Reduced Complexity Frameworks for Exploring Physics Dynamics Coupling Sensitivities

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Motivation: Extreme Weather and Climate

Resolution \(\uparrow\), better representation of:
- Extreme weather events
- Land-surface processes
- Topography
- Atm/ocn/ice/lnd interfaces
- Chemical emission/transport/reactions/removal

OLR (W/m\(^2\))

0.5°

0.25°

0.125°

July 10th, 2018

Courtesy of Colin Zarzycki (NCAR)
Motivation: Resolution Sensitivity in CAM

1 deg. (100 km)

0.25 deg. (25 km)

[Bacmeister et al. 2014, J. Climate]
Motivation: Resolution Sensitivity in CAM4

Change in **convective** precipitation

Change in **stratiform** (large-scale) precipitation

[Herrington & Reed 2017, J. Climate]
How are GCMs evaluated? Physics-Dynamics Coupling?

• Utilize a test hierarchy

Increasing Complexity

2D Shallow Water Test Cases

3D Dry Dynamical Core Test Cases

3D Aqua-Planet Experiment

3D AMIP

Deterministic tests

Tests of the statistical behavior (model ‘climate’)

[Reed & Jablonowski 2012, JAMES]
• Temperature tendency from the physical parameterizations (black), vertical pressure velocity from the dynamical core (colors)

• Magnitude of vertical velocities increase with resolution

• Horizontal scale of the physics forcing decreases with resolution

July 10th, 2018
[Herrington & Reed 2018, JAMES]
How are GCMs evaluated? Physics-Dynamics Coupling?

- Utilize a test hierarchy

**Increasing Complexity**

- **2D Shallow Water Test Cases**
- **3D Dry Dynamical Core Test Cases**
- **3D Aqua-Planet + Simplified Boundary Conditions**
- **3D Aqua-Planet Experiment**
- **3D AMIP**

**Deteministic Tests**  **Additional Complexities**  **Tests of Statistical Behavior**

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[Updated from Reed & Jablonowski 2012, JAMES]  
July 10th, 2018
NCAR’s Community Atmosphere Model version 5 (CAM 5).

The SE dynamical core with 30 vertical levels is used at the horizontal resolutions of:

- $n_e=30$ (~100 km) $\Rightarrow$ with reduced Earth radius
- $n_e=120$ (~25 km)

Full physics in Aquaplanet mode is used, with a simplified ocean covered Earth and constant SST of $29^\circ C$.

No rotation effects (i.e., 10 deg. N).

Diurnally varying, spatially uniform insolation (~340 W/m$^2$).

No direct and indirect effects of aerosols.

Tuning parameters are set to $n_e=30$ configuration for all simulations.

Such a setup mimics similar simulations with limited-area or cloud-resolving models, but at a relatively lower resolution.
RCE: Resolution Comparison

6-hr Avg. Precipitation (mm/day)

ne30 (~100 km)  
ne120 (~25 km)

July 10th, 2018  
[Reed et al. 2015, JAS]
Reduced Planet RCE: Resolution Dependence – Scale Awareness

[Reed and Medeiros 2016, GRL]

July 10th, 2018
How Do we evaluate GCMs? Physics-Dynamics Coupling?

• Utilize a test hierarchy

Deterministic Tests

Additional Complexities

Tests of Statistical Behavior

[Updated from Reed & Jablonowski 2012, JAMES]
Think Back to the CAM5 Aqua-Planet

Resolved vertical pressure velocity (colors)

Potential Temperature perturbation from parameterizations (color) with Deep convective mass fluxes (black contour)

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[Herrington & Reed 2018, JAMES]
Hypothesize $D$ proportional to $\Delta x$ in aqua-planets & and that their equilibrated solutions are described by the scaling:

$$W \sim 1/\Delta x$$
This scaling over-``predicts” the vertical velocity response to horizontal resolution on aqua-planets...

July 10th, 2018 [Herrington & Reed 2017, J. Climate]
• NCAR’s Community Atmosphere Model version 5 (CAM 5).
• The SE dynamical core with 30 vertical levels is used at the horizontal resolution of ne=30 (~100 km).
• The radius of the Earth is then decreased to mimic increase resolution.
• Select physics (i.e., none (dry), simple condensation, or stratiform precip only) in is used, with a simplified ocean covered Earth and constant SST of 29°C.
• No rotation effects.
• Any tuning parameters are set to ne=30 configuration for all simulations.
• Such a setup mimics similar to previous work with bubble experiments, but to include moisture!
Design of Idealized Bubble Experiments

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[Herrington & Reed 2018, JAMES]
Reduced Complexity

Dynamical Core

Physics

Process

Variable

Interaction

July 10th, 2018
Scaling with Bubble Test: Dry and Simple Physics

- **RED:** Consider the dry SE dynamical core only
- **BLUE:** Couple with a large-scale condensation routine from Reed and Jablonowski 2011.

