On the development of the NCAR CAM-SE-CSLAM with separate physics grid

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PDEs on the Sphere
April 5, 2017
Paris, France
Overview:

1. **Aside: Simpler models in the CESM2**
   (=Community Earth System Model version 2; release ~June 2017)

2. **Dry-mass vertical coordinate version of NCAR CAM-SE**
   (incl. discussion on total energy including condensates)

3. **Consistent finite-volume transport with SE dynamics (PDEs 2015)**

4. **Coupling to physics using a finite-volume grid**
Simpler models effort in the CESM

(started by L.Polvani and A.Clement)

Provide “out-of-the-box” support for:

- Various DCMIP tests:
  - several idealized baroclinic waves (Jablonowski, Ullrich and Polvani waves)
  - Kessler Microphysics (Kessler, 1969)
  - Toy terminator chemistry (Lauritzen et al., 2015)

- Held-Suarez forcing (Held and Suarez, 1994)

- Moist Held-Suarez forcing (Thatcher and Jablonowski, 2016)

- Aquaplanet configurations (Medeiros et al., 2016; ...)

(started by L.Polvani and A.Clement)
Moist baroclinic wave with Kessler Micro Physics

Ullrich et al. (2014) baroclinic with 3 tracers (cloud ice, rain water, water vapor)+Kessler (1969) physics

P.H. Lauritzen, C. Zarzycki & S. Goldhaber

A. KESSLER PHYSICS

The cloud microphysics update according to the following equation set:

\[
\begin{align*}
\frac{\Delta \theta}{\Delta t} &= - L \frac{\Delta q_\theta}{\Delta t} + E_r \\
\frac{\Delta q_\theta}{\Delta t} &= \frac{\Delta q_{\theta,0}}{\Delta t} + E_r \\
\frac{\Delta q_c}{\Delta t} &= - \frac{\Delta q_{\theta,0}}{\Delta t} - A_r - C_r \\
\frac{\Delta q_r}{\Delta t} &= - E_r + A_r + C_r - V_r \frac{\partial q_r}{\partial z}.
\end{align*}
\]

where $L$ is the latent heat of condensation, $A_r$ is the autoconversion rate of cloud water to rain water, $C_r$ is the collection rate of rain water, $E_r$ is the rain water evaporation rate, and $V_r$ is the rain water terminal velocity.

`.create_newcase -compsset FKESSLER -res ne30_ne30`
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   (incl. discussion on total energy including condensates)
   
   Note: NCAR CAM-SE ≠ DOE ACME CAM-SE ≠ CAM-HOMME

3. Consistent finite-volume transport with SE dynamics (PDEs 2015)

4. Coupling to physics using a finite-volume grid
NCAR CAM-SE: dry-mass eta

Consider a ‘moist’ \( \eta \)-coordinate system: The pressure is given by

\[ p(\eta) = A(\eta)p_0 + B(\eta)ps, \]

where \( ps \) is ‘moist’ surface pressure.

In a floating \( \eta \)-coordinate system, \( \dot{\eta} = 0 \), the continuity equation for \( p \) can be written as

\[ \frac{\partial}{\partial t} \left[ \left( \frac{\partial p}{\partial \eta} \right) \right] + \nabla \cdot \left[ \left( \frac{\partial p}{\partial \eta} \right) \vec{v} \right] = S^p, \]

where \( S^p(q_v) \) is the source/sink term for pressure \( (q_v \equiv \text{specific humidity}) \).
• This source/sink term:
  - makes the handling of tracers more complicated
    An inert tracer will have source/sink terms (i.e. if there are moisture changes all “wet” mixing ratios must be changed accordingly)
    - makes it harder to move towards conserving a more comprehensive total energy

• Complicates CSLAM-SE coupling in a moist atmosphere

\[
\frac{\partial}{\partial t} \left( \frac{\partial p}{\partial \eta} \right) + \nabla \cdot \left( \frac{\partial p}{\partial \eta} \vec{v} \right) = S^p,
\]

where \( S^p(q_v) \) is the source/sink term for pressure \( (q_v \equiv \text{specific humidity}) \).
NCAR CAM-SE: dry-mass eta

