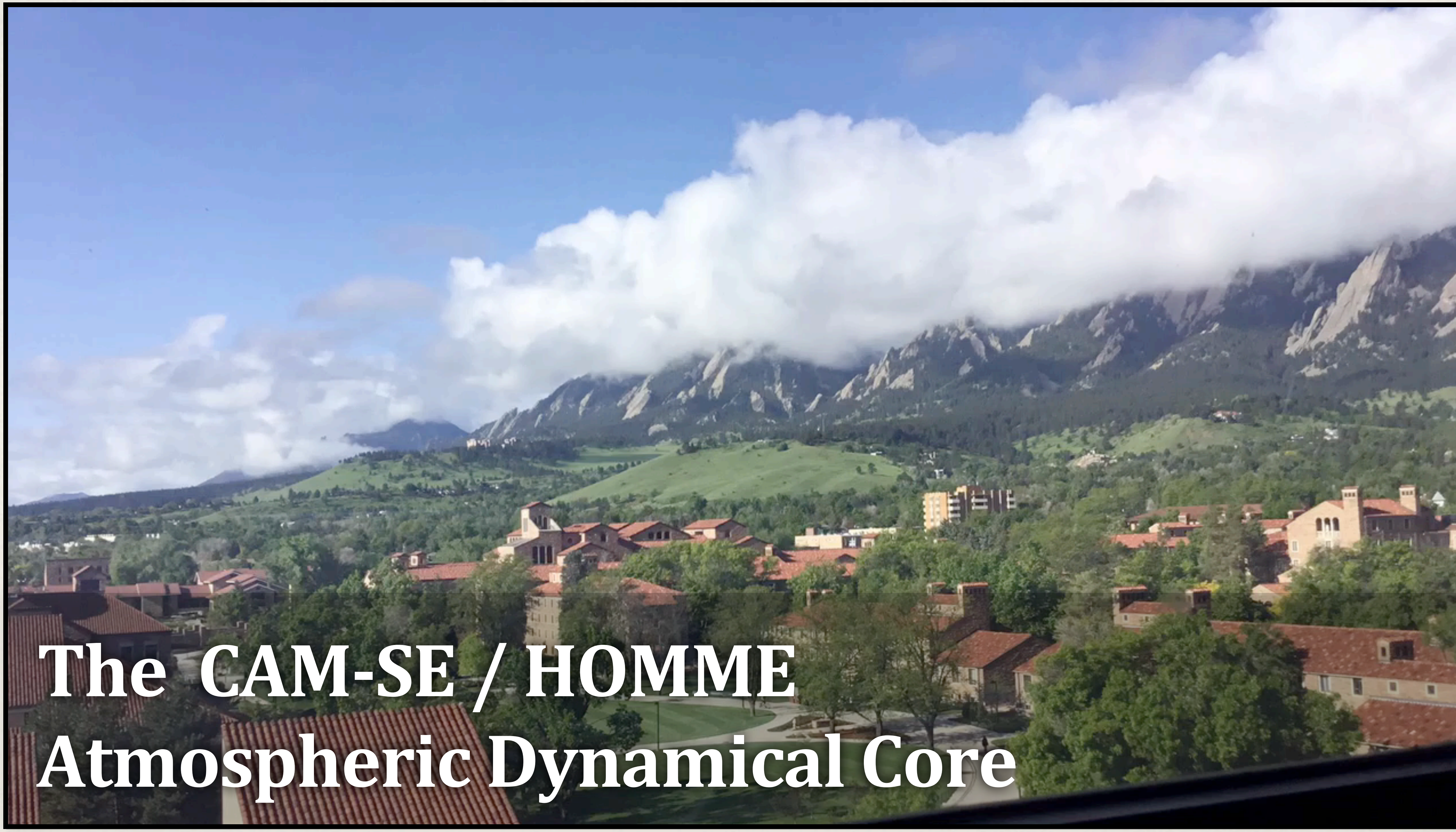

The CAM-SE / HOMME Atmospheric Dynamical Core

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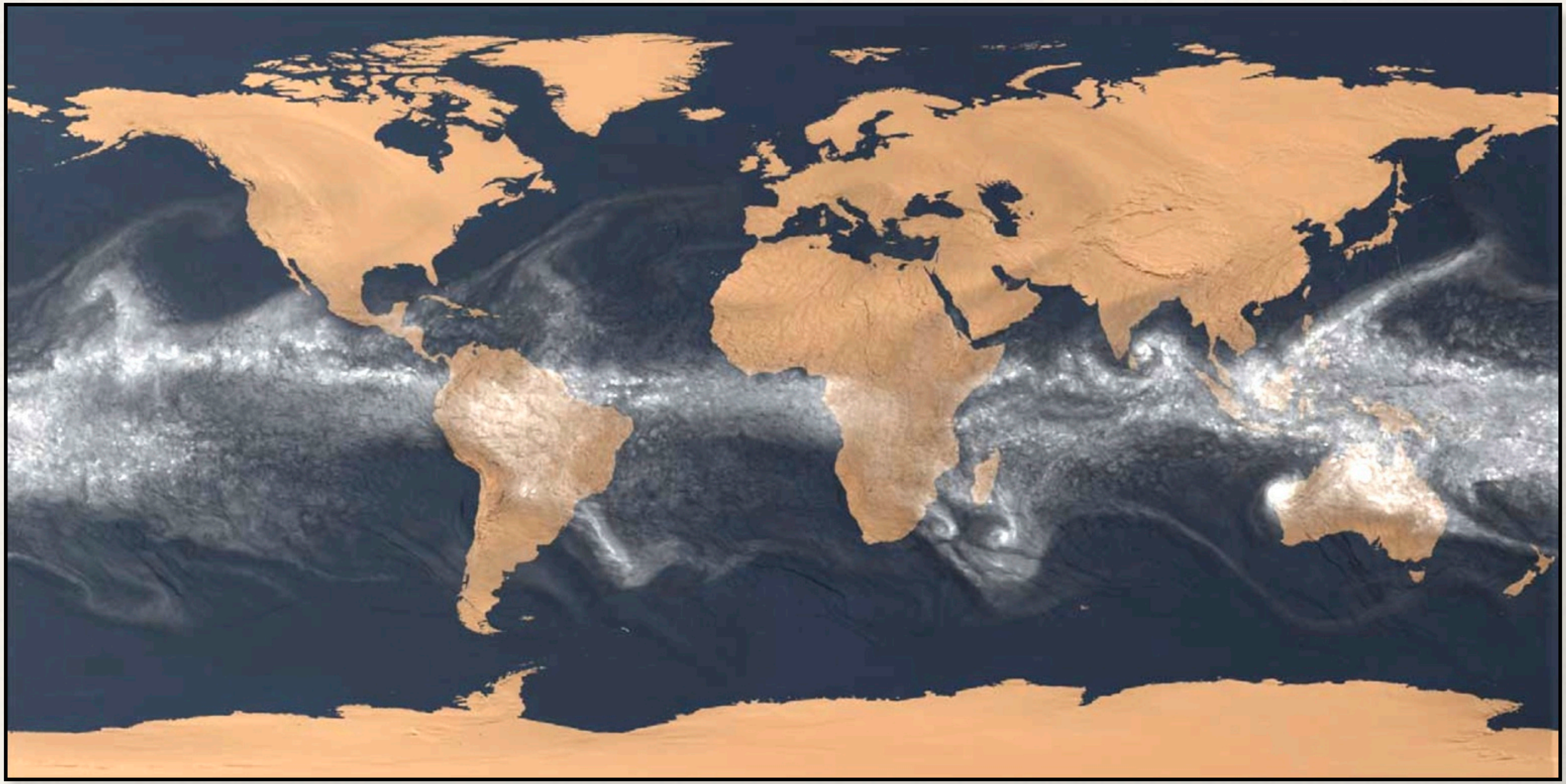
Colin Zarzycki National Center for Atmospheric Research

DCMIP 2016 Summer School *Monday, June 12th, 12:00pm*

An Atmospheric Dynamical Core in CESM and ACME

CESM ⟵ CAM-SE /HOMME ⟶ ACME



CAM-SE / HOMME is an **atmospheric dynamical core** used in both the **CESM** and **ACME** global Earth-system models

