DCMIP2016, Part 4: Splitting Supercell

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Abstract. This paper discusses a new idealized test for atmospheric dynamical cores.

1 Introduction

The supercell test permits the study of a non-hydrostatic moist feature with strong vertical velocities and associated precipitation and is based on the work of Klemp and Wilhelmson (1978).

It is assumed that the saturation mixing ratio is given by

$$q_{vs}(p,T) = \left(\frac{380.0}{p}\right) \exp\left(17.27 \times \frac{T - 273.0}{T - 36.0}\right) \tag{1}$$

The definition of this test case relies on hydrostatic and gradient wind balance, written in terms of Exner pressure π and virtual potential temperature θ_v as

$$\frac{\partial \pi}{\partial z} = -\frac{g}{c_p \theta_v}, \quad \text{and} \quad u^2 \tan\varphi = -c_p \theta_v \frac{\partial \pi}{\partial \varphi}. \tag{2}$$

Table 1. List of constants used for the Supercell test

Constant	Value	Description
X	120	Small-planet scaling factor (reduced Earth)
θ_{tr}	343 K	Temperature at the tropopause
θ_0	300 K	Temperature at the equatorial surface
z_{tr}	12000 m	Altitude of the tropopause
T_{tr}	213 K	Temperature at the tropopause
U_s	30 m/s	Maximum zonal wind velocity
U_c	15 m/s	Coordinate reference velocity
z_s	5000 m	Lower altitude of maximum velocity
Δz_u	1000 m	Transition distance of velocity
$\Delta\theta$	3 K	Thermal perturbation magnitude
λ_p	0	Thermal perturbation longitude
φ_p	0	Thermal perturbation latitude
r_p	$X \times 10000$ m	Perturbation horizontal half-width
z_c	1500 m	Perturbation center altitude
z_p	1500 m	Perturbation vertical half-width

These equations can be combined to eliminate π, leading to

$$\frac{\partial \theta_v}{\partial \varphi} = \frac{\sin(2\varphi)}{2g}\left(u^2 \frac{\partial \theta_v}{\partial z} - \theta_v \frac{\partial u^2}{\partial z}\right). \tag{3}$$

The wind velocity is analytically defined throughout the domain. Meridional and vertical wind is initially set to zero. The zonal wind is obtained from

$$\overline{u}(\varphi, z) = \begin{cases} \left(U_s \frac{z}{z_t} - U_c\right)\cos(\varphi) & \text{for } z < z_s - \Delta z_u, \\ \left(-\frac{4}{5} + 3\frac{z}{z_s} - \frac{5}{4}\frac{z^2}{z_s^2}\right) U_s - U_c & \text{for } |z - z_s| \leq \Delta z_u \\ (U_s - U_c)\cos(\varphi) & \text{for } z > z_s + \Delta z_u \end{cases} \tag{4}$$

The equatorial profile is determined through numerical iteration. Potential temperature at the equator is specified via

$$\theta_{\mathrm{eq}}(z) = \begin{cases} \theta_0 + (\theta_{tr} - \theta_0)\left(\frac{z}{z_{tr}}\right)^{\frac{5}{4}} & \text{for } 0 \leq z \leq z_{tr}, \\ \theta_{tr}\exp\left(-\frac{g(z - z_{tr})}{c_p T_{tr}}\right) & \text{for } z_{tr} \leq z \end{cases} \tag{5}$$

And relative humidity is given by

$$\overline{H}(z) = \begin{cases} 1 + \dfrac{3}{4}\left(\dfrac{z}{z_{tr}}\right)^{5/4} & \text{for } 0 \le z \le z_{tr}, \\ \dfrac{1}{4} & \text{for } z_{tr} \le z. \end{cases} \tag{6}$$

