Dynamical Cores in the Community Earth System Model (CESM)

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National Center for Atmospheric Research is a major facility sponsored by the NSF under Cooperative Agreement No. 1852977.
The CESM community is discussing how to move forward with dynamical cores (in particular, what dynamical core to use as “workhorse” for the development of CESM3):

- What configurations must dynamical core(s) support in CESM?
- What dynamical core choices do we have?
- Evaluation of “intrinsic” dynamical core properties of interest to climate and climate-chemistry modeling at ~1 degree resolution (“IPCC class workhorse model”):
  - computational performance
  - tracer transport characteristics (mixing properties, conservation of pre-existing relations, etc.)
  - axial angular momentum conservation
  - flow over real-world topography
  - total energy conservation

At WCRP meeting (“The Earth’s Energy Imbalance and its implications”, Toulouse, 2018) I presented energy budget errors from physics and dynamics -> the working group strongly recommended CMIP diagnostics and further research in this area.
"Workhorse" CESM2 configurations (CAM=Community Atmosphere Model)

- **“Standard” CAM** (1°, 32 levels, top ~42km, 33 tracers):
  Need ~20 SYPD (century long simulations)

- **CAM-Chem**: Same as CAM but with extensive chemistry (~100+ tracers)

- **CAM paleo** applications (1° and 2°, 32 levels, top ~42km, 33 tracers):
  Very high throughput requirements

- **WACCM** (1°, 70 levels, top ~144km, ~60-135 tracers):
  Need ~4 SYPD (century long simulations)

- **WACCM-x** (1°, 130 levels, top ~600km, 70+ tracers):
  Coupled to ionosphere model, species dependent thermodynamics (cp, R, ...)
  "No" SYPD requirements (model run for days to a couple of years)

Note: WACCM, WACCM-x and CAM-Chem have historically always used the dynamical core chosen by CAM!

With CESM2.2 we have released infrastructure to facilitate species dependent thermodynamics in physics and dynamical core

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New CESM configurations

- **CAM-Chem**: Same as CAM, but with extensive chemistry (200 tracers)
- **WACCM-x**: (1°, 130 levels, top ~600km, 70+ tracers)
  Coupled to ionosphere model, species dependent thermodynamics (c_p, R, ...)
  "No" SYPD requirements (model run for days to a couple of years)
- **CAM paleo** applications (2°, 32 levels, top ~40km)
  Very high throughput requirements

### Additional/new configurations moving forward:
- Increasing interest in variable resolution modeling from community
- Likely a need for ½ and ¼ configurations for, e.g., sub-seasonal to seasonal (S2S) prediction applications and other applications that are run on shorter time-scales
- Interest in community for very high resolution coupled modeling with CESM:
  - iHESP project: ¼ degree atmosphere fully coupled configuration for climate
  - iHESP: currently setting up ~6km atmosphere fully coupled configuration for climate
  - Recently funded project: EarthWorks (~4km atmosphere fully coupled CESM)

**Table:**

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<th>Frontier</th>
<th>Science Question</th>
<th>Target Configuration</th>
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<tr>
<td>Weather</td>
<td>Tropical Cyclones</td>
<td>4km refined mesh, coupled ocean, initialized</td>
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<tr>
<td>Climate</td>
<td>Hydrologic Extremes</td>
<td>4-8km refined mesh, initialized and climate simulations</td>
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<tr>
<td>Polar</td>
<td>Arctic Prediction, Ice Sheet</td>
<td>12km refined mesh, coupled ocean, land, sea ice, land ice. Initialized and climate simulations</td>
</tr>
<tr>
<td>Geospace</td>
<td>Space Weather Prediction</td>
<td>25km global atmosphere to the ionosphere, initialized</td>
</tr>
<tr>
<td>Chemistry</td>
<td>Biomass burning</td>
<td>14km refined global mesh initialized</td>
</tr>
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</table>

Note: WACCM, WACCM-x and CAM-Chem have historically always used the dynamical core chosen by CAM!
Variable resolution modeling with CAM

