



## DCMIP2016: The Splitting Supercell Test Case

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**Abstract.** This paper describes the splitting supercell idealized test case used in the 2016 Dynamical Core Model Intercomparison Project (DCMIP2016). These storms are useful testbeds for global atmospheric models because the horizontal scale of convective plumes is  $O(1\text{km})$ , emphasizing non-hydrostatic dynamics. The test case simulates a supercell on a reduced radius sphere with nominal resolutions ranging from 4km to 0.5km and is based on the work of Klemp et al. (2015). Models are initialized with an atmospheric environment conducive to supercell formation and forced with a small thermal perturbation. A simplified Kessler microphysics scheme is coupled to the dynamical core to represent moist processes. Reference solutions for DCMIP2016 models are presented. Storm evolution is broadly similar between models, although differences in final solution exist. These differences are hypothesized to result from different numerical discretizations, physics-dynamics coupling, and numerical diffusion. Intramodel solutions generally converge as models approach 0.5km resolution. These results can be used as a reference for future dynamical core evaluation, particularly with the development of non-hydrostatic global models intended to be used in convective-permitting and convective-allowing regimes.



## 1 Introduction

Supercells are strong, long-lived convective cells containing deep, persistent rotating updrafts that operate on spatial scales  $O(10\text{km})$ . They can persist for many hours and frequently produce large hail, tornados, damaging straight line winds, cloud-to-ground lightning, and heavy rain (Browning, 1964; Lemon and Doswell, 1979; Doswell and Burgess, 1993). Therefore, accurate simulation of these features is of great societal interest and critical for atmospheric models.

The supercell test applied in DCMIP2016 (Ullrich et al., 2017) permits the study of a non-hydrostatic moist flow field with strong vertical velocities and the associated precipitation. It is based on the work of Klemp and Wilhelmson (1978) and Klemp et al. (2015), assesses the behavior of global modeling systems at extremely high spatial resolution, and is used in the development of next-generation numerical weather prediction capabilities. In this regime the effective grid spacing is very similar to the horizontal scale of convective plumes, emphasizing resolved, non-hydrostatic dynamics. Further, the addition of simplified moist physics injects energy at, or near, the grid-scale in a conditionally-unstable atmosphere, which imposes significant stress on model numerics. The supercell test case therefore sheds light on the interplay of the dynamical core and subgrid parameterizations and highlights the impact of both implicit and explicit numerical diffusion on model solutions.

## 2 Description of test

The test case is defined as follows. All test cases are run on a non-rotating, reduced radius sphere with scaling factor  $X = 120$ . Therefore, for a  $4^\circ$  ( $1^\circ$ ) mesh, the grid spacing of the reduced radius sphere is approximately 4km (1km) near the equator. Klemp et al. (2015) demonstrated excellent agreement between simulations using this value of  $X$  and those completed on a flat plane with equivalent resolution. The model top is placed at 20km with uniform vertical grid spacing ( $\Delta z$ ) equal to 500m, resulting in 40 full vertical levels. No surface drag is imposed at the lower boundary (free slip condition). Water vapor ( $q_v$ ), cloud water ( $q_c$ ) and rain water ( $q_r$ ) are handled by a simple Kessler microphysics routine (Kessler, 1969). In particular, the configuration of Kessler microphysics used here is outlined in detail in Appendix C of Klemp et al. (2015).

All simulations are integrated for 120min (7200s). Outputs of the full three-dimensional prognostic fields as well as all variables pertaining to the microphysical routines were required with time between outputs required to be no longer than 15min. Four different horizontal resolutions were specified;  $4^\circ$ ,  $2^\circ$ ,  $1^\circ$ , and  $0.5^\circ$ . When considering the radius reduction, this results in approximate grid spacings of 4km, 2km, 1km, and 0.5km, respectively. Note that here we use ‘(nominal) resolution’ and ‘grid spacing’ interchangeably to refer to the length of a single grid cell or distance between gridpoints. All relevant constants mentioned here and in the following section are defined in Table 1.

### 2.1 Mean atmospheric background

The mean atmospheric state is designed such that it consists of large instability (convective available potential energy (CAPE) of approximately  $2200 \text{ m}^2 \text{ s}^{-1}$ ) and strong low-level wind shear, both of which are strong precursors of supercell formation (Weisman and Klemp, 1982).



The definition of this test case relies on hydrostatic and gradient wind balance, written in terms of Exner pressure  $\pi$  and virtual potential temperature  $\theta_v$  as

$$\frac{\partial \pi}{\partial z} = -\frac{g}{c_p \theta_v}, \quad \text{and} \quad u^2 \tan \varphi = -c_p \theta_v \frac{\partial \pi}{\partial \varphi}. \quad (1)$$

Defining  $u = u_{eq} \cos \varphi$  to maintain solid body rotation, where  $u_{eq}$  is the equatorial wind velocity, these equations can be  
 5 combined to eliminate  $\pi$ , leading to

$$\frac{\partial \theta_v}{\partial \varphi} = \frac{\sin(2\varphi)}{2g} \left( u_{eq}^2 \frac{\partial \theta_v}{\partial z} - \theta_v \frac{\partial u_{eq}^2}{\partial z} \right). \quad (2)$$

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

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

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

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

And relative humidity is given by

$$\bar{H}(z) = \begin{cases} 1 - \frac{3}{4} \left( \frac{z}{z_{tr}} \right)^{5/4} & \text{for } 0 \leq z \leq z_{tr}, \\ \frac{1}{4} & \text{for } z_{tr} \leq z. \end{cases} \quad (5)$$

It is assumed that the saturation mixing ratio is given by

$$15 \quad q_{vs}(p, T) = \left( \frac{380.0}{p} \right) \exp \left( 17.27 \times \frac{T - 273.0}{T - 36.0} \right) \quad (6)$$

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

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



and iteration procedure

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

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

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

$$5 \quad q_{\text{eq}}^{(i)} = \overline{H}(z) q_{vs}(p_{\text{eq}}^{(i)}, T_{\text{eq}}^{(i)}) \quad (11)$$

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

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

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

10 Once the equatorial profile has been constructed, the virtual potential temperature through the remainder of the domain can be computed by iterating on (2),

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

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 (1),

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

and so

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

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

Note that, for (13-14), Smolarkiewicz et al. (2017) also derive an analytic solution for the meridional variation of the initial  
 20 background state for shallow atmospheres.