Pressure and temperature at the equator are obtained by iterating on hydrostatic balance with initial state

$$\theta_{v,\text{eq}}^{(0)}(z) = \theta_{\text{eq}}(z), \tag{7}$$

and iteration procedure

$$\pi_{\text{eq}}^{(i)} = 1 - \int_0^z \frac{g}{c_p \theta_{v,\text{eq}}^{(i)}} dz \tag{8}$$

$$p_{\text{eq}}^{(i)} = p_0 (\pi^{(i)})^{c_p/R_d} \tag{9}$$

$$T_{\text{eq}}^{(i)} = \theta_{\text{eq}}(z) \pi_{\text{eq}}^{(i)} \tag{10}$$

$$q_{\text{eq}}^{(i)} = H(z) q_{vs}(p_{\text{eq}}^{(i)}, T_{\text{eq}}^{(i)}) \tag{11}$$

$$\theta_{v,\text{eq}}^{(i+1)} = \theta_{\text{eq}}(z)(1 + M_v q_{\text{eq}}^{(i)}) \tag{12}$$

This iteration procedure appears to converge to machine epsilon after approximately 10 iterations. The equatorial moisture profile is then extended through the entire domain,

$$q(z,\varphi) = q_{\text{eq}}(z). \tag{13}$$

Once the equatorial profile has been constructed, the virtual potential temperature through the remainder of the domain can be computed by iterating on (3),

$$\theta_v^{(i+1)}(z,\varphi) = \theta_{v,\text{eq}}(z) + \int_0^{\varphi} \frac{\sin(2\phi)}{2g} \left(\overline{u}^2 \frac{\partial \theta_v^{(i)}}{\partial z} - \theta_v^{(i)} \frac{\partial \overline{u}^2}{\partial z} \right) d\varphi. \tag{14}$$

Again, approximately 10 iterations are needed for convergence to machine epsilon. Once virtual potential temperature has been computed throughout the domain, Exner pressure throughout the domain can be obtained from (2),

$$\pi(z,\varphi) = \pi_{eq}(z) - \int_0^{\varphi} \frac{u^2 \tan\varphi}{c_p \theta_v} d\varphi, \tag{15}$$

and so

$$p(z,\varphi) = p_0 \pi(z,\varphi)^{c_p/R_d}, \tag{16}$$

$$T_v(z,\varphi) = \theta_v(z,\varphi)(p/p_0)^{R_d/c_p}. \tag{17}$$

1.1 Potential temperature perturbation

To initiate convection, a thermal perturbation is introduced in the initial potential temperature field:

$$\theta'(\lambda,\phi,z) = \begin{cases} \Delta\theta\cos^2\left(\frac{\pi}{2}R_\theta(\lambda,\varphi,z)\right) & \text{for } R_\theta(\lambda,\varphi,z) < 1, \\ 0 & \text{for } R_\theta(\lambda,\varphi,z) \geq 1, \end{cases} \tag{18}$$

where

$$R_\theta(\lambda,\varphi,z) = \left[\left(\frac{R_c(\lambda,\varphi;\lambda_p,\varphi_p)}{r_p}\right)^2 + \left(\frac{z-z_c}{z_p}\right)^2\right]^{1/2}. \tag{19}$$

Note: An additional iterative step will be required here to bring the potential temperature perturbation into hydrostatic balance. Without this additional iteration, large vertical velocities will be generated as the model rapidly adjusts to hydrostatic balance.

1.2 Grid spacings, simulation time, output and diagnostics

- Moist simulations should be performed at 1° resolution with 30 vertical levels for 2 hours.
- Plots of vertical velocity and rainwater should be produced at 5 km altitude after 30, 60, 90 and 120 minutes over the domain $[0, 130E] \times [40S, 40N]$.
- A plot of maximum vertical velocity over the duration of the simulation should be produced.
- Experiments could address the coupling frequency between the dynamics and physics.
- A variable resolution simulation should be performed that (a) studies the effect of the supercell transitioning from fine resolution to coarse resolution and (b) high resolution simulations down to 0.125° over the supercell.