CAM-SE Design Goals

Successor to CAM-FV

parallel scalability

conservation of mass, energy vorticity

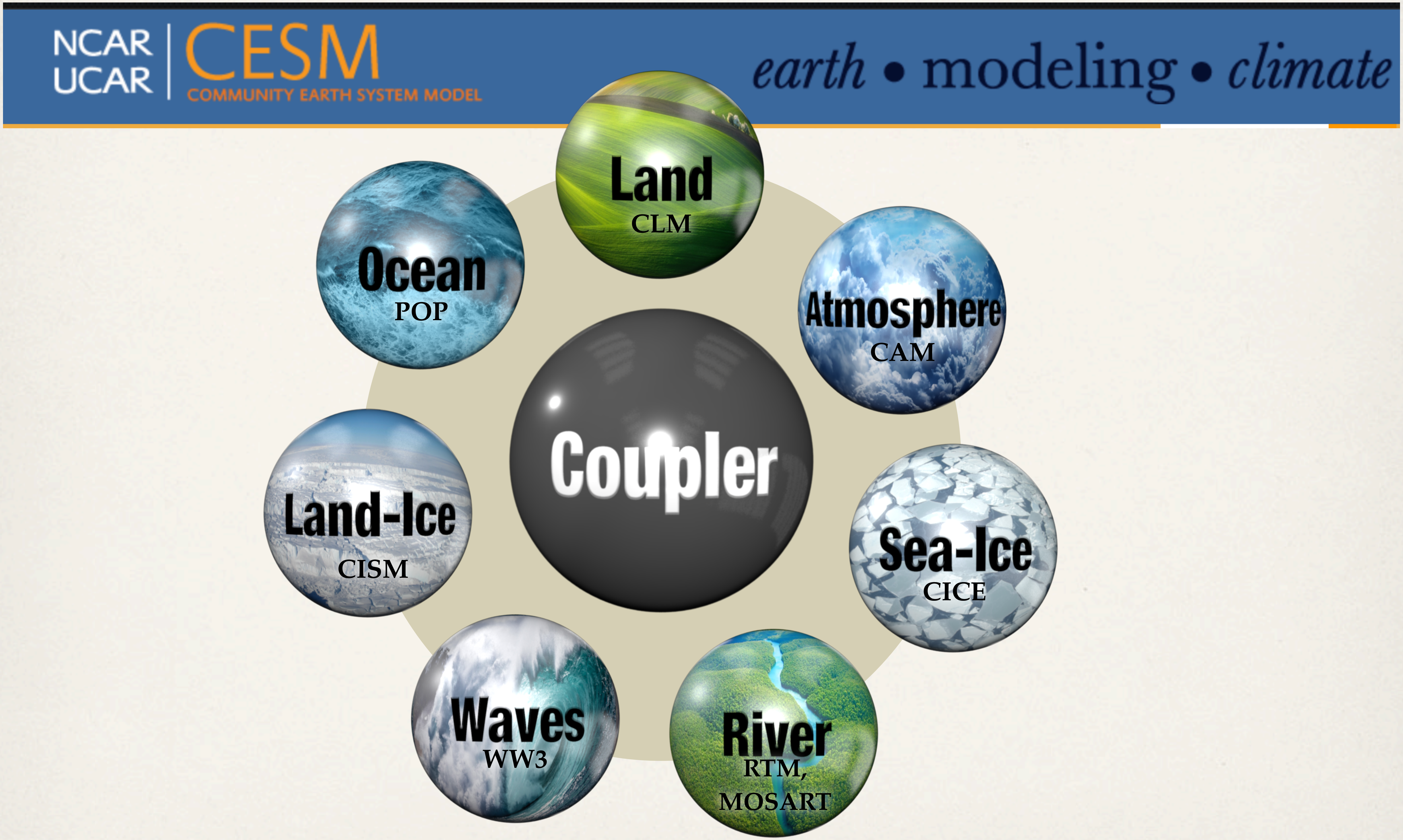
no polar filtering

vector invariant momentum equation

compatibility

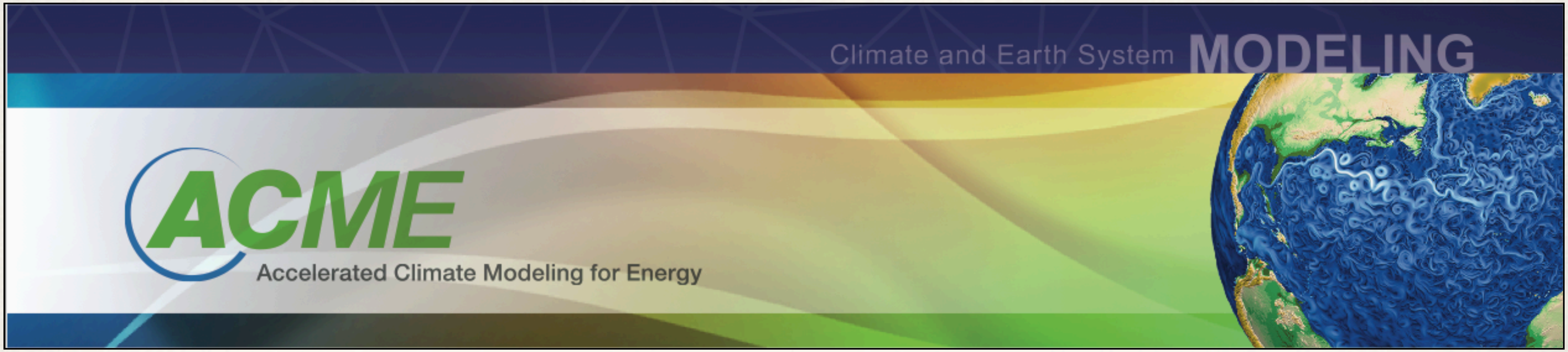
CAM-SE was designed from ground up to achieve excellent **parallel scalability** relative to it predecessor CAM-FV, as well as local **conservation of mass, energy, and vorticity**. Significant changes include the use of the cubed sphere grid to **avoid polar filtering**, and the **vector invariant form** of the momentum equation. Most other features of CAM-FV were retained for **compatibility**.