## 2.2 Potential temperature perturbation

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

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



where

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

An additional iterative step is then required 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. Plots showing the initial state of the supercell are shown in Figs. 1 and 2 for reference. The test case is designed such that the thermal perturbation will induce a convective updraft immediately after initialization. As rain water is generated by the microphysics, reduced buoyancy and a subsequent downdraft at the equator in combination with favorable vertical pressure gradients near the peripheral flanks of the storm will cause it to split into two counterrotating cells that propagate transversely away from the equator until the end of the test (Rotunno and Klemp, 1982, 1985; Rotunno, 1993; Klemp et al., 2015).

## 2.3 Physical and Numerical Diffusion

As noted in Klemp et al. (2015), dissipation is an important process near the grid-scale, particularly in simulations investigating convection in unstable environments such as this. To represent this process and ensure solution convergence as resolution is increased for a given model, a constant second-order diffusion is applied to all momentum equations ( $\nu = 500 \text{ m}^2 \text{ s}^{-1}$ ) and scalar equations ( $\nu = 1500 \text{ m}^2 \text{ s}^{-1}$ ). In the vertical, this diffusion is applied to the perturbation from the background state only in order to prevent the initial perturbation from mixing out.

Models that contributed supercell test results at DCMIP2016 are listed in Table 2. They are formally described in Ullrich et al. (2017) and the references therein. Note that not all DCMIP2016 participating groups submitted results for this particular test. Due to the multitude of differing implicit and explicit diffusion in the participating models, some groups chose to apply variations in how either horizontal or vertical diffusion were treated in this test case. Deviations from the above specified diffusion are as follows. CSU applied uniform three-dimensional second order diffusion with coefficients of  $\nu = 1500 \text{ m}^2 \text{ s}^{-1}$  for  $q_v$  and  $\theta_v$ ,  $\nu = 1000 \text{ m}^2 \text{ s}^{-1}$  for  $q_c$  and  $q_r$ , and  $\nu = 500 \text{ m}^2 \text{ s}^{-1}$  for divergence and relative vorticity. FV<sup>3</sup> applied divergence and vorticity damping separately to the velocity fields along the floating Lagrangian surface. A Smagorinsky diffusion is also applied to the horizontal wind. ICON applied constant horizontal second-order diffusion to the horizontal and vertical velocity components ( $\nu = 500 \text{ m}^2 \text{ s}^{-1}$ ) as well as the scalar variables  $\rho$ ,  $\theta_v$  and  $q_{v,c,r}$  ( $\nu = 1500 \text{ m}^2 \text{ s}^{-1}$ ). No explicit diffusion was applied in the vertical. NICAM applied a dynamically-defined fourth-order diffusion to all variables in the horizontal with vertical dissipation being implicitly handled by the model's vertical discretization.

## 3 Results

### 3.1 Time evolution of supercell at control resolution

Fig. 3 shows the temporal evolution (every 30min, out to 120min test termination) of the supercell for contributing models at the control resolution of 1km. The top four panels for each model highlight a cross-section at 5km elevation through vertical



velocity ( $w$ ) while the bottom four show a cross-section (at the same elevation) through the rain water ( $q_r$ ) field produced by the Kessler microphysics. For  $w$ , red contours represent rising motion while blue contours denote sinking air. Note that the longitudes plotted vary slightly in each of the four time panes to account for zonal movement. This analysis framework follows that originally outlined in Klemp et al. (2015).

- 5 All model solutions show bulk similarities. With respect to vertical velocity, a single, horseshoe-shaped updraft is noted at 30min in all models, although the degree to which the maximum updraft velocities are centered on the equator vary. A corresponding downdraft is located immediately to the east of the region of maximum positive vertical velocity. This downdraft is single-lobed (e.g., ACME-A) or double-lobed (e.g., GEM) in all simulations. Separation of the initial updraft occurs by 60min across all models, although variance begins to develop in the meridional deviation from the equator of the splitting supercell.
- 10 Models such as NICAM, FV<sup>3</sup>, OLAM, and ICON all have larger and more distinct north-south spatial separation, while FVM, GEM, ACME-A, and TEMPEST show only a couple degrees latitude between updraft cores. Structural differences also begin to emerge. For example, FVM, GEM, ACME-A, and TEMPEST all exhibit three local maxima in vertical velocity at 60min; two large updrafts mirrored about the equator with one small maximum still located over equator centered near the initial perturbation. Similar behavior is noted in the  $q_r$  fields. This is in contrast with other models which lack a third updraft on the
- 15 equatorial plane. Generally speaking,  $q_r$  maxima are collocated with the locations of maximum updraft velocities, and thereby conversion from  $q_v$  and  $q_c$  to  $q_r$  in the Kessler microphysics.

