Adapting the MPAS Dynamical Core for Geospace Applications

Modifying MPAS to permit a constant pressure upper boundary

Joseph Klemp and William Skamarock

National Center for Atmospheric Research

Boulder, Colorado, USA

MPAS

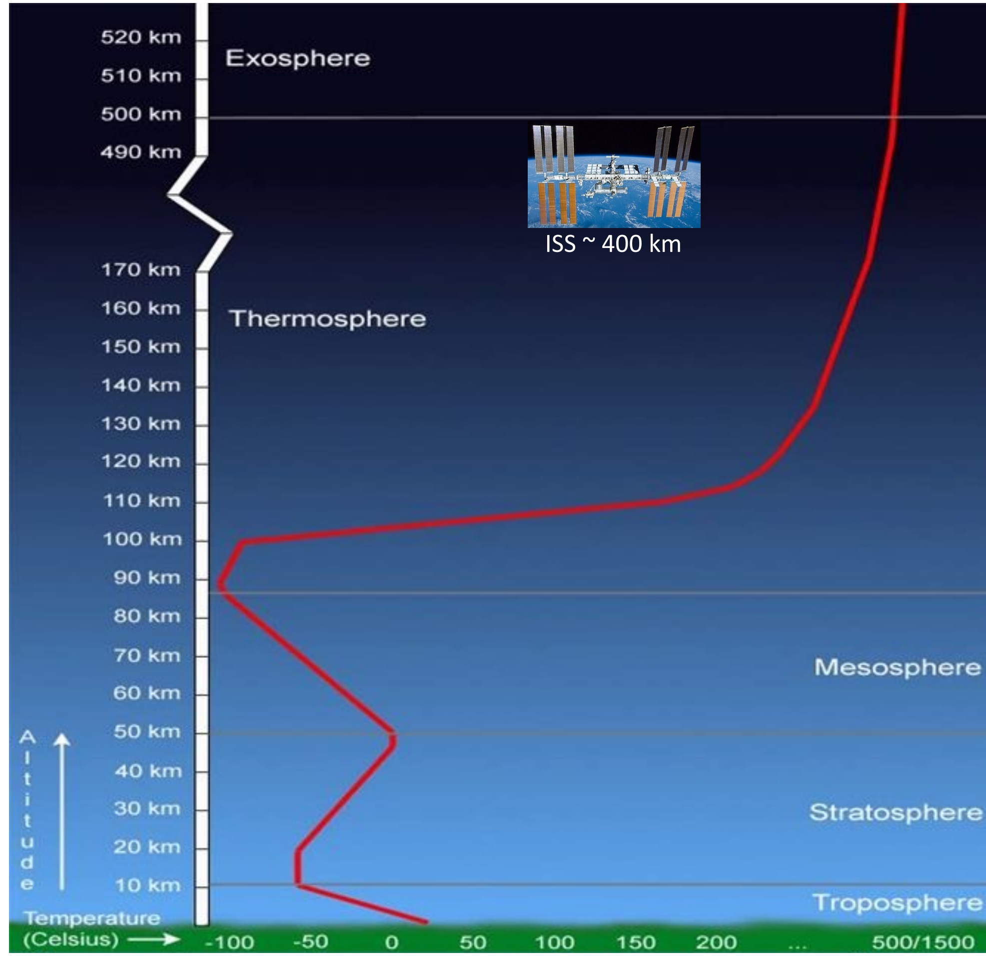
Average Temperature Profile in the Earth's Atmosphere

p (hPa): 10^{-8}, 10^{-6}, 10^{-4}, 10^{0}, 10^{3}

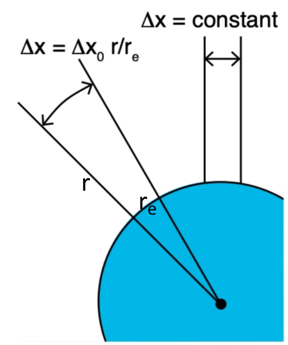
ρ (kg/m^3): 10^{-12}, 10^{-9}, 10^{-6}, 10^{-3}, 10^{0}