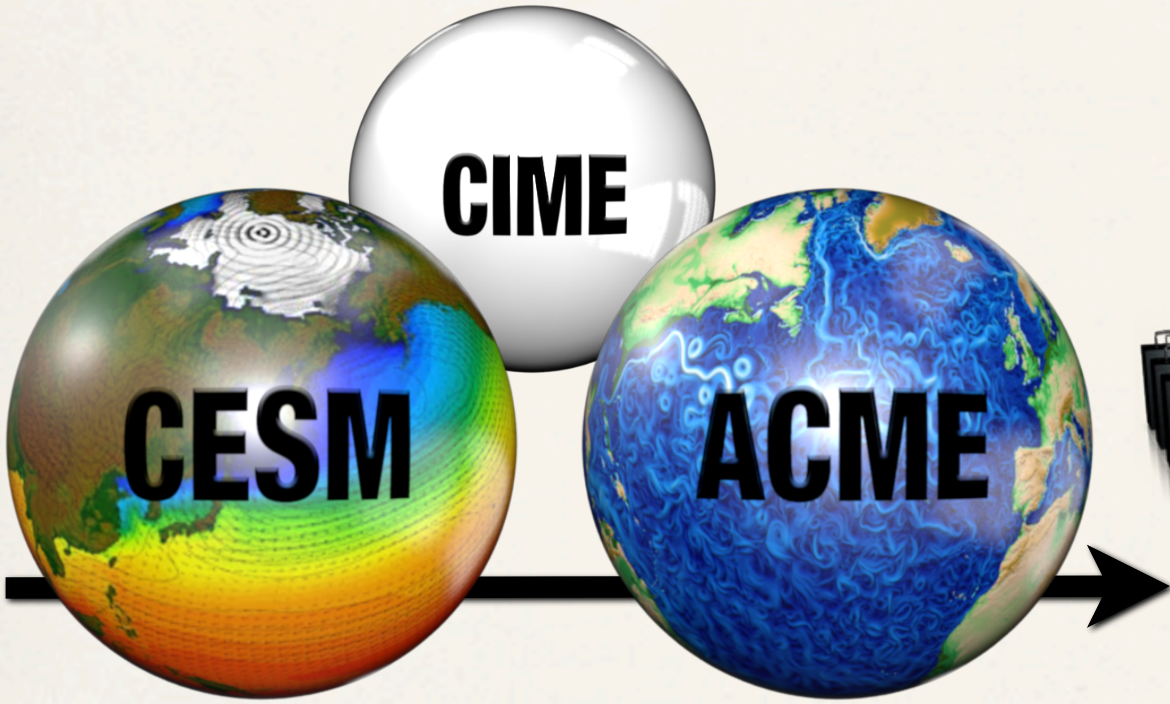
The Community Earth-System Model



CESM stands for the **Community Earth System Model**, which is a **global climate model** composed of multiple components representing **functional subsystems** of the Earth-system, communicating with each other through a **coupler**.