While the aggregate response of a single updraft eventually splitting into poleward-propagating symmetric storms about the equator is well-matched between the configurations, notable differences exist through the end of the runs. This spread in model solutions continues to increase through 90min and is most notable at the test conclusion (120min). FVM, GEM,

20 ACME-A, OLAM, and MPAS all show two discrete supercells approximately 30° from the equator. FV<sup>3</sup> and TEMPEST both produce longitudinally-transverse storms that stretch towards the equator in addition to the two main cells. Each of the splitting supercells split a second time in ICON, forming, in conjunction with a local maximum at the equator, five maxima of vertical velocity (and correspondingly rainwater). NICAM produces two core supercells (as more clearly evident in the  $q_r$  field at 120min), but has noticeable alternating weak updrafts and downdrafts in the north-south space between the two storm cores.

- 25 The relative smoothness of the storms as measured by the vertical velocity and rain water fields also varies between models, particularly at later times. ACME-A, FVM, GEM, OLAM, and MPAS produce updrafts that are relatively free of additional, small-scale local extrema in the vicinity of the core of the splitting supercell. Conversely, CSU, FV<sup>3</sup>, ICON, NICAM, and TEMPEST all exhibit solutions with additional convective structures, with multiple updraft maxima versus two coherent cells. This spread is somewhat minimized when looking at rain water, implying that the overall dynamical character of the cells as
- 30 noted by precipitation generation is more similar, with all models other than ICON showing cohesive rain water maxima O(10 g/kg).



### 3.2 Resolution sensitivity of supercell

Fig. 4 shows the same cross-section variables as Fig. 3 except across the four specified test resolutions (nominally 4km, 2km, 1km, 0.5km, from left to right) at test termination of 120min (+7200sec). Therefore, the third panel from the left for each model (1km) should match the fourth panel from the left for each model in Fig. 3.

5 As resolution increases (left to right) models show increasing horizontal structure in both the vertical velocity and rain water fields. Updraft velocity generally increases with resolution, particularly going from 4km to 2km, implying that the supercell is underresolved at 4km resolution. This is supported by previous mesoscale simulations investigating supercells in other frameworks (Potvin and Flora, 2015; Schwartz et al., 2017), although it should be emphasized that this response is also subject to each numerical scheme's effective resolution (Skamarock, 2004) and that the resolvability of real-world supercells  
10 can depend on the size of individual storms.

At the highest resolutions, there is a distinct group of models that exhibit more noise, particularly in vertical velocity, at +120min at higher resolutions. CSU, GEM, and NICAM appear to have the largest vertical velocity variability at 0.5km, while ACME-A, FVM, MPAS, and TEMPEST appear to produce the smoothest solutions. This result is likely due to the differences in explicit diffusion treatment as noted before, as well as differences in the numerical schemes' implicit diffusion.

15 It is also assumed that differences in the coupling between the dynamical core and subgrid parameterizations lead to some of these behaviors (Thatcher and Jablonowski, 2016). As before, rain water cross-sections tend to be less noisy at 0.5km than vertical velocity, although CSU and NICAM both show some additional local maxima in the field associated with some of the aforementioned  $w$  maxima.

### 3.3 Convergence of global supercell quantities with resolution

20 While Fig. 4 highlights the structural convergence with resolution, more bulk, integrated measures of supercell intensity are also of interest. Fig. 5 shows the maximum resolved updraft velocity over the global domain as a function of time for each dynamical core and each resolution (increasing model resolution is denoted by darker lines). All models show increasing updraft velocity as a function of resolution, further confirming that, at 4km, the supercell is underresolved dynamically. For the majority of models and integration times, the gap between 4km and 2km grid spacing is the largest in magnitude, with  
25 subsequent increases in updraft velocity being smaller as models further decrease horizontal grid spacing. At 0.5km, the majority of models appear relatively converged, with FV<sup>3</sup>, ICON, and MPAS showing curves nearly on top of one another at these resolutions. Other models show larger differences between 0.5km and 1km curves, implying that these configuration may not yet be converged in this bulk sense, and further grid refinement or modifications to the dissipation schemes are necessary to achieve convergence.

30 The maximum updraft velocity as a function of resolution for particular model configurations varies quite widely. NICAM produces the weakest supercell, with velocities around  $30 \text{ m s}^{-1}$  at 0.5km, while ACME-A, TEMPEST, GEM, and CSU all produce supercells that surpass  $55 \text{ m s}^{-1}$  at some point during the supercell evolution. Models that have weaker supercells at 0.5km tend to also have weaker supercells at 4km (e.g., NICAM) while the same is true for stronger supercells (e.g.,



TEMPEST), likely due to configuration sensitivity. This agrees with the already discussed structural plots (Fig. 4) which demonstrated model solutions were generally converging with resolution on an intramodel basis but not necessarily across models.

Fig. 6 shows the same analysis except for area-integrated precipitation rate for each model and each resolution. Similar results are noted as above – with most models showing large spread at 4km resolutions, but general convergence in precipitation by 0.5km. All models produce the most precipitation at 120min with the 4km simulation. This is consistent with Klemp et al. (2015), who postulated this behavior is due to increased spatial extent of available  $q_r$  to fall out of the column at these grid spacings, even though updraft velocities are weaker at coarser resolutions. Unlike maximum vertical velocity, the integrated precipitation rate does not monotonically increase with resolution for most models. At 120min, integrated rates at 0.5km range by approximately a factor of two, from a low of  $70\text{--}75 \times 10^5 \text{ kg s}^{-1}$  (ACME-A, FVM, OLAM) to a high of  $150\text{--}160 \times 10^5 \text{ kg s}^{-1}$  (CSU, FV<sup>3</sup>), highlighting the sensitivity of final results that have been already been discussed.