θ (K): 10^{7}, 10^{5}, 10^{4}, 10^{3}, 300

ν (m^2/s): 10^{7}, 10^{4}, 10^{2}, 10^{-1}, 10^{-5}



Modifications to MPAS Numerics for Deep Atmosphere Applications

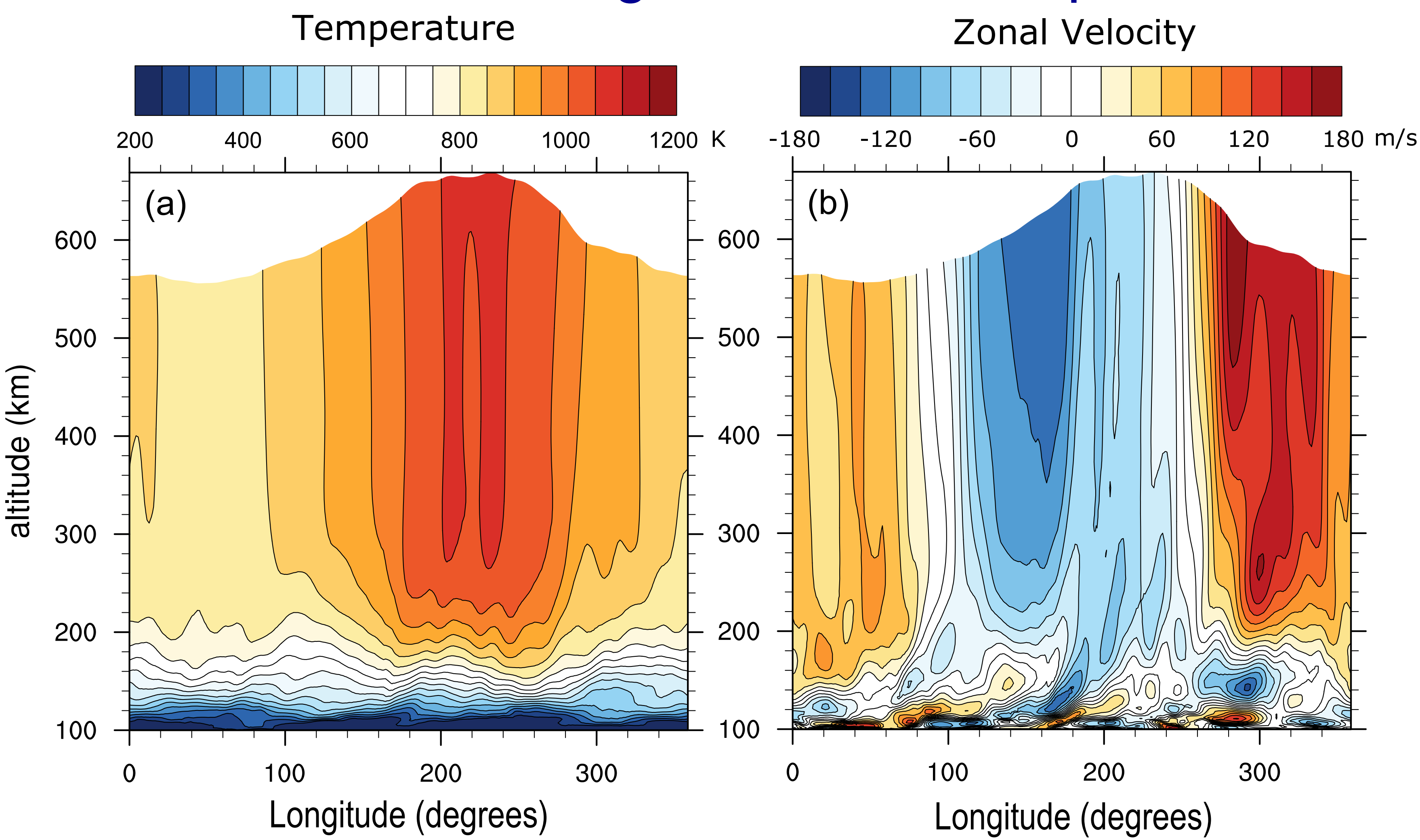


- Use actual geocentric distance *r* instead of the Earth radius r_e in the governing equations and the grid mesh configuration
- Allow gravity to vary with height, $g(z) = g_0 \frac{r_e^2}{(r_e+z)^2}$
- Include Coriolis force terms involving vertical velocity components