2 Conclusions

TEXT

Appendix A: Uniform Diffusion

Author contributions. TEXT

Acknowledgements. [Include a complete list of DCMIP2016 student participants here along with sponsors]

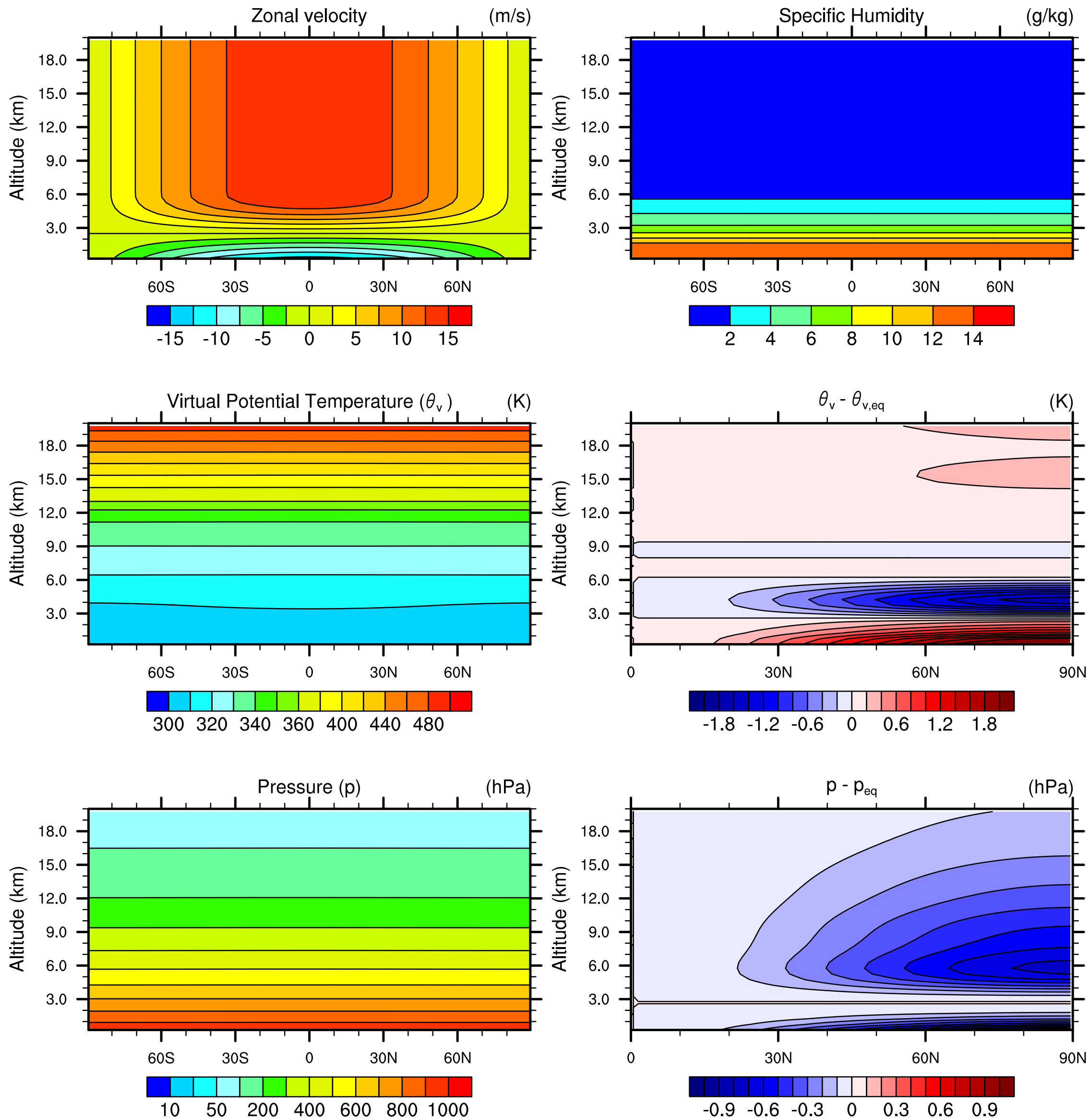

Figure 1. Initial state for the supercell test.