#### 4 Conclusions

Non-hydrostatic dynamics are required for accurate representation of supercells. The results from this test case show that clear differences and uncertainties exist in storm evolution when comparing identically initialized dynamical cores at similar nominal grid resolutions. Intramodel convergence in bulk, integrated quantities appears to generally occur at approximately 0.5km grid spacing. However, intermodel differences are quite large even at these resolutions. For example, maximum updraft velocity within a storm between two models may vary by almost a factor of two even at the highest resolutions assessed at DCMIP2016.

Structural convergence is weaker than bulk integrated metrics. Two-dimensional horizontal cross-sections through the supercells at various times show that some models are well-converged between 1km and 0.5km, while results from other models imply that finer resolutions are needed to assess whether convergence will occur with a particular test case formulation and model configuration. Interestingly, in some cases maximum, bulk quantities converge faster than snapshots of cross-sections.

We postulate that these differences and uncertainties likely stem from not only the numerical discretization and grid differences outlined in Ullrich et al. (2017), but also from the form and implementation of filtering mechanisms (either implicit or explicit) specific to each modeling center. The simulation of supercells at these resolutions are particularly sensitive to numerical diffusion since damping of prognostic variables in global models is occurring at or near the scales required for resolvability of the storm. This is different from other DCMIP2016 tests (baroclinic wave and tropical cyclone), which produced dynamics that were less non-hydrostatic in nature and required resolvable scales well coarser than the grid cell level.

Given the lack of an analytic solution, we emphasize that the goal of this paper is not to define particular supercells as optimal answers. Rather, the main intention of this test was to produce a verifiable database for models to use as an initial comparison point when evaluating non-hydrostatic numerics in dynamical cores. We acknowledge that as groups continued to develop non-hydrostatic modeling techniques that small changes in the treatment of diffusion in the dynamical core will likely lead to changes in their results from DCMIP2016. We recommend that modeling centers developing or optimizing non-



hydrostatic dynamical cores perform this test and compare their solutions to the baselines contained in this manuscript as a check of sanity relative to a large and diverse group of next-generation dynamical cores currently under development in the atmospheric modeling community.

### Code availability

- 5 Information on the availability of source code for the models featured in this paper can be found in Ullrich et al. (2017). For this particular test, the initialization routine, microphysics code, and sample plotting scripts are available at <https://github.com/ClimateGlobalChange/DCMIP2016>.

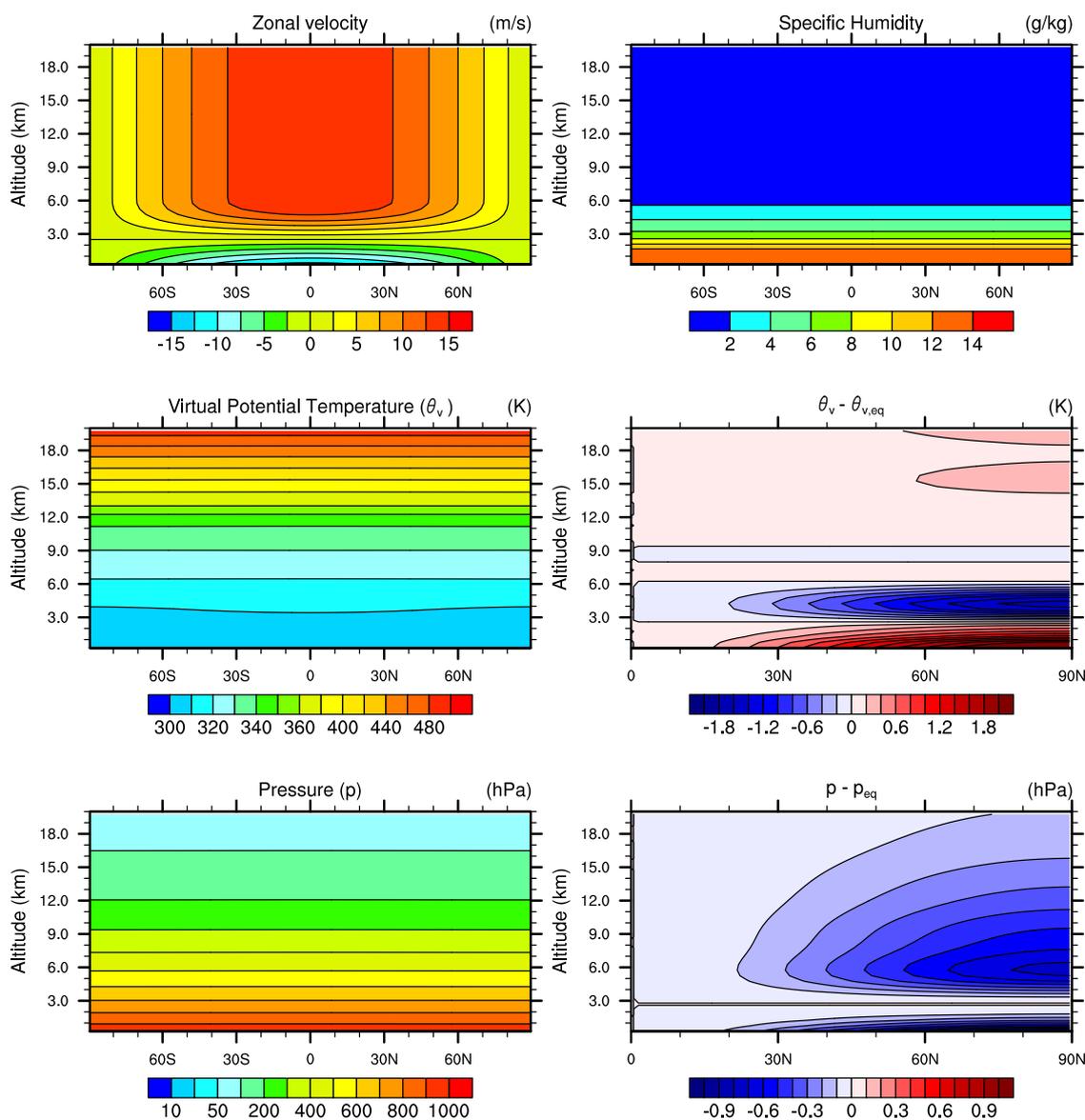
*Author contributions.* CMZ prepared the text and corresponding figures in this manuscript. Model data and notations about model-specific configurations were provided by the individual modeling groups. PAU assisted with formatting of the test case description in Section 2.