If one uses a dry mass vertical coordinate

\[ p(\eta_d) = A(\eta_d)p_0 + B(\eta_d)p_{sd}, \]

where \( p_{sd} \) is dry surface pressure, then the continuity equation for pressure does not have sources/sinks

\[ \frac{\partial}{\partial t} \left[ \left( \frac{\partial p_d}{\partial \eta_d} \right) \right] + \nabla \cdot \left[ \left( \frac{\partial p_d}{\partial \eta_d} \right) \vec{v} \right] = 0. \]
NCAR CAM-SE: dry-mass eta

The $\eta^{(d)}$-coordinate adiabatic and frictionless atmospheric primitive equations assuming floating Lagrangian vertical coordinates [Starr, 1945; Lin, 2004] can be written as

$$\frac{\partial \vec{v}}{\partial t} + (\zeta + f) \hat{k} \times \vec{v} + \nabla_{\eta^{(d)}} \left( \frac{1}{2} \vec{v}^2 + \Phi \right) + \frac{1}{\rho} \nabla_{\eta^{(d)}} p = 0,$$

$$\frac{\partial T}{\partial t} + \vec{v} \cdot \nabla_{\eta^{(d)}} T - \frac{1}{c_p \rho} \omega = 0,$$

$$\frac{\partial}{\partial t} \left( \frac{\partial p^{(d)}}{\partial \eta^{(d)}} m^{(\ell)} \right) + \nabla_{\eta^{(d)}} \cdot \left( \frac{\partial p^{(d)}}{\partial \eta^{(d)}} m^{(\ell)} \vec{v} \right) = 0, \quad \ell = d, v, cl, ci, ...$$

where $\rho$ is the full density $\sum_{\ell} \rho^{(\ell)}$, $p$ is the sum of the partial pressures $p^{(d)} + p^{(v)}$ (dry and water vapor pressure; note that cloud liquid and cloud ice do not exert a pressure), $\Phi$ is the geopotential height ($\Phi = g z$, where $g$ is the gravitational constant), $\hat{k}$ is the unit vector normal to the surface of the sphere, $\zeta = \hat{k} \cdot \nabla \times \vec{v}$ is vorticity, $f$ Coriolis parameter, and $\omega = Dp/Dt$ is the pressure vertical velocity.
The $\eta^{(d)}$-coordinate adiabatic and frictionless atmospheric primitive equations assuming floating Lagrangian vertical coordinates [Starr, 1945; Lin, 2004] can be written as

$$\frac{\partial \vec{v}}{\partial t} + (\zeta + f) \hat{k} \times \vec{v} + \nabla_{\eta^{(d)}} \left( \frac{1}{2} \vec{v}^2 + \Phi \right) + \frac{1}{\rho} \nabla_{\eta^{(d)}} p = 0,$$

$$\frac{\partial T}{\partial t} + \vec{v} \cdot \nabla_{\eta^{(d)}} T - \frac{1}{c_p \rho} \omega = 0,$$

$$\frac{\partial}{\partial t} \left( \frac{\partial p^{(d)}}{\partial \eta^{(d)}} m^{(\ell)} \right) + \nabla_{\eta^{(d)}} \cdot \left( \frac{\partial p^{(d)}}{\partial \eta^{(d)}} m^{(\ell)} \vec{v} \right) = 0, \quad \ell = d, v, cl, ci, ...$$

where $\rho$ is the full density $\sum_{\ell} \rho^{(\ell)}$, $p^{(d)} + p^{(v)}$ is the sum of the partial pressures (dry and water vapor pressure; note that solid liquid and cloud ice do not exert a pressure), $\Phi$ is the geopotential height ($\Phi = g z$ where $g$ is the gravitational constant), $\hat{k}$ is the unit vector normal to the surface of the atmosphere, $\zeta = \hat{k} \cdot \nabla_{\eta^{(d)}}$ is vorticity, $f$ Coriolis parameter, and $\omega$ is the angular velocity.