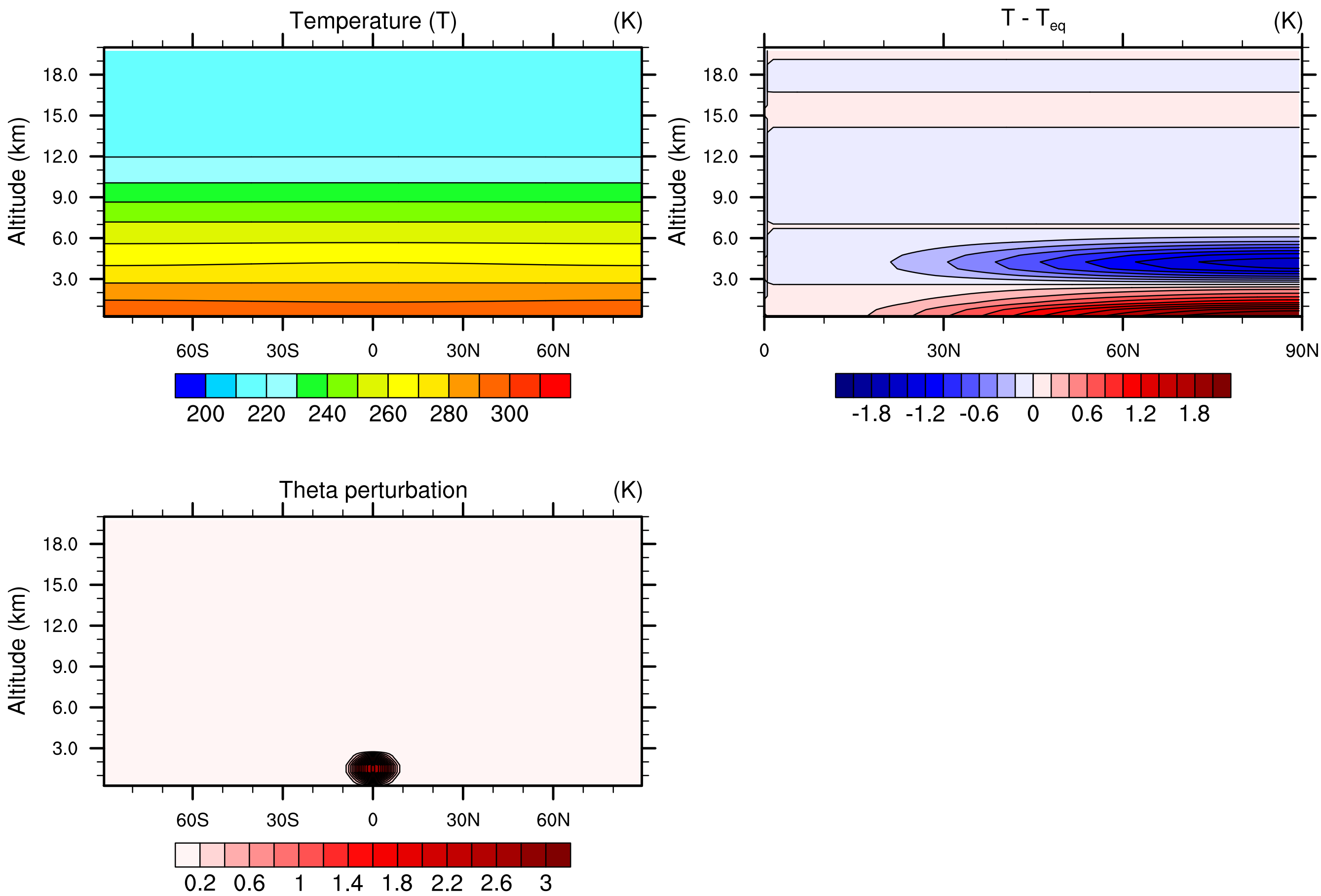

Figure 2. Initial state for the supercell test (cont'd).

References

Klemp, J. B. and Wilhelmson, R. B.: The simulation of three-dimensional convective storm dynamics, Journal of the Atmospheric Sciences, 35, 1070–1096, 1978.