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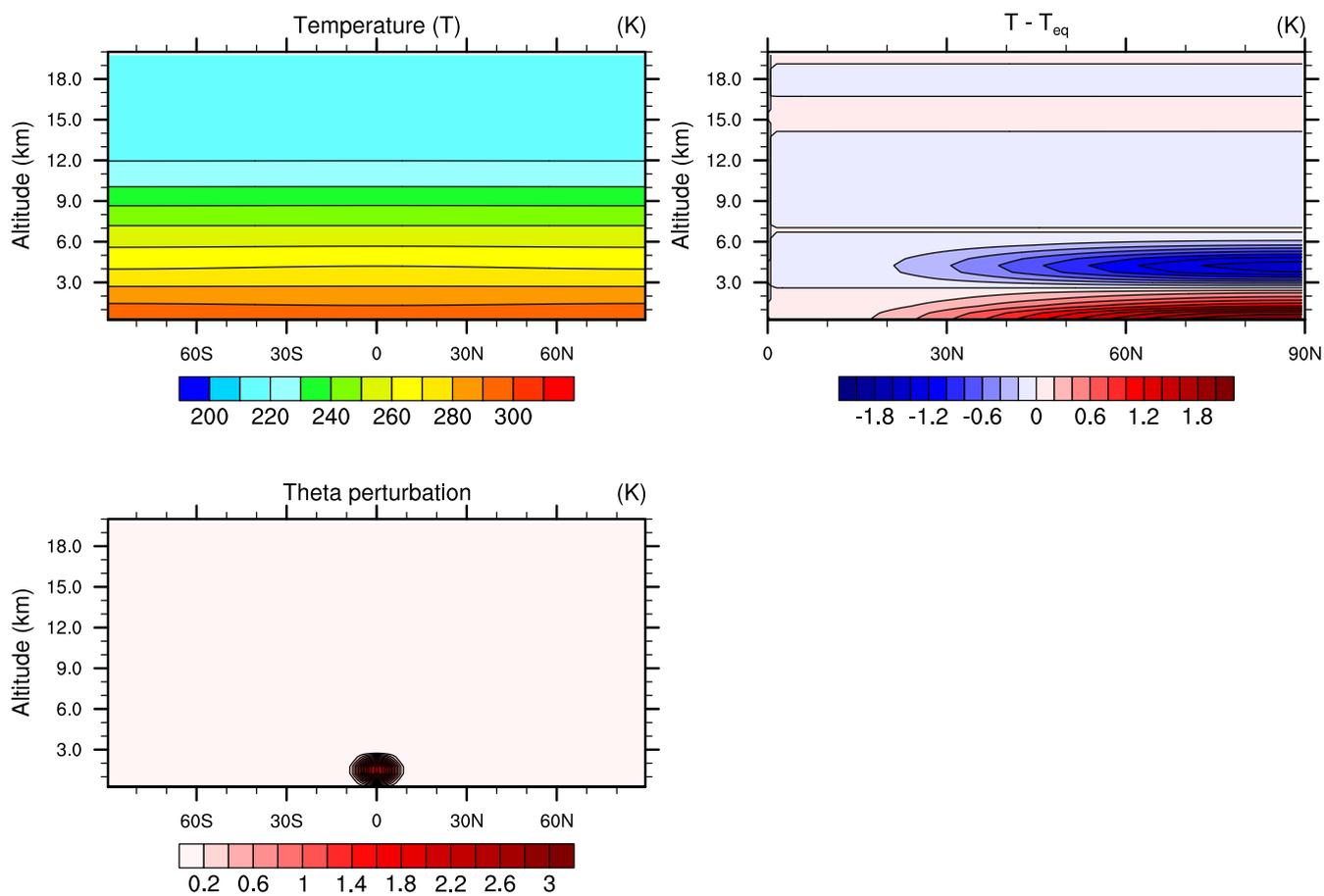


