NCAR CESM2.0 release of CAM-SE:

A reformulation of the spectral-element dynamical core in dry-mass vertical coordinates with comprehensive treatment of condensates and energy

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Introduction

For some time the atmosphere component of the CESM (Community Earth System Model), called **CAM** (Community Atmosphere Model), has supported a **Spectral-Element (SE)** dynamical core option; the SE dynamical core is based on a continuous Galerkin finite-element method discretized on the gnomonic cubed-sphere and it supports static mesh-refinement (see Figure) .

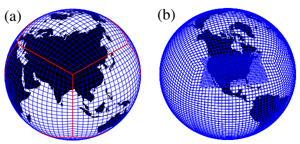


Figure 1. (a) The gnomonic equi-angular cubed-sphere grid that define the elements in CAM-SE. The red lines show the cubed-sphere panel edges. (b) A low resolution conformal mesh-refinement grid (elements) referred to as the CONUS-grid (Contiguous United States) used in CAM-SE.

In CESM1 the SE dynamical core was imported from **HOMME** (High-Order Methods Modeling Environment) as an external code base. In CESM2 the SE dynamical core resides in the CESM repository and has undergone numerous software engineering changes, science changes and performance optimizations described in separate sections below. The new version is referred to as **CAM-SE** (≡SE in **CESM2**) and its predecessor is referred to as **CAM-HOMME** (≡SE in **CESM1**).

NEW Dry-mass vertical coordinate

Consider a general terrain following vertical coordinate $\eta^{(d)}$ that is a function of dry air mass per unit area $M^{(d)}$

$$\eta^{(d)} = h(M^{(d)}, M_s^{(d)})$$

where $M_s^{(d)}$ is dry air mass in a column (per unit area) and

$$h(M_s^{(d)}, M_s^{(d)}) = 1 \text{ and } h(M_t^{(d)}, M_s^{(d)}) = 0$$

where $M_t^{(d)}$ is dry air mass (per unit area) above model top.

=> Model interface levels (index k+1/2) are defined as

$$M_{k+1/2}^{(d)} = A_{k+1/2} M_t^{(d)} + B_{k+1/2} M_s^{(d)}$$

where $A_{k+1/2}$ and $B_{k+1/2}$ are the 'usual' hybrid coefficients.

Note that by removing superscript (d) from the equations above (so that the dry variables represent moist variables), then the vertical coordinate is the usual **hybrid-pressure coordinate** widely used in hydrostatic global modeling

NEW Condensate loading

Define set of components of moist air

$$\mathcal{L}_{all} = \{`d', `wv', `cl', `ci', `rn', `sw'\}$$

referring to *dry* air, *w*ater *v*apor, *c*loud *l*iquid, *c*loud *i*ce, *r*ai*n*, and *snow*. Including condensates in the equations of motion has the following consequences:

NEW **Hydrostatic equation** includes condensates

$$p(z) = -g \int_{z'=z}^{z'=\infty} \rho \, dz',$$

$$= -g \int_{z'=z}^{z'=\infty} \rho^{(d)} \left(\sum_{\ell \in \mathcal{L}_{all}} m^{(\ell)} \right) dz'$$

where g is gravitational acceleration, $\rho^{(d)}$ is the density of dry air and total density is

$$\rho = \rho^{(d)} \left(\sum_{\ell \in \mathcal{L}_{all}} m^{(\ell)} \right)$$

where $m^{(l)}$ is (dry) mixing ratio for component l of moist air.

NEW **Energy conversion term in the thermodynamic equation**

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

where ω is vertical pressure velocity, T temperature and

$$c_p = \frac{\sum_{\ell \in \mathcal{L}_{all}} c_p^{(\ell)} m^{(\ell)}}{\sum_{\ell \in \mathcal{L}_{all}} m^{(\ell)}}$$

where $c_p^{(l)}$ is the heat capacity of component l at constant p, **includes condensates**. Same for pressure-gradient force.

