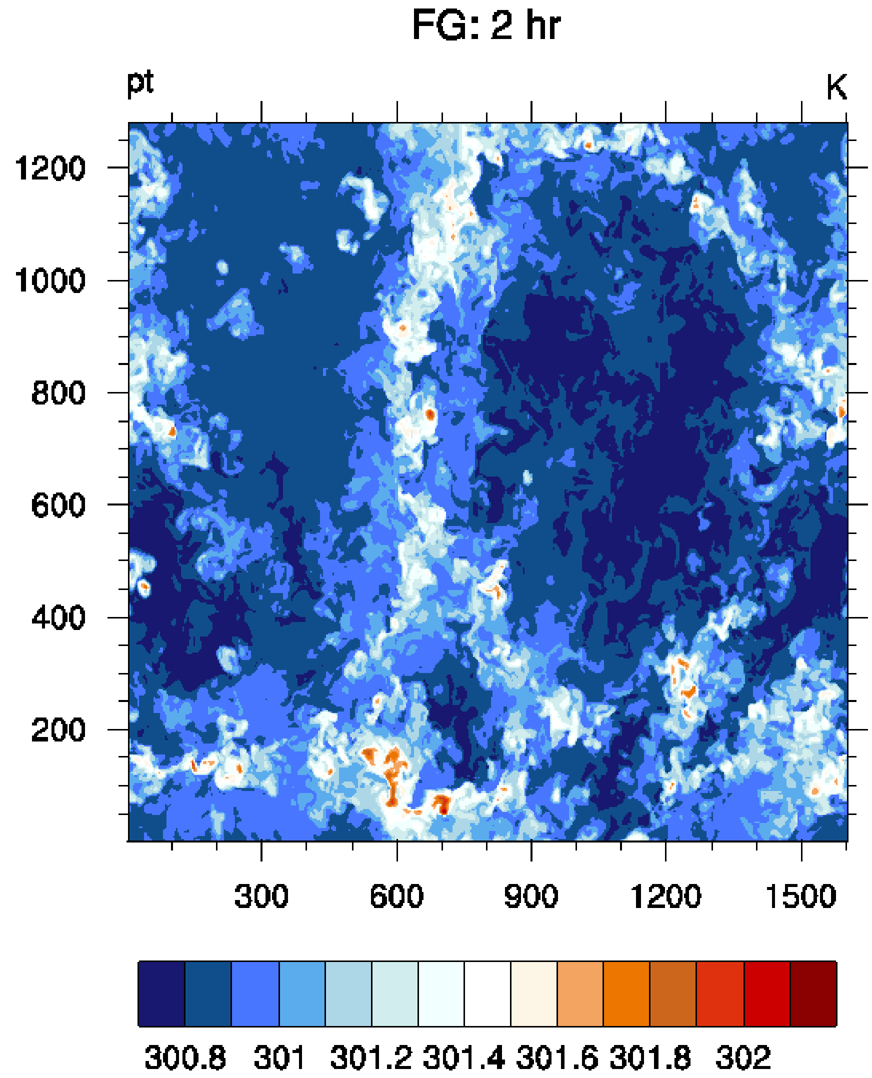
Test Case

- Domain Size: 1.6 x 1.28 x 1.2 km
- Fine grid vertical extent: 200 m
- Surface Heat flux varied sinusoidally between of 0.08 and 0.12 K m /s
- Simulated Time: 2 hr

	No. of Grid Points	Δx,Δy,Δz	CPU cores	Wall time
Coarse Grid	200 x 160 x 300 = 9.6 M	8, 8, 4	80	5.5 hrs
Fine Grid (Nesting ratio: 2)	400 x 320 x 100 = 12.8 M	4, 4, 2	160	5.5 hrs
Reference	400 x 320 x 600 = 76.8 M	4, 4, 2	200	9.3 hrs