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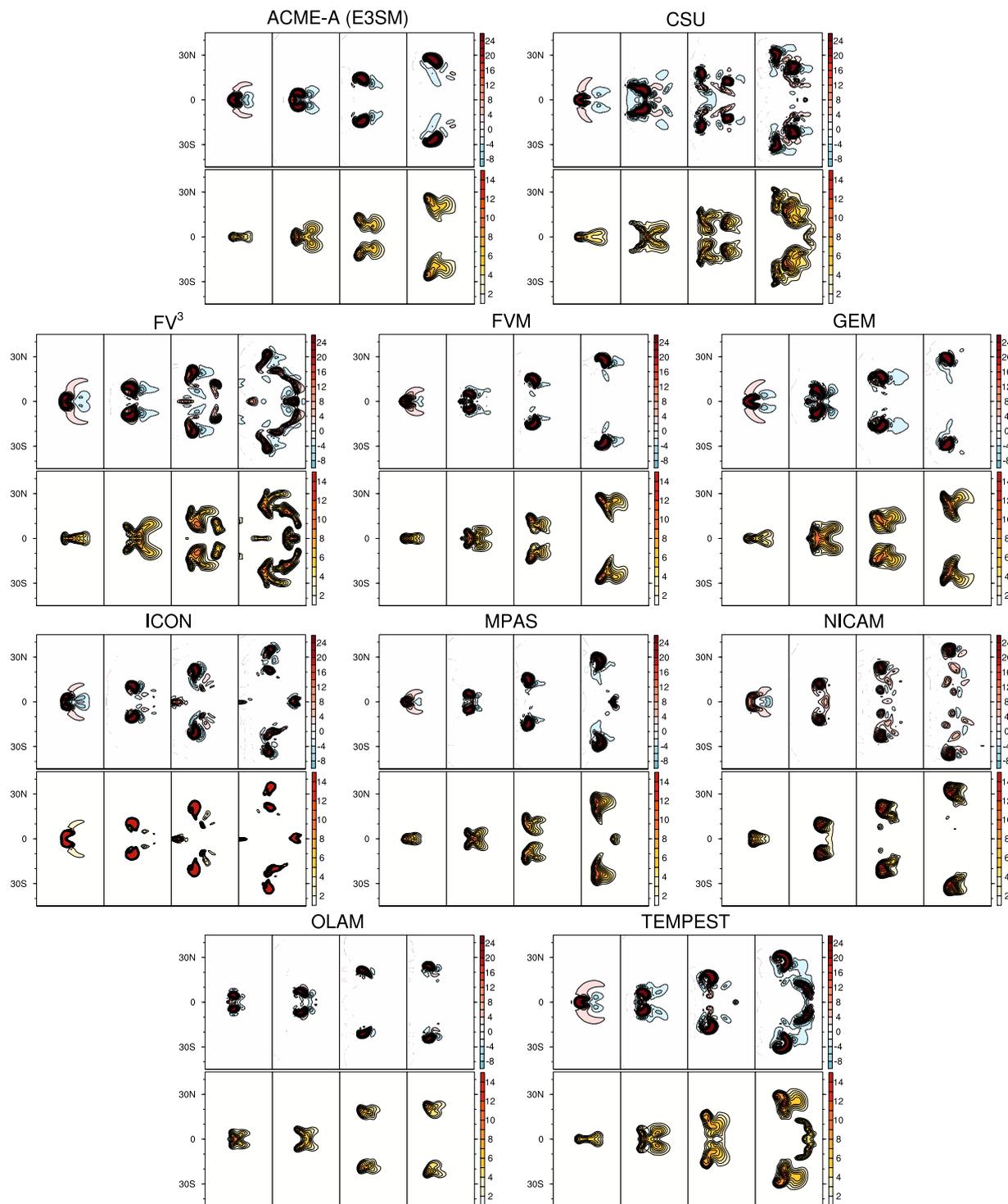
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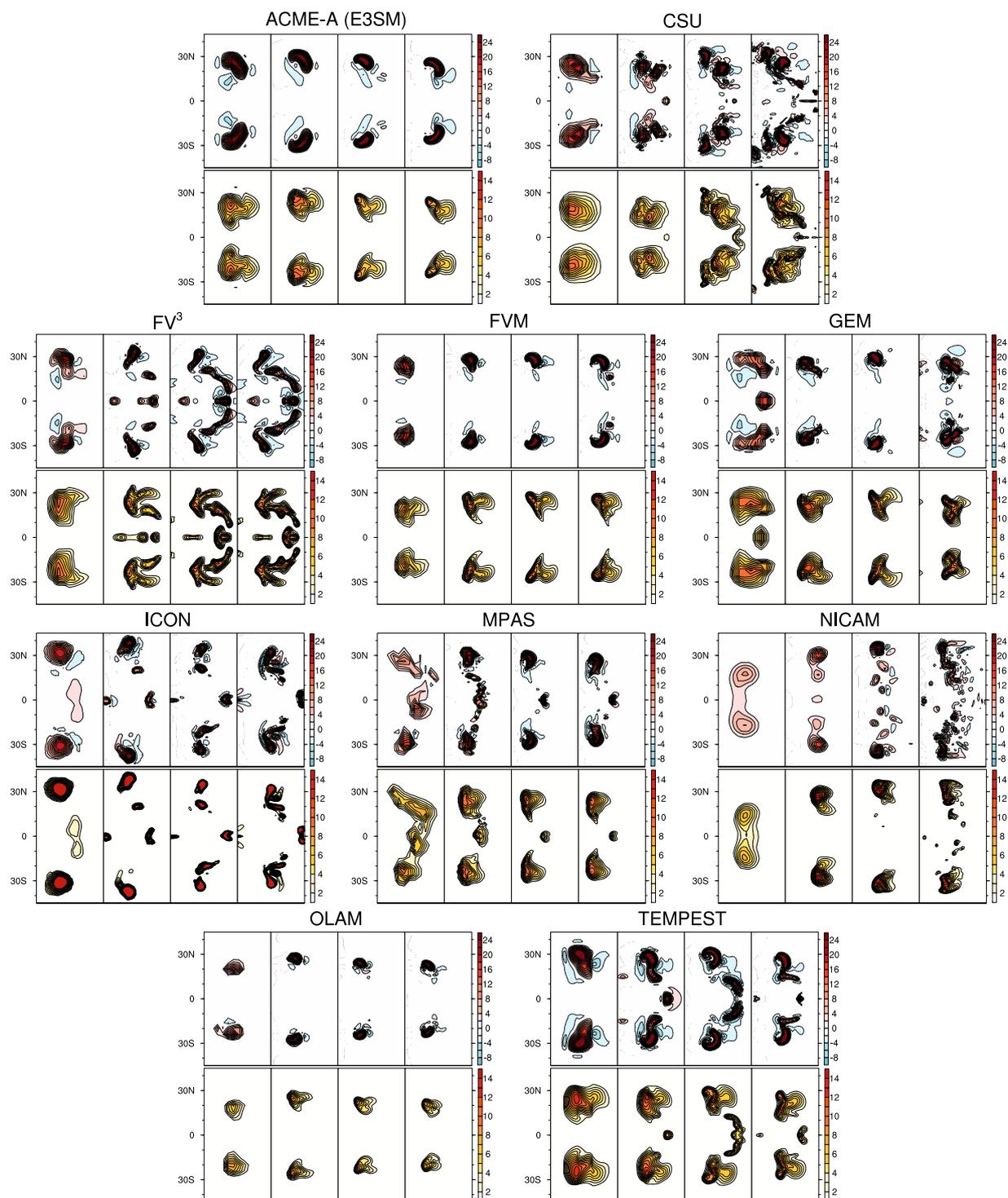
**Figure 1.** Initial state for the supercell test. All plots are latitude-height slices at  $0^\circ$  longitude. Deviations from equatorial values are shown for virtual potential temperature and pressure.