$$\rho = \rho^{(d)} \left( \sum_{\ell} m^{(\ell)} \right), \text{ where } \ell = 'd', 'v', 'cl', 'ci'$$

$$c_p = \frac{\sum_{\ell} \left[ m^{(\ell)} c_p^{(\ell)} \right]}{\sum_{\ell} m^{(\ell)}}$$

dry air ’d’, water vapor ’v’, cloud liquid ’cl’ and cloud ice ’ci’
Internal Energy
(similarly for total kinetic energy)

The total internal energy integrated over the entire atmosphere is given by

\[ I_{tot} = \iiint \rho c_p T \, dz \, \cos(\theta) r \, d\lambda \, d\theta \]

Using the hydrostatic balance this equation can be written as

\[ I = \sum_\ell I^{(\ell)} = -\frac{1}{g} \sum_\ell \iiint c_p^{(\ell)} m^{(\ell)} T \left( \frac{\partial p^{(d)}}{\partial \eta^{(d)}} \right) d\eta^{(d)} \, \cos(\theta) r \, d\lambda \, d\theta, \]

where \( I^{(d)} \) is the total internal energy of dry air, \( I^{(v)} \) the total internal energy of water vapor, etc.
Energy diagnostics for NCAR CAM-SE

do n=1,nsplit
  do r=1,rsplit
    a. advance adiabatic equations of motion in floating Lagrangian layer (Lin, 2004)
    b. advance hyperviscosity operators on u,v,T,dp
    c. add momentum diffusion back as heating
  end do
  do vertical remapping of u,v,T and tracers
end do

Energy diagnostics (multi-year average values) from AMIP simulation

\[
\begin{align*}
\frac{dE}{dt} \text{ of } 2D \text{ dyn} & : 0.070 \text{ W/m}^2 \\
\frac{dE}{dt} \text{ of frictional heating from } (u,v) \text{ diffusion} & : 0.757 \text{ W/m}^2 \\
\frac{dE}{dt} \text{ of } T \text{ diffusion} & : 0.074 \text{ W/m}^2 \\
\frac{dE}{dt} \text{ of } dp \text{ diffusion} & : -0.003 \text{ W/m}^2 \\
\frac{dE}{dt} \text{ of } 1D \text{ dyn} & : -0.207 \text{ W/m}^2 \\
\frac{dE}{dt} \text{ dycore} & : -0.1367 \text{ W/m}^2
\end{align*}
\]
The total internal energy integrated over the entire atmosphere is given by

\[ I_{tot} = \iiint \rho c_p T \, dz \, \cos(\theta) \, r \, d\lambda \, d\theta \]

Using the hydrostatic balance this equation can be written as

\[ I = \sum_\ell I^{(\ell)} \]

The internal energy in CAM physics is defined as

\[ I^{(CAM)}_{tot} = -\frac{1}{g} \iiint c_{pd} T (1 + m_v) \left( \frac{\partial p_d}{\partial \eta_d} \right) \, d\eta_d \, \cos(\theta) \, r \, d\lambda \, d\theta \]

Discrepancy \(~0.5 \, W/m^2\)
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4. Coupling to physics using a finite-volume grid
CAM-SE-CSLAM: Consistent Coupling of a Conservative Semi-Lagrangian Finite-Volume Method with Spectral Element Dynamics

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CAM-SE-CSLAM without moisture

March 2017

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CAM-SE-CSLAM without moisture

Spectral-Element Method: CAM-SE

Mass change over CSLAM control volume \( A_k \) implied by SE

\[
(\Delta p^{n+1} - \Delta p^n) \Delta A_k = \sum_{\epsilon=1}^{4} \left[ \mathcal{F}_F^{(\epsilon)} + \mathcal{F}_G^{(\epsilon)} + \mathcal{F}_D^{(\epsilon)} \right],
\]

Lauritzen et al. (2017)

Finite-Volume Method: CSLAM

CSLAM discretization is given by

\[
(\widetilde{\Delta p}^{n+1} - \widetilde{\Delta p}^n) \Delta A_k = \sum_{\epsilon=1}^{4} \left[ \mathcal{F}_C^{(\epsilon)} \right] = -\sum_{\epsilon=1}^{4} s_{k\ell}^{\epsilon} \int_{A_k^\epsilon} \Delta p^n \, dA.
\]

Harris et al. (2011), Lauritzen et al. (2010)
CAM-SE-CSLAM without moisture

**Spectral-Element Method: CAM-SE**

Mass change over CSLAM control volume $A_k$ implied by SE

$$
(\Delta p^{n+1} - \Delta p^n) \Delta A_k = \sum_{\epsilon=1}^{4} \left[ \mathcal{F}_{C}^{(\epsilon)} + \mathcal{F}_{G}^{(\epsilon)} + \mathcal{F}_{D}^{(\epsilon)} \right],
$$

(Lauritzen et al., 2016; in prep).

