Idealized Nonhydrostatic Supercell Simulations in the Global MPAS

Joe Klemp, Bill Skamarock, and Sang-Hun Park
National Center for Atmospheric Research
Boulder, Colorado
Supercell Thunderstorms

Typical characteristics:

- Strong, long-lived convective cells
- Deep, persistent rotating updrafts
- May propagate transverse to the mean winds
- May split into two counter-rotating storms
- Produce most of the world’s intense tornadoes

3 April 1964 Oklahoma Splitting Supercell Storms

Wilhelmson & Klemp (JAS, 1982)
3 km Global MPAS-A Simulation
2010-10-23 Initialization

GOES East, 2010-10-27 00 UTC

4 day forecast
valid 2010-10-27 03 UTC

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Simulations on a Reduced-Radius Earth Sphere

**Observations:**

- Global grids required to resolve nonhydrostatic phenomena are often beyond the realm of feasibility (and not cost effective).
- Simulations on a reduced-radius sphere permit nonhydrostatic resolutions at reasonable computational cost.
- Phenomena on a reduced-radius earth sphere may have little physical relevance to the real atmosphere.

**Our philosophy:**

- Idealized small-planet simulations should exhibit strong similarity to physically relevant geophysical flows
- For nonhydrostatic phenomena good correspondence with flow in a Cartesian geometry
Equations
- Fully compressible nonhydrostatic equations
- Permits explicit simulation of clouds

Solver Technology
- C-grid centroidal Voronoi mesh
- Unstructured grid permits conformal variable-resolution grids
- Most of the techniques for integrating the nonhydrostatic equations come from WRF.

Supercell Simulation
- Initial sounding representative of supercell environment
- Convection initiated with low-level warm bubble (3° K)
- Minimal model physics (simple Kessler microphysics)
- Constant 2nd order viscosity (500 m²/s) – permits convergence
- \( z_t = 20 \text{ km}, \Delta z = 500 \text{ m}, \text{No Coriolis force (} f = 0 \text{)} \)
Initial Sounding for Supercell Tests

Based on historical supercell simulations (Weisman and Klemp, 1982, 1984)

On the sphere: $U_i = U_{eq} \cos \phi$

CAPE $\sim 2200 \text{ m}^2/\text{s}^2$
Balanced Initial Conditions on the Sphere ($f = 0$)

hydrostatic equation: \[ \frac{\partial \pi}{\partial z} = -\frac{g}{c_p \theta_v} \]

gradient wind equation: \[ u^2 \tan \phi = -c_p \theta_v \frac{\partial \pi}{\partial \phi} \]

Cross differentiating and equating $\pi_{\phi z}$:

\[ \frac{\partial \theta_v^{(i+1)}}{\partial \phi} = \frac{\sin 2\phi}{2g} \left\{ U_{eq}^2 \frac{\partial \theta_v^{(i)}}{\partial z} - \theta_v^{(i)} \frac{\partial U_{eq}^2}{\partial z} \right\} \]

Converges in ~ 3 iterations
Kessler Cloud Microphysics

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Differential Equation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Potential temperature</td>
<td>[ \frac{d\theta}{dt} = -\frac{L}{c_p \pi} \left( \frac{dq_{vs}}{dt} + E_r \right) ]</td>
</tr>
<tr>
<td>Water vapor mixing ratio</td>
<td>[ \frac{dq_v}{dt} = \frac{dq_{vs}}{dt} + E_r ]</td>
</tr>
<tr>
<td>Cloud water mixing ratio</td>
<td>[ \frac{dq_c}{dt} = -\frac{dq_{vs}}{dt} - A_r - C_r ]</td>
</tr>
<tr>
<td>Rain water mixing ratio</td>
<td>[ \frac{dq_r}{dt} = -E_r + A_r + C_r - V_r \frac{dq_r}{dz} ]</td>
</tr>
</tbody>
</table>

Kessler subroutine (~40 lines of code) computes increments to \( \theta, q_v, q_c, q_r \) at the end of each time step.
Supercell Simulations, MPAS & Reference Cloud Model

- Full MPAS model code used for idealized simulations
- Grid generated on flat plane with periodic boundaries

Vertical velocity contours at 1, 5, and 10 km (c.i. = 3 m/s)
30 m/s vertical velocity surface shaded in red
Rainwater surfaces shaded as transparent shells
Perturbation surface temperature shaded on baseplane
Maximum Vertical Velocity

$W_{\text{max}}$ (m/s)

Time (s)

Flat plane, $\Delta \sim 500$ m

$X = 120$, $\Delta \sim 500$ m

$X = 120$, $\Delta \sim 1000$ m
Rain Water $q_r$, $X = 120$, $\Delta \sim 500$ m, $z = 5$ km

Values:
- $c.i. 1$ gm/kg
- $X = 120$
- $\Delta \sim 500$ m
- $z = 5$ km

Locations:
- 30 min
- 60 min
- 90 min
- 120 min
- 40N
- 40S
- 0
- 40E
- 80E
- 120E
Vertical Velocity, $X = 120$, $\Delta \sim 500$ m, $z = 5$ km

- c.i. 2 m/s
- Longitude: 0° to 120°E
- Latitude: 40°S to 40°N
- Time: 30 min, 60 min, 90 min, 120 min

$\Delta \sim 500$ m
$z = 5$ km
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Vertical Velocity $w$ at 2 h, $z = 5$ km

- Flat plane: $\Delta \sim 500$ m
- $X = 120$: $\Delta \sim 500$ m
- $X = 120$: $\Delta \sim 1000$ m

c.i. 2 m/s
Rain Water $q_v$ at 2 h, $z = 5$ km

flat plane
$\Delta \sim 500$ m

X = 120
$\Delta \sim 500$ m

X = 120
$\Delta \sim 1000$ m

c.i. 1 g/kg
Vertical Velocity $w$ at 2 h, $z = 2.5$ km

- Flat plane
  - $\Delta \sim 500$ m
- $X = 120$
  - $\Delta \sim 500$ m
  - $\Delta \sim 1000$ m

c.i. 1 m/s
Supercell Testcase- Summary

- Realistic supercell storms can be simulated in an idealized atmospheric environment with simple physics.
- Good correspondence between simulation on reduced radius sphere ($X = 120$) and results in a Cartesian geometry.
- Grid size $\Delta \sim 1$ km retains much of the supercell structure obtained with $\Delta \sim 500$ m.
- Further simulations needed to explore behavior as resolution is further reduced.