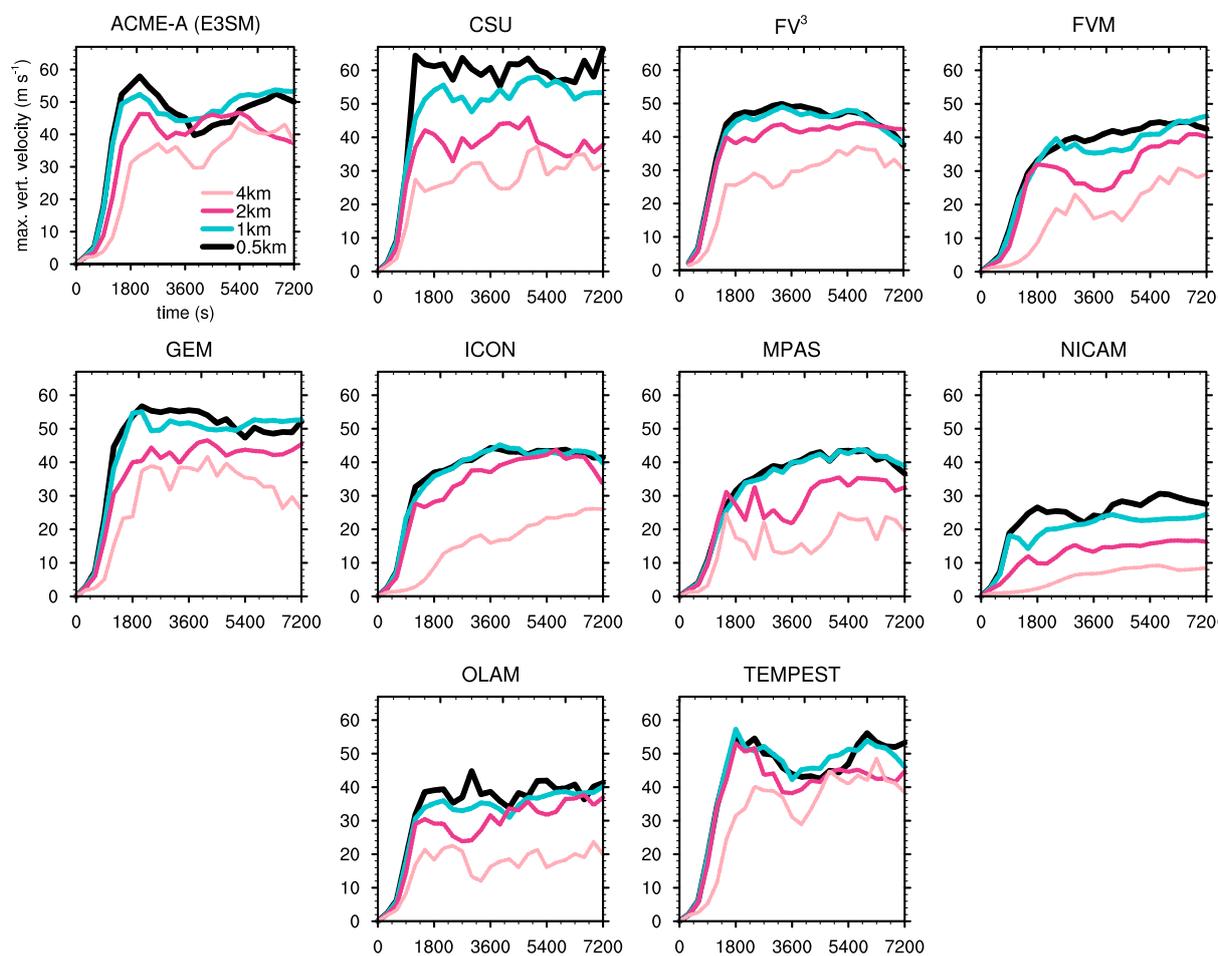
**Figure 2.** Same as Fig. 1 for temperature and potential temperature.



