Analyzing Physics-Dynamics Coupling in an Ensemble of Simplified GCMs

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What is DCMIP?


In 2016: use **idealized moist test cases** and focus on **non-hydrostatic dynamical cores** and their physics-dynamics coupling

Three “core” test cases with idealized physics processes:

• **Test 1:** Dry and moist (Kessler-physics) baroclinic instability test with “toy” terminator chemistry (110 km, 30 vertical levels)
• **Test 2:** Moist tropical cyclone test
• **Test 3:** Moist mesoscale storm test (supercell)

Recent paper: “DCMIP2016: a review of non-hydrostatic dynamical core design and intercomparison of participating models”, Ullrich et al. (2017) in GMD

“Living” Test case document and DCMIP-2016 web page:

https://github.com/ClimateGlobalChange/DCMIP2016
https://www.earthsystemcog.org/projects/dcmip-2016/
Warm-Rain Kessler Physics Scheme

\[
\frac{\Delta \theta}{\Delta t} = \frac{L}{c_p \pi} \left( \frac{\Delta q_{vs}}{\Delta t} - E_r \right) \quad \text{Potential temperature}
\]

\[
\frac{\Delta q_v}{\Delta t} = - \frac{\Delta q_{vs}}{\Delta t} + E_r
\]

\[
\frac{\Delta q_c}{\Delta t} = \frac{\Delta q_{vs}}{\Delta t} + E_r - A_r - C_r
\]

\[
\frac{\Delta q_r}{\Delta t} = -E_r + A_r + C_r - V_r \frac{\partial q_r}{\partial z}
\]

3 prognostic hydrometeors

Condensation
Auto-conversion
Precipitation
Rain water evaporation
Collection rate of rain water
DCMIP-2016 Models (in blue: comparison models)

- ACME (E3SM) (DoE, CU)
- FV3 (GFDL)
- Tempest (UC Davis)
- CAM SE (NCAR), hydrost.
- ICON (DWD & MPI, Germany)
- DYNAMICO (LMD, IPSL, France), hydrostatic
- CSU_LZ (CSU)
- OLAM (U. Miami)
- NICAM (Riken, U. Tokyo)
- MPAS (NCAR)
- CAM FV (NCAR), hydrostatic
- FVM (ECMWF)
- GEM (Environment Canada)
**DCMIP-2016 Snapshots: “Toy” Terminator Chemistry**

Tracer advection test with correlated tracers: Cly is the sum of Cl and Cl2 (needs to stay constant)

Lauritzen et al. (2015)
Snapshots of the dry baroclinic wave

Surface pressure at day 10 ($\Delta x=110$ km): overall patterns similar, details differ

- Some Gibb’s ringing in ACME (spectral element model)
- Some grid imprinting (wave 4 and wave 5 signals) in CSU_LZ, DYNAMICO, FV3, ICON, NICAM, apparent in the Southern Hemispheres
Snapshots of the moist baroclinic wave

Surface pressure at day 10 ($\Delta x=110$ km): overall patterns similar, details differ

- Patterns look almost identical to the dry surface pressure patterns
- Moisture effects weaken high pressure systems and strengthen low pressure systems (e.g. visible in ICON and MPAS)
15-Day Time Series: **dry and moist ps maxima**

- Moisture effects **weaken high pressure** systems
- Presence of moisture **widens the ensemble spread** early in the simulations
- Points to the uncertainties in the physics-dynamics interactions and the possible impact of effective resolutions
15-Day Time Series: **dry and moist ps minima**

- **Moisture effects:** slight *tendency to strengthen low pressure* systems
- **Presence of moisture** considerably *widens the ensemble spread*
- **Models tend to diverge after day 12**
Impact of Resolution: **Moist ps maxima**

- Impact of the horizontal resolution on the evolution of the surface pressure maxima is small (in moist CAM FV, similar to FV3 model)
- However, $P_S_{\text{min}}$ spread in DCMIP models increases (next slide), physics-dynamics interactions most apparent in low pressure regions with precipitation and updraft
Impact of Resolution: **Moist ps minima**

- Increasing the horizontal resolutions from 1° (110 km) to 0.5° /0.25° (55/28 km) strengthens the surface pressure minima in moist CAM FV.
- Possible pathway: high precipitation rates force intensification.
- \( PS_{\text{min}} \) spread in DCMIP models includes the effects of the effective resolutions.
Impact of Physics time step: **Moist ps minima**

Increased resolutions often come with decreased physics time steps

- Varying the physics time step from 1800 s, 900 s to 450 s has **very little impact** on the minimum surface pressure evolution in CAM FV(0.5°).
- Suggests that physics time step is not the main driver for the model differences among DCMIP models.
Impact of Model Design & Resolution: Moist $p_{\text{min}}$

- Increasing the horizontal resolutions from 1° (110 km) to 0.5° /0.25° (55/28 km) strengthens the surface pressure minima in CAM FV and CAM SE.
- $p_{\text{min}}$ spread in DCMIP models includes the effects of the effective resolutions and coupling uncertainties.
Precipitation rates in the moist baroclinic wave