NEW **Total energy equation includes condensates**

Integrate adiabatic and frictionless equations of motion over the entire domain:

$$\frac{\partial}{\partial t} \int_{\eta=0}^{\eta=1} \iint_S \left(\frac{\partial M^{(d)}}{\partial \eta^{(d)}} \right) \sum_{\ell \in \mathcal{L}_{all}} \left[m^{(\ell)} \left(K + c_p^{(\ell)} T + \Phi_s \right) \right] dA d\eta^{(d)} = 0$$

where $K=0.5 \times \mathbf{v}^2$ is kinetic energy (per unit mass), and Φ_s is surface geopotential.

NEW Modified hyperviscosity

Hyperviscosity applied on **approximate pressure surfaces**

$$\nu \nabla^4 \Xi = \nu \nabla^4_{\eta_d} - \nu \frac{\partial \Xi}{\partial M^{(d)}} \nabla^4_{\eta_d} M^{(d)}, \qquad \Xi = \mathbf{v}, T$$

and for $\Delta M^{(d)}$ (=dry layer mass) only apply hyperviscosity to difference between $\Delta M^{(d)}$ and **reference dry layer mass**.

NEW Reduced damping

Viscosity coefficients have been reduced significantly:

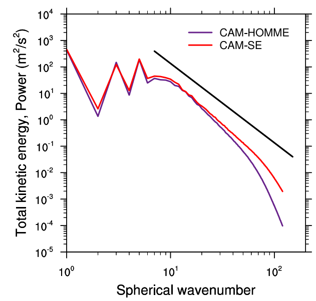


Figure Total kinetic energy spectrum of the horizontal winds at the 200 hPa level in CAM-HOMME and CAM-SE at 1° horizontal resolution, computed as the mean spectra from 30 days of 6-hourly instantaneous spectra. Black line is the κ^{-3} reference scaling, where κ is spherical wave-number.

NEW Improved performance

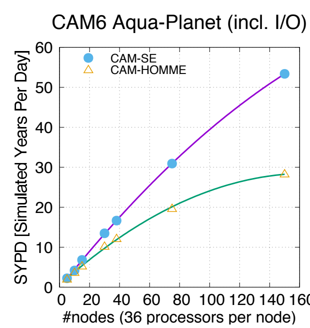


Figure Throughput in terms of simulated years per day for CAM6 Aqua-planet including standard I/O as a function of number of nodes on NCAR's Cheyenne supercomputer.. Note that for the right-most data-points there is only 9 physics columns per processor.

CAM6 Aqua-planet simulation

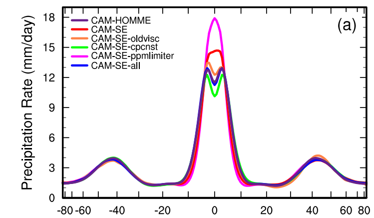
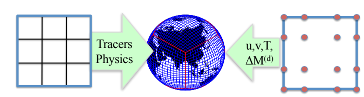


Figure 4.5 year average zonally averaged total precipitation rate as a function of latitude for CAM6 Aqua-planet simulations.

CAM-SE	= new SE dynamical core (CESM2)
CAM-HOMME	= old SE dynamical core (CESM1)
-oldvisc	= CAM-SE with CAM-HOMME viscosity coefficients
-cpcnst	= CAM-SE with $c_p = c_p^{(d)}$ (CAM-HOMME setting)
-ppmlimter	= CAM-SE with limiter on the vertical remapping of wind components
-all	= CAM-SE with the 3 above changes

NEW Optional finite-volume tracer transport and finite-volume physics grid



Tracer transport with CSLAM (Conservative Semi-Lagrangian Muli-tracer) scheme consistently coupled to SE (*Mon. Wea. Rev.* paper: DOI:10.1175/MWR-D-16-0258.1).

State passed to physics is integrated over (CSLAM) finite-volumes (manuscript in preparation).

Reference

Lauritzen, P.H. and co-authors (2017): NCAR CESM2.0 release of CAM-SE: A reformulation of the spectral-element dynamical core in dry-mass vertical coordinates with comprehensive treatment of condensates and energy: *J. Adv. Model. Earth Syst.*, submitted.

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