- Recent release of CESM2.2 has support for 3 variable resolution meshes:
Surface Mass Balance (SMB) Temporal Evolution

\[ \text{SMB} = \text{ACCUM}^* + \text{RUNOFF} \]

*includes meltwater storage/refreezing

- Too much ACCUM at low res
- Too much RUNOFF at low res*

Slide courtesy of Adam Herrington


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The following dynamical cores have been or are being integrated into the CESM:

- **Spectral-Element (SE)** dynamical core with option for accelerated transport scheme (CSLAM)
  - highly scalable hydrostatic dynamical core with flexible mesh-refinement options
  - capability of running physics on a separate (coarser/finer) grid for uniform grid applications
  (see “Physics-dynamics coupling with element-based high-order Galerkin methods: quasi equal-area physics grid”, MWR, 2018)

- **FV3**: GFDL’s dynamical core used by NCEP for global weather forecasting
  - scalable finite-volume dynamical core (currently using hydrostatic version)
  - mesh-refinement/nesting and non-hydrostatic version not currently supported in CESM

- **MPAS**: NCAR’s global weather forecast model
  - non-hydrostatic finite-volume dynamical core that allows for flexible mesh-refinement

**Release notes**:
- **SE and SE-CSLAM**, **FV3**, and **MPAS** released with CESM2.2 (bug fix in preparation)
- Integration in progress

**Diagrams**:
- SE and SE-CSLAM
- FV3
- MPAS

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Aside: Dynamical cores and high top configurations

- Our experience with the spectral-element dynamical core has been that higher top configurations with tops at ~140km and ~600km have required significant efforts to stabilize (numerical method less diffusive compared to FV)

- We are seeing significant differences between FV and SE-CSLAM at higher elevations that we are trying to understand (likely due to more resolved gravity waves)
Aside: QBO with WACCM-SE-CSLAM

Initial simulations with WACCM-SE-CSLAM showed almost no QBO signal compared to WACCM-FV.
- It did not appear to be “tunable” with gravity wave tuning parameters.
Aside: QBO with WACCM-SE-CSLAM

Changing to FV3 vertical remapping for u, v, T, and water species improved QBO simulation significantly!
Aside: QBO with WACCM-SE-CSLAM

Still, we need higher vertical resolution for a good simulation of the QBO (e.g., 110 levels)
I would like to highlight that we are extremely close to a major achievement:

Changing between 5 state-of-the-art dynamical cores is a one line change in run-script:

```
se-cslam: /create_newcase -res ne30pg3_ne30pg3_mg17 ...
se      : /create_newcase -res ne30_ne30_mg17 ...
fv3     : /create_newcase -res C96_C96_mg17 ...
fv      : /create_newcase -res f09_f09_mg17 ...
mpas    : /create_newcase -res mpasa120_mpasa120 ...
```

Works already for CESM simpler models

That means diagnostics coded in physics can seamlessly be used with all dynamical cores
We are, at this point, interested in the performance for standard CMIP-like configurations!

All cores run at approximately 1 degree resolution (setup provided by developers). Note that the grids differ in number of degrees of freedom:

FV (55296), FV3 (55296), SE (48600), MPAS (40962); for comparison:
Note: FV3 has 35% more columns than MPAS and 13% more columns than SE

We are not considering threading or GPU performance in this initial study
### Preliminary performance data

<table>
<thead>
<tr>
<th>FKESSLER, 33 tracers, 1 month (no I/O)</th>
<th>QPC6, 1 month (incl. I/O)</th>
</tr>
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<tbody>
<tr>
<td><strong>Setup 1: Effectively dynamical core performance</strong></td>
<td><strong>Setup 2: “Full” model performance</strong></td>
</tr>
<tr>
<td>● Baroclinic wave with simple physics (physics is “free”)</td>
<td>● CAM6 physics (Aqua-planet)</td>
</tr>
<tr>
<td>● No I/O</td>
<td>● Timings include history I/O, writing restart file, etc.</td>
</tr>
<tr>
<td>● 33 tracers (=CAM6 #tracers)</td>
<td>● 33 tracers (=CAM6 #tracers)</td>
</tr>
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</table>
Preliminary performance