For each face $\epsilon$ in cell $a_k$, find a swept area $a_k^{(\epsilon)}$ so that

$$
\mathcal{F}_{C}^{(\epsilon)} = \mathcal{F}_{C}^{(\epsilon)} + \mathcal{F}_{G}^{(\epsilon)} + \mathcal{F}_{D}^{(\epsilon)}.
$$

*Lagrangian consistency constraint:* The upstream areas must span the sphere without cracks or overlaps.

CSLAM discretization is given by

$$
(\tilde{\Delta} p^{n+1} - \tilde{\Delta} p^n) \Delta A_k = \sum_{\epsilon=1}^{4} \left[ \mathcal{F}_{C}^{(\epsilon)} \right] = -\sum_{\epsilon=1}^{4} \mathcal{F}_{C}^{(\epsilon)}.
$$

---

**NCAR National Center for Atmospheric Research Climate & Global Dynamics**

climate • models •
In principle, the consistent CSLAM algorithm can be used with any fluxes that obey the Lipschitz criterion ... and no search algorithm needed anymore!
CAM-SE

CAM-SE-CSLAM

CAM-SE reference

Lauritzen et al. (2017)
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CAM-SE-CSLAM with moisture

“This is where the fun begins!” – Staniforth et al. (2006)
Mapping $u,v, T, \omega$ from dynamics grid (GLL) to finite-volume (CSLAM) grid

Temperature: Integrate basis function representation of $dp \times T$ over physics grid control volumes (high-order remapping; conserves dry internal energy)

$(u,v)$: Evaluate basis function representation of contra-variant velocity components at physics control volume centers (high-order interpolation)
Mapping $u, v, T, \omega$ from dynamics grid (GLL) to finite-volume (CSLAM) grid

Note that physics grid averages/moves fields away from boundary of element where the solution is least smooth (in element interior the polynomials are $C^\infty$)
CAM-SE with “rougher” topography

Held-Suarez forcing with real-world topography (6 months spin-up; 2 years and 9 months average)
Note: dry test so no moist physics feedbacks

bnd_topo = '/home/pel/run_scripts/topo/ne30np4_nc3000_Nsw042_Nrs008_Co060_Fi001_ZR_test_vX_111416.nc'

Using CAM-FV topography (rougher than what SE uses)
CAM-SE-CSLAM

Held-Suarez forcing with real-world topography (6 months spin-up; 2 years and 9 months average)
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CAM-FV topography (rougher than what SE uses)
CAM-SE-CSLAM configuration

Figure 3: (a) The latitude-longitude grid, (b) the cubed-sphere grid based on an equi-angular central projection and (c) icosahedral grid based on hexagons and pentagons. The triangular grids used by models herein are the dual of the hexagonal grid.

volume implementation (i.e., the Lin and Rood, 1996, algorithm). An example of a two-dimensional extension based on the PPM algorithm that is third-order is given in, e.g., Ullrich et al. (2009).

CAM-ISEN is an isentropic version of CAM FV. Instead of the hybrid sigma-pressure vertical coordinate, an isentropic vertical coordinate is used (Chen and Rasch 2009). Apart from the vertical coordinate the model design is identical to CAM FV.