The ACME Climate Model



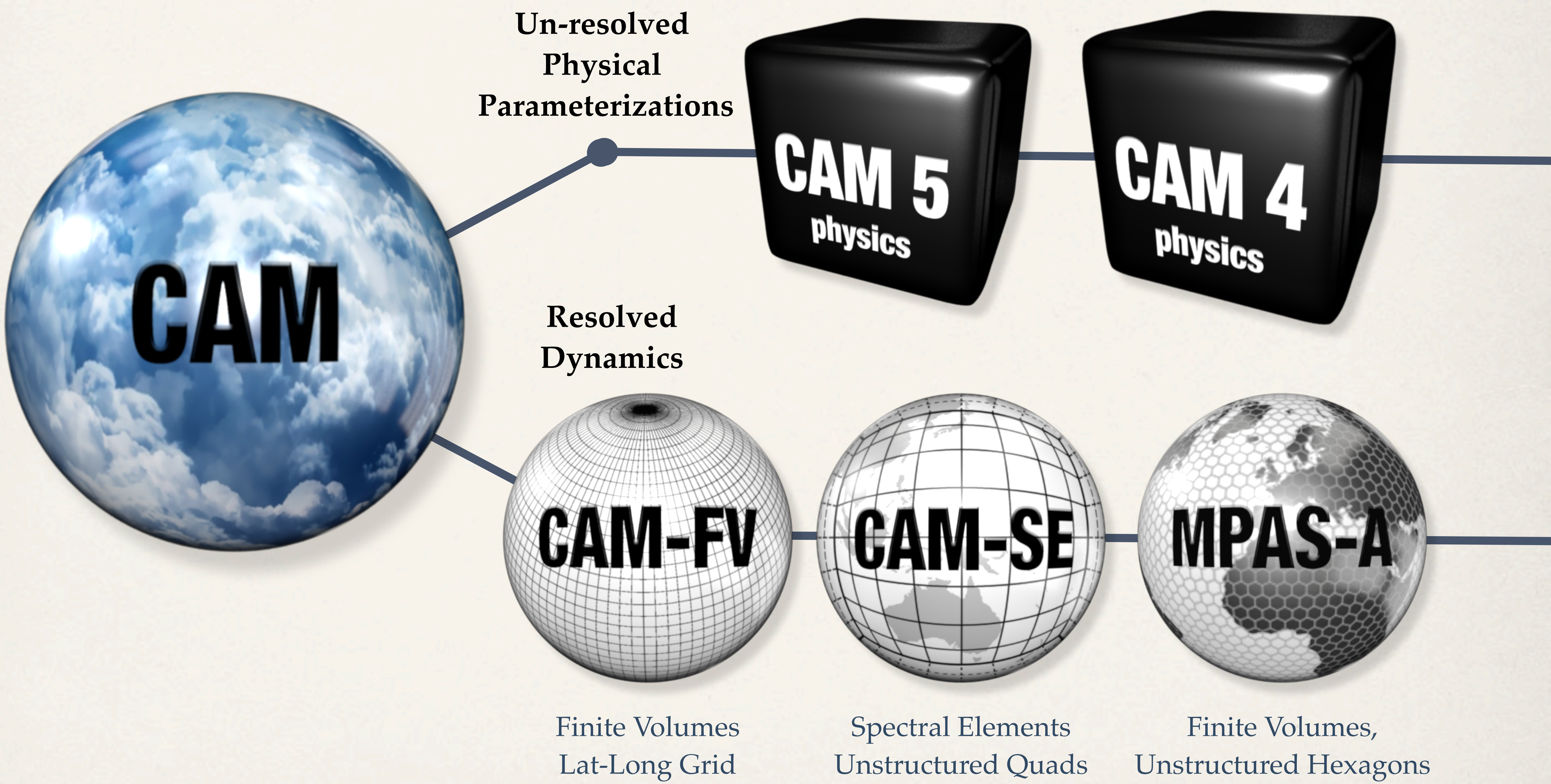


DOE Leadership Class Machines
2015-2050 Timescale

ACME is a Department of Energy Model, that **began as a branch of CESM**.
It is being **customized** to satisfy **DOE specific goals** including **high-end performance** on DOE's next generation Leadership Class Supercomputers, with a focus on **near term (-2050) climate projections**.

CAM Atmosphere Component: Physics + Dynamics

configure option -dyn se



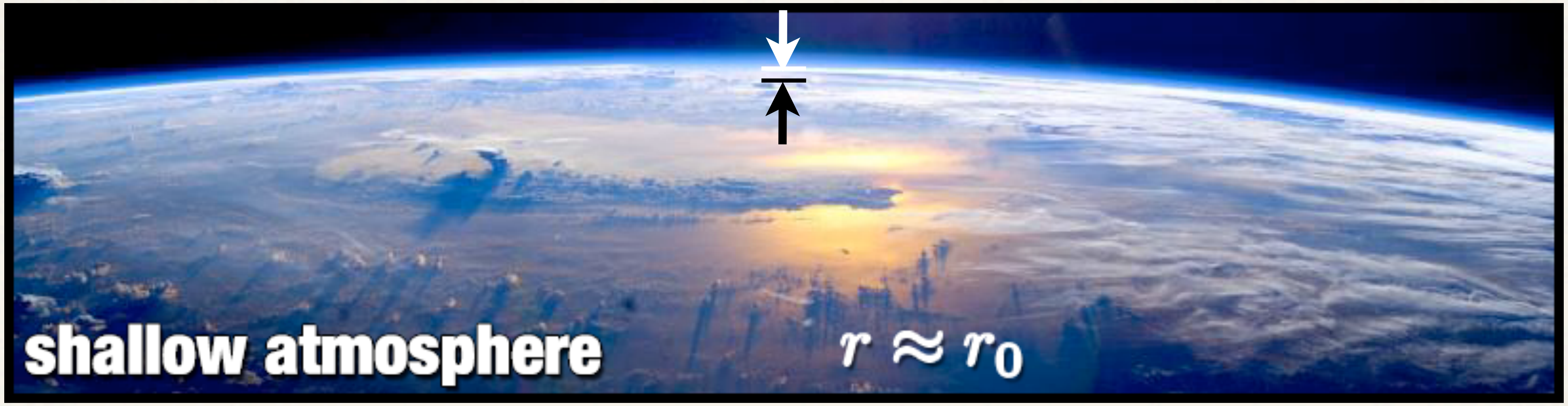
Within CESM, the **CAM** atmosphere component consists of a **physical parameterization package** coupled with one of several possible **dynamical cores** (including CAM-SE)