Precipitation rates at day 9 ($\Delta x=110$ km):
overall patterns similar, details differ

- FV3 strengthens the fastest, already shows 4th precipitation band
- Differing levels of ‘noise’ (broken contours) and diffusion in the precipitation bands are apparent
Precipitation rates in the moist baroclinic wave

Precipitation rates at day 10 ($\Delta x=110$ km): overall patterns similar, details differ

- At day 10 precipitation bands become very narrow, tend to break up in some models (with very strong grid-point scale precipitation)

- 3 models already develop 5\textsuperscript{th} precipitation band
Precipitation rates: Impact of Resolution

Moist CAM FV/SE baroclinic wave, precipitation, Day 10

- Increasing horizontal resolution sharpens the precipitation patterns and increases the peaks in CAM FV and CAM SE
Precipitation rates: Impact of Physics Time Step

- Physics time steps in CAM FV have little effect on patterns
Vertical velocity in the **moist baroclinic wave**

500 m vertical velocity at day 10 ($\Delta x=110$ km): overall patterns similar, details differ

- Precipitation bands tightly connected to the narrow updraft areas
- Reduced updrafts translate into reduced precipitation rates
- Noisy updraft areas lead to noise in precipitation rates
Specific humidity in the moist baroclinic wave

500 m specific humidity at day 10 ($\Delta x=110$ km):
overall patterns similar, details differ

- High levels of specific humidity are advected from the moist tropical areas into the midlatitudes (ahead of the low pressure systems)
- Specific humidity provides moisture source for the Kessler precipitation scheme
Temperature in the **moist baroclinic wave**

500 m temperature at day 10 ($\Delta x=110$ km): overall patterns similar, details differ

- Breaking waves at day 10 (also visible in the specific humidity field)
- Updrafts are connected to the strong temperature fronts
Relative vorticity in the moist baroclinic wave

500 m relative vorticity at day 10 ($\Delta x=110$ km):
overall patterns similar, details differ

- Maxima and minima differ (by about 30%) and are found in very narrow strips (challenges the 110 km grid spacing)

- Vorticity highlights noise and the diffusive properties of the model
Seems to be predicted rather well, field is dominated by large-scale resolved advection.

Vertically integrated water vapor at day 10 (Δx=110 km): overall patterns similar, only details differ.

- Seems to be predicted rather well, field is dominated by large-scale resolved advection.
Integrated cloud water: moist baroclinic wave

Vertically integrated cloud water at day 10 ($\Delta x=110$ km)

- Cloud water highlights the physics-dynamics interactions
- Generation of cloud water is not resolved, parameterized in the Kessler warm rain scheme
- Model differences become more apparent
Integrated rain water: moist baroclinic wave

Vertically integrated rain water at day 10 ($\Delta x=110$ km)

- Rain water further highlights the physics-dynamics interactions
- Rain water comes from cloud water pool, parameterized in the Kessler scheme
- Differences become even more apparent
- Coherent patterns break up for this metric
Tracer consistency in the **dry** baroclinic wave

Vertically integrated tracers (weighted sum) at day 10 ($\Delta x=110$ km)

- Correlated tracer should stay perfectly correlated
- Analytical solution: zero variations
- Magnitudes of the tracer errors differ greatly ($10^{-1} - 10^{-6}$), caused by limiters, diffusion and monotonic constraints in the numerics
1500 m Kinetic Energy Spectra: dry and moist

- KE spectra provide information about the diffusion properties
- Some dry dynamical cores flatten their KE spectra
- Despite nominal 1° resolutions, resolved scales vary widely as indicated by the wide spread at high wavenumbers, spread narrows in moist runs
Snapshots: Supercell Simulations (dx=1 km)

- Time series of vertical velocity (top row) and rain water (bottom row) at 5 km after 30, 60, 90 and 120 minutes (horizontal resolution is 1 km)

Very wide model spread: diffusion processes differ

**w** vertical velocity

**q_r** rain water
Snapshots: Supercell Simulations (dx=1 km)

- Time series of vertical velocity (top rows) and rain water (bottom rows) at 5 km after 30, 60, 90 and 120 minutes (horizontal resolution is 1 km)

Very wide model spread: hard to disentangle
Conclusions

• The interactions between a dynamical core and moisture processes can already be simulated with very simple model configurations, like the Kessler warm-rain scheme

• Rich data base: moist dynamical core configurations reveal aspects of the physics-dynamics coupling, related to different dynamical cores, resolutions and physics time steps

• Idealized test cases are a useful tool (with quick turn around times) to test/understand the moisture aspects

• Causes and effects can be analyzed more easily, but are still difficult to disentangle

• We currently further analyze the impact of various numerical & diffusion choices and physics-dynamics coupling decisions (e.g. $\Delta t$)
References


DCMIP-2016 project page: https://www.earthsystemcog.org/projects/dcmip-2016/