FKESSLER, 33 tracers, 1 month (no I/O)

Why is SE-CSLAM slower than SE?
- Double advection of water species (maybe not necessary)
- Mapping to-from dynamics and physics grid (not optimized)
- Overhead in computing dry air mass fluxes for CSLAM
- CSLAM has been coded so that sides of CSLAM control volumes on the edges of elements are duplicated on each element (reduces communication cost but is more work per degree of freedom - hurts performance at lower core counts)

At high core counts MPI communication becomes large for FV3 and FV

At low core counts FV and FV3 are clearly faster (methods are likely cheaper per degree of freedom compared to SE)
Since physics is embarrassingly parallel and 50% of runtime, all dycores have better scaling characteristics.

With 1800 processors (typical core count for development runs) all cores are within 4 SYPD of each other!

For maximum throughput (e.g. for paleo climate applications or meeting IPCC deadlines) SE and SE-CSLAM can get 50-55 SYPD with 5400 cores.

FV3 reaches scaling limit 3456 processor with ~40 SYPD.

### Preliminary performance data

**QPC6, 1 month (incl. I/O)**

- **SE**: Red circles
- **SE-CSLAM**: Green triangles
- **FV**: Blue triangles
- **FV3 (hydrostatic)**: Pink triangles

![Graph showing performance data](image-url)
Preliminary performance data

FKESSLER, 1 month (incl. I/O), 900 cores

- Spectral-element advection is the slowest in terms of cost per additional tracer.
- FV and FV3 use dimensionally split advection schemes (computationally cheaper than fully 2D schemes such as CSLAM).
- FV lat-lon advection algorithm cheaper than cubed-sphere version.
- Note: This plot would look different at large core counts (“just” 900 cores used here) ...
Tracer transport characteristics

- Mass-conservation
- Shape-preservation (overshooting, undershooting)
- Mixing for a single tracer: entropy measure (should be invariant in time)
- Mixing diagnostics for two non-linearly correlated tracers: 3 mixing error norms
- Three or more tracers adding to a constant (practical example: total reactive Chlorine in stratosphere, aerosols)
- Linear correlation with idealized terminator chemistry (practical example: photolysis driven chemistry)

Test case setup: moist baroclinic wave with a bunch of inert tracers and two reactive chlorine species

All diagnostics computed in physics! No reference solution needed

All tests at ~1 degree (would be interesting to test variable resolution …)
Min (=0.1) and max (=1.0) should be preserved and, in particular, range should not be expanded.

FV and FV3 produce large errors! Could be remedied with more restrictive limiters, however, not entirely due to dimensionally split scheme (limiters limit only in coordinate directions!)

Shape-preservation
Non-linear correlation diags: scatter plots
Non-linear correlation diags: scatter plots

Lauritzen and Thuburn (2012)
SE produces significantly more unmixing than other cores.

SE-CSLAM and FV3 produce similar amounts of real mixing.

FV best due to higher resolution at 40N compared to other grids.

FV3 produces larger amounts of overshooting.

SE and FV produce a little overshooting.

SE-CSLAM produce none!

SE-CSLAM and FV have the least amount of unmixing.
Three tracers adding to a constant

Lauritzen and Thuburn (2012)
Terminator chemistry test
(Lauritzen et al., 2015)

Consider 2 reactive chemical species, Cl and Cl\textsubscript{2}:

\[
\text{Cl}_2 \rightarrow \text{Cl} + \text{Cl} : k_1
\]
\[
\text{Cl} + \text{Cl} \rightarrow \text{Cl}_2 : k_2
\]

• In any flow-field \( \text{Cl}_y = \text{Cl} + 2\times\text{Cl}_2 \) should be constant at all times (linear correlation preservation for reactive species).
Terminator chemistry diagnostic

Lauritzen and Thuburn (2012)

FV3, FV3 and SE-CSLAM perform significantly better than SE

Note: contour range/intervals different on each plot!
Axial angular momentum diagnostics

Setup: Held-Suarez forcing with flat Earth. Dynamical core should not be a source/sink of AAM
Plots show torque due to dynamical core as a function of time (days)

Only SE (and SE-CSLAM) do well on this test. FV and FV3 dynamical cores have spurious torques on the same order of magnitude as the physics torques.
The challenge of energy budget closure in Earth system models: dynamical core errors, physics errors, physics-dynamics coupling errors, ...