HOMME: The High Order Method Modeling Environment

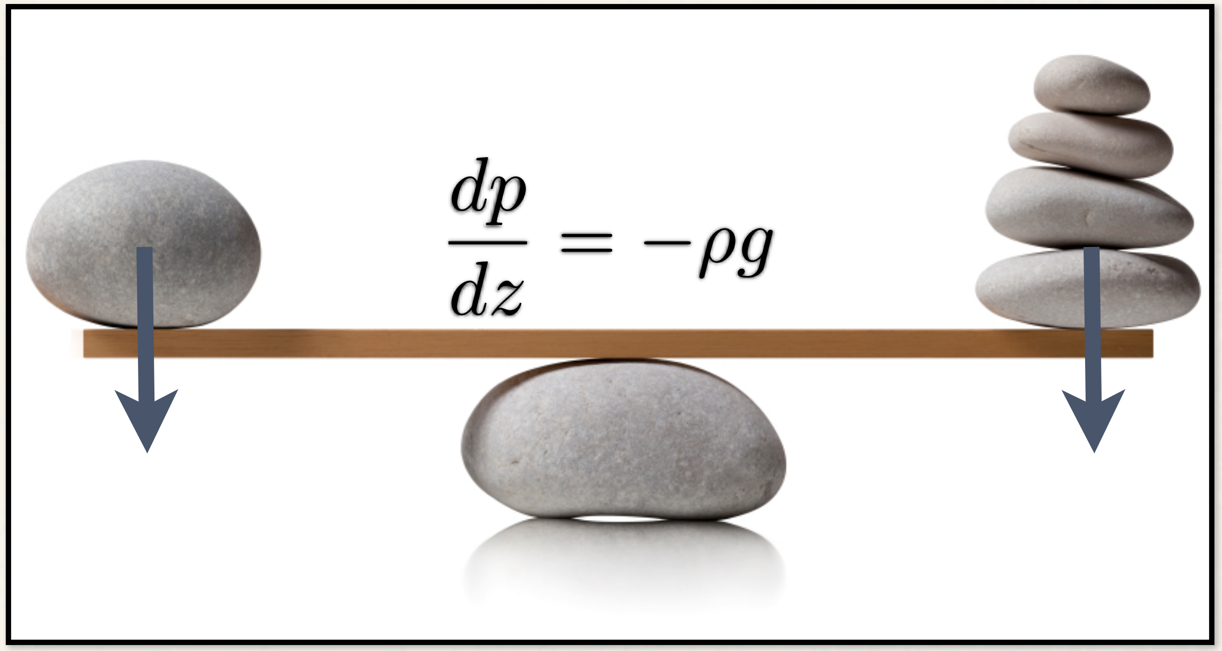
```
configure option –target preqx (ACME only)
```

The CAM-SE dy-core is part of **HOMME**, the High Order Method Modeling Environment, which is a collection of **shared Fortran modules** together with a **collection of dynamics targets**. The **CAM-SE** dynamical core **combines** the **shared modules** + the explicit primitive equation **PREQx target**. HOMME also contains targets for **shallow water** solvers, and other **experimental solvers** under development.

PREQx: Approximations



Spherical Geoid $\Phi \approx gz$



Hydrostatic Balance

The **PREQx target** in CAM-SE simulates the **primitive equations of motion** using the shallow atmosphere, spherical geoid, and hydrostatic balance **approximations** to improve throughput at hydrostatic scales.