(Model the environment/bubble after aqua-planets)

The \( w = \sqrt{B_0H^H/D} \) scaling works, even with moisture!!
Test the Scaling: Choice of Physics Time-Step

- Conventionally, physics packages only update the state periodically
- Incrementally increase the physics time-step (dycore $\Delta t = 75$ s)

[Graph showing the effect of different physics time-steps on the minimum omega (hPa/day) at various radii.

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[Herrington & Reed 2018, JAMES]
Test the Scaling: Choice of Dynamical Core

- Is this sensitive to the choice of dynamical core and therefore potentially physics-dynamics coupling decisions?
- **Results are similar with CAM-FV core!**
Test the Scaling: Choice of Hyperviscosity Coefficient

- Recover the scaling by reducing the horizontal hyper-viscosity coefficients (for specific humidity, only).
Relate back to Aqua-planet?

- What if we rescale the more complex Aqua-planet simulations?

Need to build up additional complexity!
How Do we evaluate GCMs? Physics-Dynamics Coupling?

• Utilize a test hierarchy

Increasing Complexity

2D Shallow Water Test Cases → 3D Dry Dynamical Core Test Cases → 3D Dynamical Core + Moist Simplified-Physics Test Cases → 3D Aqua-Planet + Simplified Boundary Conditions → 3D Aqua-Planet Experiment → 3D AMIP

Deterministic Tests

Additional Complexities

Tests of Statistical Behavior

July 10th, 2018

[Updated from Reed & Jablonowski 2012, JAMES]
Simple-Physics

Dynamical Core

Physics

Process

Variable

Interaction

July 10th, 2018
Simple-Physics Dynamical Core Comparison – Coupling Role?

Wind Speed (m/s)
At Day 10

Differing strengths and shapes:

FV & SE
at 0.25°
(≈ 28 km)

EUL & SLD
at T340
(≈ 39 km)
DCMIP-2016: Dynamical Core Intercomparison Project

Wind Speed (m/s) At Day 10

Differing strengths and shapes:

Various Models from around the world at 0.5° (∼ 56 km)

July 10th, 2018 [Reed et al. 2018, in prep.]
Final Thoughts

• Standard and reduced complexity CAM simulations show a sensitivity to horizontal resolution. The magnitude of this sensitivity is not expected from simple scaling arguments.

• Isolating interactions between a dynamical core and moisture processes using simplified physics packages can reveal aspects of the physics-dynamics coupling that impact this resolution sensitivity (i.e., coupling frequency!).

• Reduced complexity testbeds are a useful tool (with quick turn around times) to test/understand physics-dynamics coupling, since they can be analyzed more easily than traditional climate modeling approaches.

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Radiative-convective equilibrium model intercomparison project

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(a) SAM-Small Domain
(b) SAM-Large Domain
(c) NICAM
(d) CAM

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\begin{align*}
\text{Pressure, hPa} & & \text{Pressure, hPa} & & \text{Pressure, hPa} & & \text{Pressure, hPa} \\
1000 & 0 & 0.1 & 0.2 & 0.3 & 1000 & 0 & 0.1 & 0.2 & 0.3 & 1000 & 0 & 0.1 & 0.2 & 0.3 \\
1000 & 0 & 0.1 & 0.2 & 0.3 & 1000 & 0 & 0.1 & 0.2 & 0.3 & 1000 & 0 & 0.1 & 0.2 & 0.3 \\
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1000 & 0 & 0.1 & 0.2 & 0.3 & 1000 & 0 & 0.1 & 0.2 & 0.3 & 1000 & 0 & 0.1 & 0.2 & 0.3 \\
\end{align*}
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\begin{align*}
\text{Cloud Fraction} & & \text{Cloud Fraction} & & \text{Cloud Fraction} & & \text{Cloud Fraction} \\
0 & 0.1 & 0.2 & 0.3 & 0 & 0.1 & 0.2 & 0.3 & 0 & 0.1 & 0.2 & 0.3 & 0 & 0.1 & 0.2 & 0.3 \\
0 & 0.1 & 0.2 & 0.3 & 0 & 0.1 & 0.2 & 0.3 & 0 & 0.1 & 0.2 & 0.3 & 0 & 0.1 & 0.2 & 0.3 \\
0 & 0.1 & 0.2 & 0.3 & 0 & 0.1 & 0.2 & 0.3 & 0 & 0.1 & 0.2 & 0.3 & 0 & 0.1 & 0.2 & 0.3 \\
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0 & 0.1 & 0.2 & 0.3 & 0 & 0.1 & 0.2 & 0.3 & 0 & 0.1 & 0.2 & 0.3 & 0 & 0.1 & 0.2 & 0.3 \\
\end{align*}
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