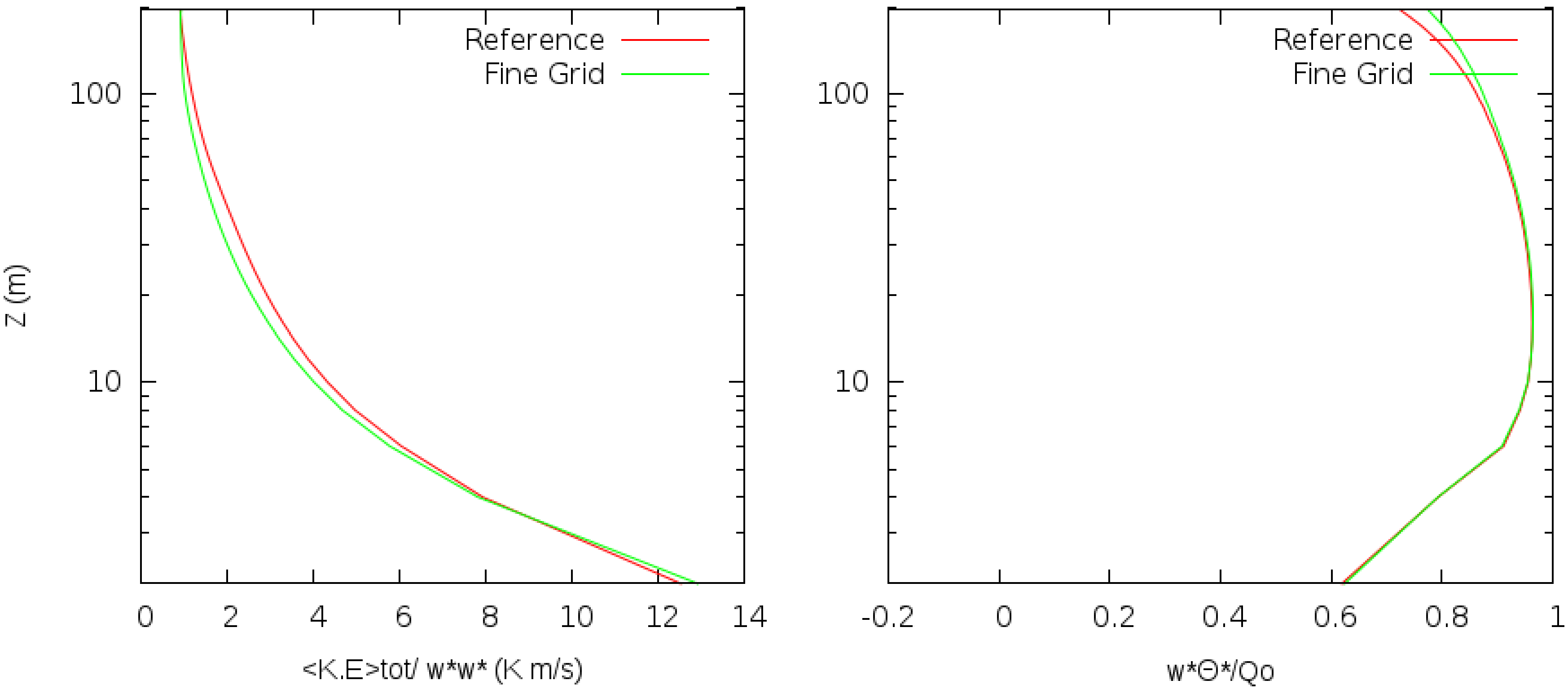
Results: Potential Temperature at 100m





Results: T.K.E and Heat Flux

Averaged profiles after 2 hour simulation



Future Work

- Evaluate speed-up for large-scale simulations
- Identify optimal nesting ratio and processor distribution between CG & FG
- Include topography / surface heterogeneities
- Alternative interpolation and coupling strategy
- “Sponge” Layer

Thank you for listening.