PREQx: Prognostics

horizontal wind

$$\partial_t \mathbf{u} + (\zeta + f)\hat{\mathbf{k}} \times \mathbf{u} + \nabla(\frac{1}{2}\mathbf{u}^2 + \Phi) + \dot{\eta}\partial_\eta \mathbf{u} + \frac{RT_v}{p}\nabla p = 0$$

temperature

$$\partial_t T + \mathbf{u} \cdot \nabla T + \dot{\eta}\partial_\eta T - \frac{RT_v \omega}{c^\star p} = 0$$

tracer mixing ratio

$$\partial_t (mq) + \nabla \cdot (mq\mathbf{u}) + \partial_\eta (mq\dot{\eta}) = 0$$

surface pressure

$$\partial_t p_s + \int_{\eta_t}^{1} \nabla \cdot (m\mathbf{u}) d\eta = 0$$

Prognostic equations **predict the time evolution** of **zonal** and **meridional wind velocity** u,v the atmospheric **temperature** T the **hydrostatic surface-pressure** ps and **mixing ratios**, for tracking water vapor and other tracers.

PREQx: Diagnostics

vertical pressure-velocity

$$\omega = \dot{p} = \mathbf{u} \cdot \nabla p - \int_{\eta_t}^{\eta} \nabla \cdot (m\mathbf{u}) d\eta'$$

vertical flux

$$m\dot{\eta} = B(\eta) \int_{\eta_t}^{1} \nabla \cdot (m\mathbf{u}) d\eta' - \int_{\eta_t}^{\eta} \nabla \cdot (m\mathbf{u}) d\eta'$$

geopotential

$$\Phi = \Phi_s + \int_{\eta}^{1} \frac{RT_v}{p} m \, d\eta'$$

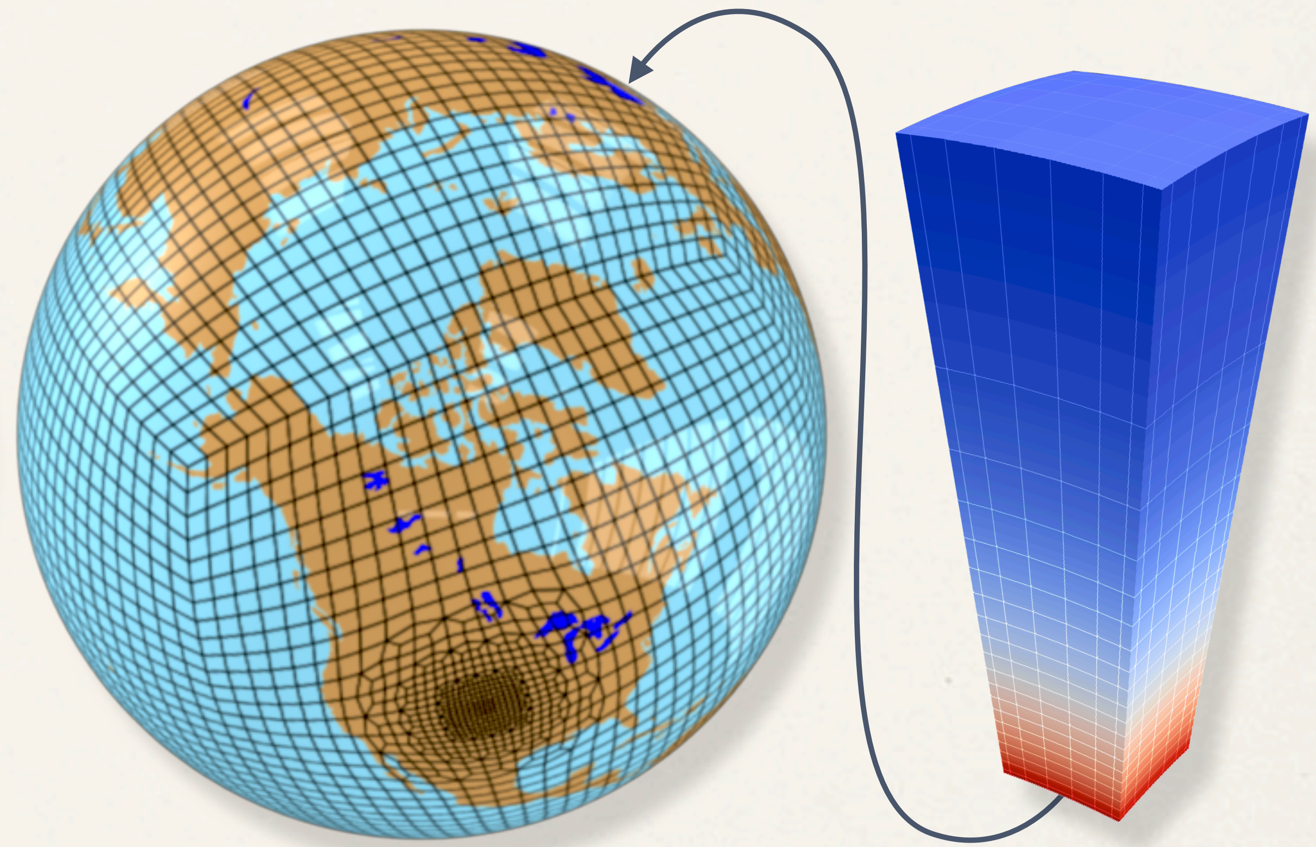
Diagnostic equations compute **vertically integrated quantities** needed **to close** the prognostic equations. The **geopotential height** is obtained from a column integral of the **hydrostatic balance** condition, while the **pressure velocity** (omega) and the **vertical mass flux** are obtained from column integration of the **continuity equation**.