Above ~ 150 km

- Include variable atmospheric composition and its coupling to the dynamics
- Include (large) kinematic viscosity and thermal diffusivity terms
- Add appropriate physics and chemistry for the upper atmosphere (solar and Joule heating, ion drag, oxygen disassociation, etc.)
- Modify vertical coordinate to permit a constant pressure upper boundary

Diurnal Heating in the Thermosphere



Vertical cross section along the equator from the WACCM- X 2.0 Model at 00Z on 21 January 2000

Coordinate Transform for Variable Height Model Top

$$z = \left(\frac{\zeta - z_p}{H_0 - z_p}\right)^2 (H - H_0) + \zeta, \qquad \text{for} \quad z > z_p$$

Hydrostatic equation:

$$\frac{\partial \phi}{\partial z} = -\frac{g}{R_d T}, \qquad \phi = \ln(p/p_0)$$

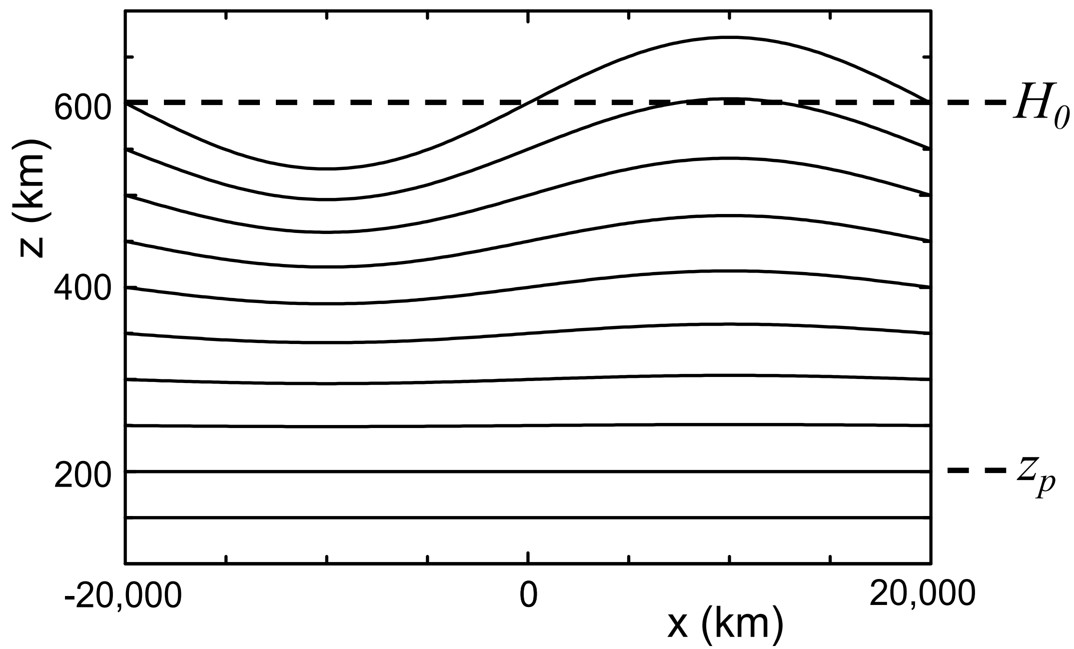
Adjustment of model top H to constant pressure surface ϕ_{top}:

$$H = H^* + \frac{R_d T}{g}(\phi^* - \phi_{\text{top}})$$

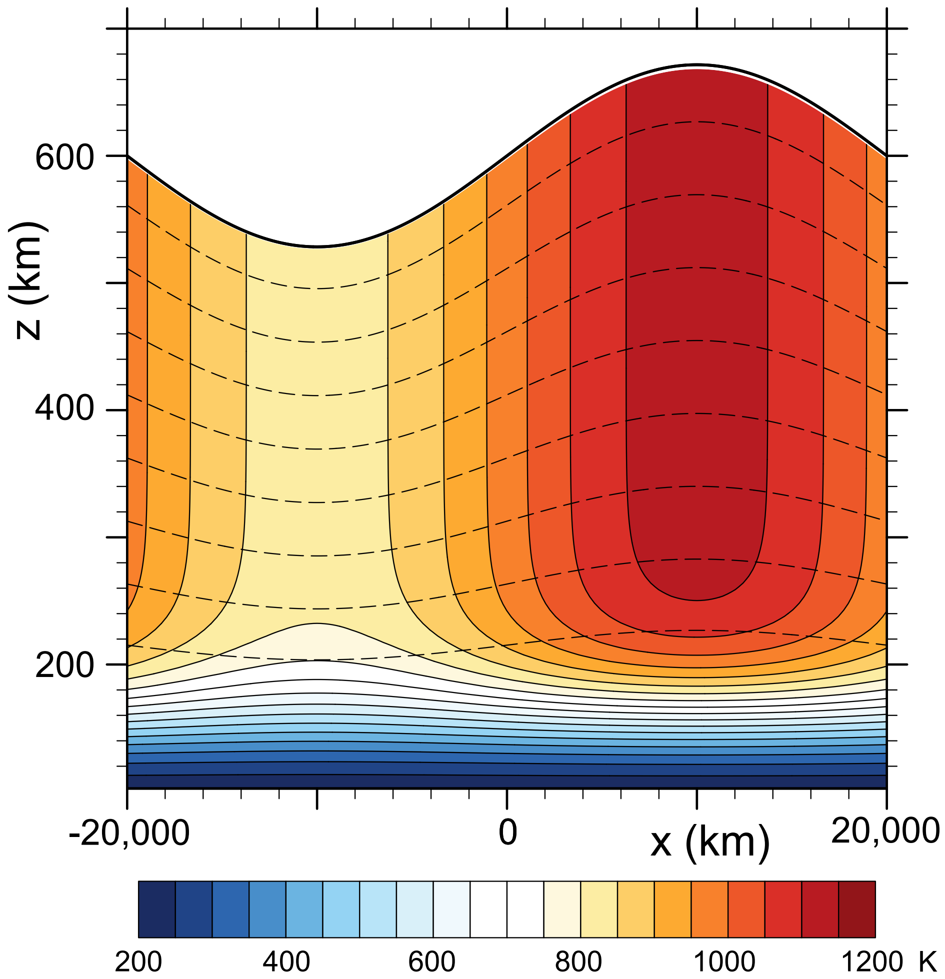
Material surface at top boundary:

$$\begin{aligned} \omega &= \zeta_z(w - z_x - z_t) \\ &= 0 \quad \text{at} \quad \zeta = H_0 \end{aligned}$$

Height of coordinate surfaces with a constant pressure upper boundary.



Diurnal Heating Test Case



Initial (inverse) temperature:

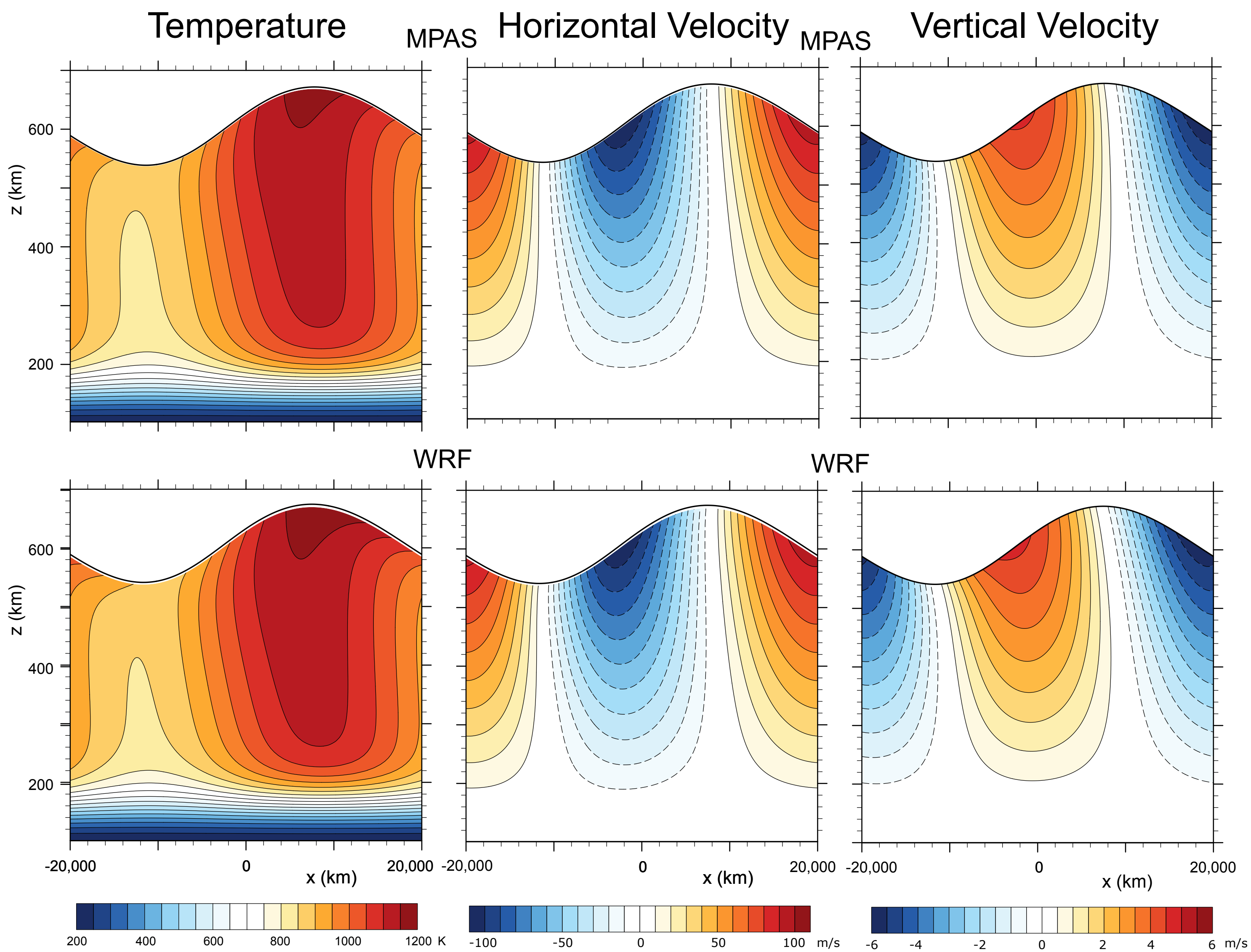
$$T^{-1} = T_b^{-1} - \left(T_b^{-1} - T_t^{-1}\right) \tanh \frac{z - z_b}{z_d}$$

Diurnal temperature variation as $z \to \infty$:

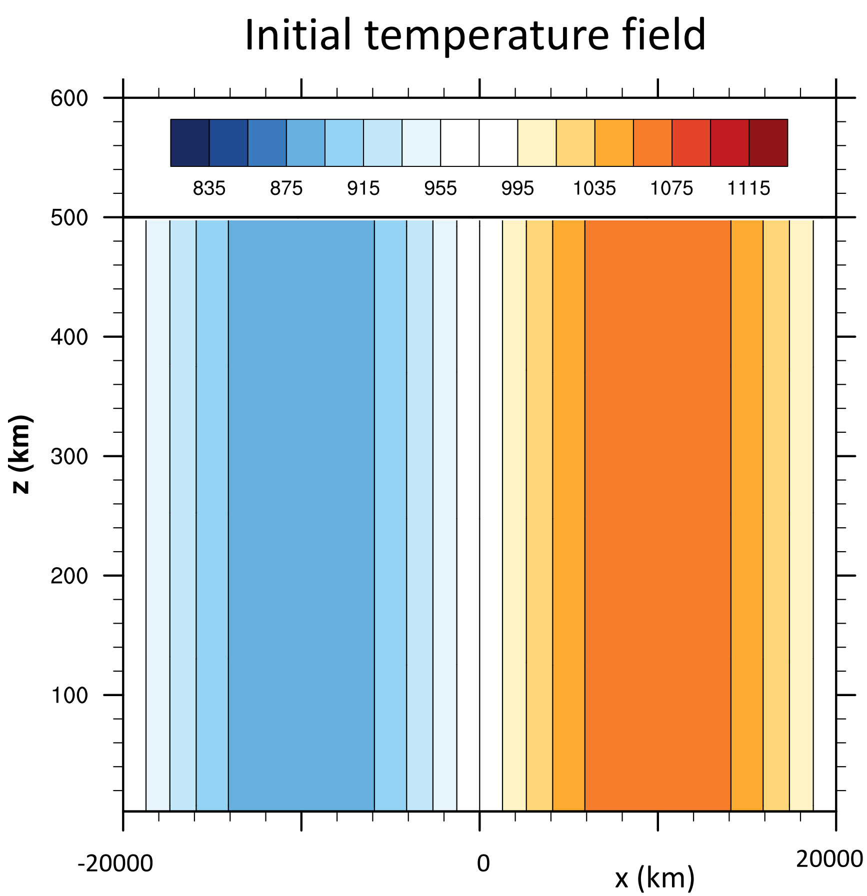
$$T_t = \overline{T} + \Delta T_d \cdot \sin 2\pi \left(\frac{x}{L_e} + \omega t \right)$$

Physically realistic solutions require dissipation in the horizontal momentum equation.

MPAS and WRF Results at 1 day



Diurnal Heating with Rigid Lid Upper Boundary



Simplified test case configuration to compare with linear analytic solution

- Initial temperature independent of height:

$$T = \bar{T} + \Delta T_d \cdot \sin\left(\frac{2\pi x}{L_e}\right)$$

- Heating function independent of height:

$$\frac{\partial T}{\partial t} = 2\pi \Delta T_d \cdot \cos 2\pi \left(\frac{x}{L_e} + \omega t\right)$$