• Energy budgets are complicated and require inline diagnostics in model code to assess errors (in particular, there can easily be compensating errors in the system):

\[-\partial E_{\text{phys}}^{(\text{fix})} = \partial E_{\text{phys}}^{(\text{pwork})} + \partial E_{\text{dyn}}^{(\text{adiab})} + \partial E^{(\text{pdc})} + \partial E^{(\text{discr})}\]

Energy fixer

Pressure work (physics assumes constant pressure during physics updates)

Dynamical core

Physics-dynamics coupling

Continuous total energy formula discrepancy between physics and dynamics (e.g. internal energy, hydrostatic-nonhydrostatic, …)
The challenge of energy budget closure in Earth system models: dynamical core energy errors, physics errors, physics-dynamics coupling errors.

- Energy budgets are complicated and require inline diagnostics in model code to assess errors (in particular, there can easily be compensating errors in the system).

\[ -\partial \widehat{E}_{phys}^{(efix)} = \partial \widehat{E}_{phys}^{(pwork)} + \partial \widehat{E}_{dyn}^{(adiab)} + \partial \widehat{E}^{(pdc)} + \partial \widehat{E}^{(discr)} \]

Energy fixer
Pressure work (physics assumes constant pressure during physics updates)
Dynamical core
Physics-dynamics coupling
Continuous total energy formula discrepancy between physics and dynamics (e.g. internal energy, hydrostatic-nonhydrostatic, …)

SE-CSLAM: -0.2 W/m²
FV and FV3: -1.1 W/m²
SE-CSLAM: 0.6 W/m²
FV and FV3: 0.05 W/m²

0.3 W/m²

Lauritzen and Williamson, 2019

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Summary

- Unfortunately there is no one dynamical core / numerical method that is overall superior

- More testing in the pipeline:
  - idealized tests with real-world topography
  - moist physics (Aqua-planet, “real-world” AMIP and coupled)

- CESM/SIMA deliverables and progress:
  - CAM-Chem version with mesh-refinement (SE) is being used for science now
  - WACCM with SE-CSLAM is being evaluated
  - Close to having a SE and SE-CSLAM WACCM-x configuration ready for testing
  - Working on CAM-MPAS
Joint WCRP and DCMIP Summer School on Earth System Model Development
Dynamical cores and physics-dynamics coupling

August 10 – 14, 2020
National Center for Atmospheric Research, Mesa Lab
Boulder, Colorado, USA

OVERVIEW

The Dynamical Core Model Intercomparison Project (DCMIP) and its joint World Climate Research Programme (WCRP) Summer School highlights the newest modeling techniques for global Earth system models. The overarching theme of this summer school is physics-dynamics coupling.

The objectives of the joint WCRP and DCMIP Summer School are (1) to teach a group of 30 extraordinary multi-disciplinary students and postdocs how today’s and future atmospheric models are or need to be built, and (2) to use idealized test cases to expose selected model design choices in simplified modeling frameworks based on NCAR’s Community Earth System Model (CESM) and the Department of Energy’s (DOE’s) Energy Exascale Earth System Model (E3SM). DCMIP 2020 thereby continues the DCMIP 2008, DCMIP 2012 and DCMIP 2016 model intercomparison and...
Increased hyperviscosity (4th order) on divergence, vorticity and T in sponge
Was not possible to stabilize model with 2nd-order damping only!

Divergence damping (3x increase)

Vorticity and T damping (5x increase)