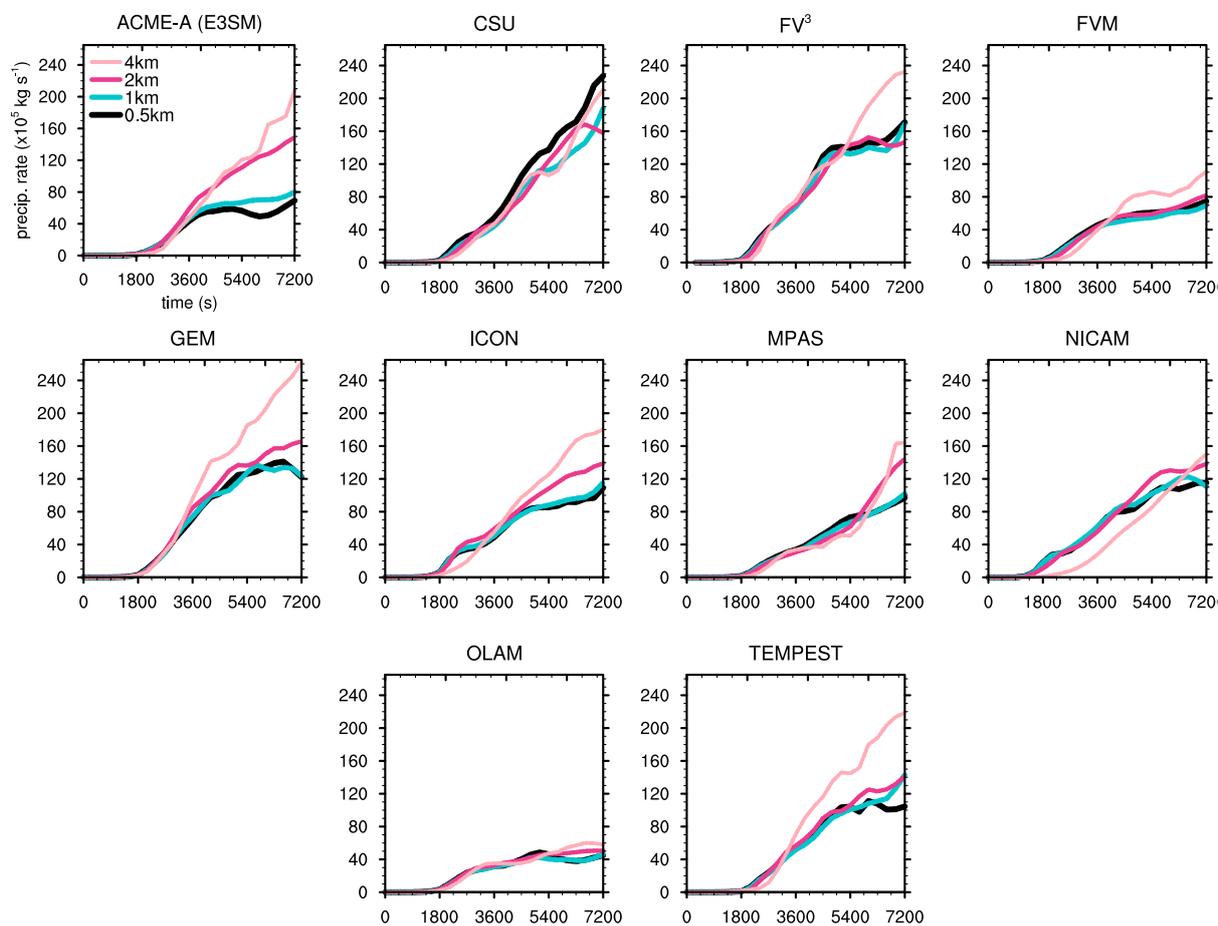
**Figure 3.** Time evolution of cross-sections of 5km vertical velocity (top) and 5km rain water (bottom) for each model with the r100 configuration of the test case. From left to right, fields are plotted at 30min (1800s), 60min (3600s), 90min (5400s), and 120min (7200s).



**Figure 4.** Resolution sensitivity of cross-sections of 5km vertical velocity (top) and 5km rain water (bottom) plotted at 120min (7200s) for each model. From left to right, nominal model resolutions are 4km, 2km, 1km, and 0.5km.



**Figure 5.** Maximum domain updraft velocity ( $\text{m s}^{-1}$ ) as a function of time for each model at each of the four specified resolutions. Increasing darkness of each line denotes increased resolution (from 4km to 0.5km).



**Figure 6.** Same as Fig. 5 except showing area-integrated instantaneous precipitation rate ( $\times 10^5 \text{ kg s}^{-1}$ ).



**Table 1.** List of constants used for the Supercell test.

Constant	Value	Description
$X$	120	Small-planet scaling factor (reduced Earth)
$\theta_{tr}$	343 K	Temperature at the tropopause
$\theta_0$	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	Wind shear velocity
$U_c$	15 m/s	Coordinate reference velocity
$z_s$	5000 m	Height of shear layer top
$\Delta z_u$	1000 m	Transition distance of velocity
$\Delta\theta$	3 K	Thermal perturbation magnitude
$\lambda_p$	0	Thermal perturbation longitude
$\varphi_p$	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



**Table 2.** Participating modeling centers and associated dynamical cores that submitted results for the splitting supercell test.

Short Name	Long Name	Modeling Center or Group
ACME-A (E3SM)	Energy Exascale Earth System Model	Sandia National Laboratories and University of Colorado, Boulder, USA
CSU	Colorado State University Model	Colorado State University, USA
FV <sup>3</sup>	GFDL Finite-Volume Cubed-Sphere Dynamical Core	Geophysical Fluid Dynamics Laboratory, USA
FVM	Finite Volume Module of the Integrated Forecasting System	European Centre for Medium-Range Weather Forecasts
GEM	Global Environmental Multiscale model	Environment and Climate Change Canada
ICON	ICOsahedral Non-hydrostatic model	Max-Planck-Institut für Meteorologie / DWD, Germany
MPAS	Model for Prediction Across Scales	National Center for Atmospheric Research, USA
NICAM	Non-hydrostatic Icosahedral Atmospheric Model	AORI / JAMSTEC / AICS, Japan
OLAM	Ocean Land Atmosphere Model	Duke University / University of Miami, USA
TEMPEST	Tempest Non-hydrostatic Atmospheric Model	University of California, Davis, USA