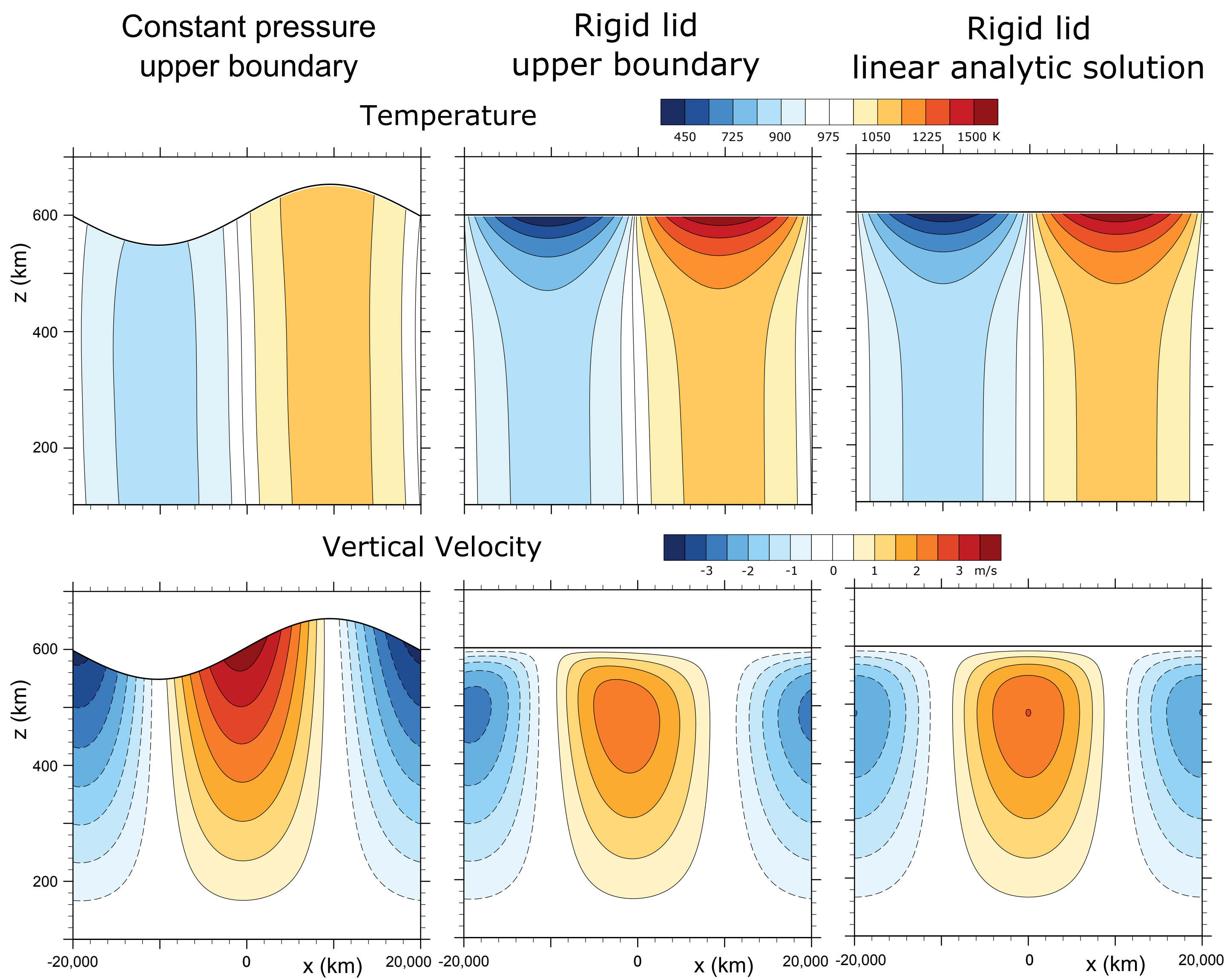
- Linear analytic solution:

$$w = \omega \frac{\Delta T_d}{\bar{T}} \left[z - H_0 \frac{e^{z/H_s} - 1}{e^{H_0/H_s} - 1} \right] \cdot \cos 2\pi \left(\frac{x}{L_e} + \omega t\right)$$

$$T = \bar{T} + \Delta T_d \left[1 + \frac{R H_0}{c_v H_s} e^{-(H_0 - z)/H_s} \right] \cdot \sin 2\pi \left(\frac{x}{L_e} + \omega t\right)$$

MPAS

Comparison with Rigid Lid Results at 1 day



MPAS

Summary

- Height-based hybrid terrain-following coordinates seem well suited for deep atmosphere domains.

- For applications extending into the thermosphere, realistic simulations may require an upper boundary that permits vertical expansion/contraction of the atmosphere.

- For a height-based vertical coordinate, the rigid lid upper boundary can be relaxed through a simple coordinate transform that requires only minor modifications to the model numerics.

- Applying a hydrostatic adjustment each time step, the upper boundary can adaptively move to follow a desired constant pressure surface.

- An idealized diurnal heating test case confirms the viability of the technique and emphasizes the importance of relaxing the rigid lid constraint.