3.2. Cubed-sphere grid models
The assessment includes two dynamical cores that are defined on cubed-sphere grids. The finite-volume cubed-sphere model (GEOS FV CUBED) is a cubed-sphere version of CAM FV developed at the Geophysical Fluid Dynamics Laboratory (GFDL) and the NASA Goddard Space Flight Center. The advection scheme is based on the Lin and Rood (1996) method but adapted to non-orthogonal cubed-sphere grids (Putman and Lin 2007, 2009). Like CAM FV, the GEOS FV CUBED dynamical core is second-order accurate in two dimensions. Both a weak second-order divergence damping mechanism and an additional fourth-order divergence damping scheme is used with coefficients $0.005 \times \Delta A_{\text{min}} / \Delta t$ and $0.05 \times \Delta A_{\text{min}} / \Delta t$, respectively, where $\Delta A_{\text{min}}$ is the smallest grid cell area in the domain. The strength of the divergence damping increases towards the model top to define a 3-layer sponge. In contrast to CAM FV and CAM ISEN, the cubed-sphere model does not apply any digital or FFT filtering in the polar regions and mid-latitudes. Nevertheless, an external-mode filter is implemented that damps the horizontal momentum equations. This is accomplished by subtracting the external-mode damping coefficient $(0.02 \times \Delta A_{\text{min}} / \Delta t)$ times the gradient of the vertically-integrated horizontal divergence on the right-hand-side of the vector momentum equation.

GEOS FV CUBED applies the same inner and outer operators in the advection scheme (PPM) to avoid the inconsistencies described in Lauritzen (2007) when using different orders of inner and outer operators. The cubed-sphere grid is based on central angles. The angles are chosen to form an equal-distance grid at the cubed-sphere edges (undocumented). The equal-distance grid is similar to an equidistant cubed-sphere grid that is explained in Nair et al. (2005). The resolution is specified in terms of the number of cells along a panel side. As an example, 90 cells along each side of a cubed-sphere face yield a global grid spacing of about 1°.

The second cubed-sphere dynamical core is NCAR's spectral element High-Order Method Modeling Environment (HOMME) (Thomas and Loft 2004, Nair et al. 2009). Spectral elements are a type of a continuous-Galerkin h-p finite element method (Karniadakis and Sherwin 1999, Canuto et al. 2007), where $h$ is the number of elements and $p$ the polynomial order. Rather than using cell averages as prognostic variables as in geos_fv_cubed, the finite element method uses $p$-order polynomials to represent the prognostic variables inside each element. The spectral element method is compatible, meaning it is an analog so that the integral properties of the divergence, gradient and curl operators, making the method elementwise mass-conservative (to JAMES-D u,v,T,p physics tracers No mapping of tracers needed).
“Tendencies from physics parameterizations are low order anyway so I can just use low order mapping ...”

Mapping tendencies not state!
Temperature tendency: FT

CAM-SE-CSLAM with linear interpolation from phys to dyn: 5 month average
CAM4 SE-CSLAM-physgrid: linear interpolation phys to dyn: 5 month average
Temperature tendency: FT

CAM-SE-CSLAM with cubic tensor product interpolation from phys to dyn:
18 month average
PRECT
(TOTAL PRECIPITATION RATE)

CAM-SE-CSLAM with cubic tensor product interpolation from phys to dyn:
18 month average
Figure 3: (a) The latitude-longitude grid, (b) the cubed-sphere grid based on an equi-angular central projection and (c) icosahedral grid based on hexagons and pentagons. The triangular grids used by models herein are the dual of the hexagonal grid.

Volume implementation (i.e., the Lin and Rood, 1996, algorithm). An example of a two-dimensional extension based on the PPM algorithm that is third-order is given in, e.g., Ullrich et al. (2009).

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Multiscale Modeling Framework (MMF)

“Cloud Resolving Convective Parameterization” or “Superparameterization”

Approach trying to improve the representation of cloud processes by using the simulated statistics of 2D CRM.

Grabowski & Smolarkiewicz (1999), Khairoutdinov & Randall (2001), and many others.

Many studies have shown the ability of the MMF to simulate various atmospheric events with a wide range of time scales.

But, there are inherent limits:

- Confinement of CRMs with cyclic boundary conditions
- Use of 2D CRMs
- Need to choose a particular direction for the 2D CRMs
Quasi-3D Multiscale Modeling Framework

In Q3D MMF

- CRMs are seamlessly connected
- Two perpendicular sets of CRMs are used
- Each CRM is three-dimensional, (although it is applied to a narrow channel-like domain)