Horizontal Grid: Unstructured Quadrilaterals

Uniform Resolution
Cubed Sphere

Variable Resolution
Conforming Quadrilaterals

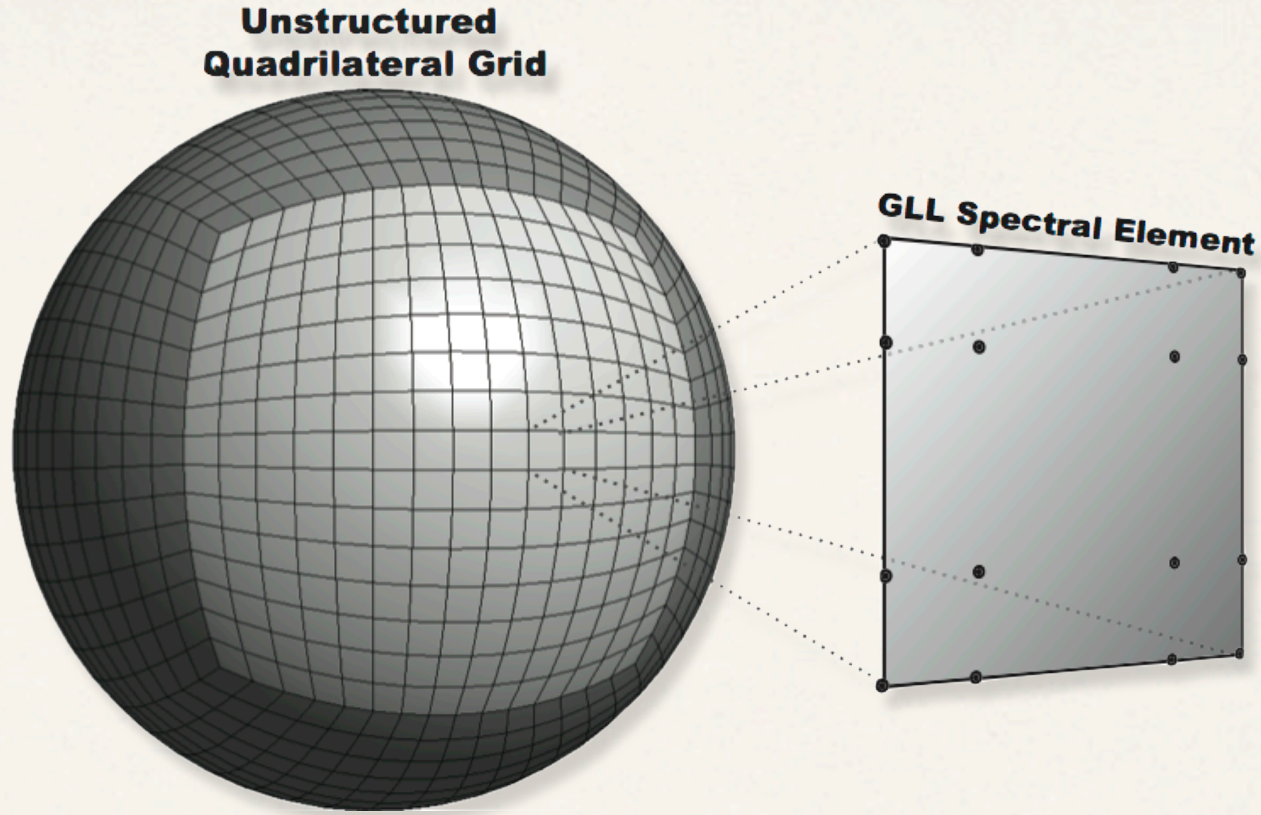
Vertical column
at each quad



`configure option: -hgrid ne30np4`

CAM-SE partitions the globe as an **unstructured horizontal grid** of **conforming quadrilateral elements**. The elements are arranged in a **cubed-sphere configuration** for **uniform grid** simulations, but can vary in size and shape for **variable-resolution simulations**. Each quadrilateral element extends vertically in a column.

Horizontal Discretization: 4th Order Nodal SE



NE elements per cube edge

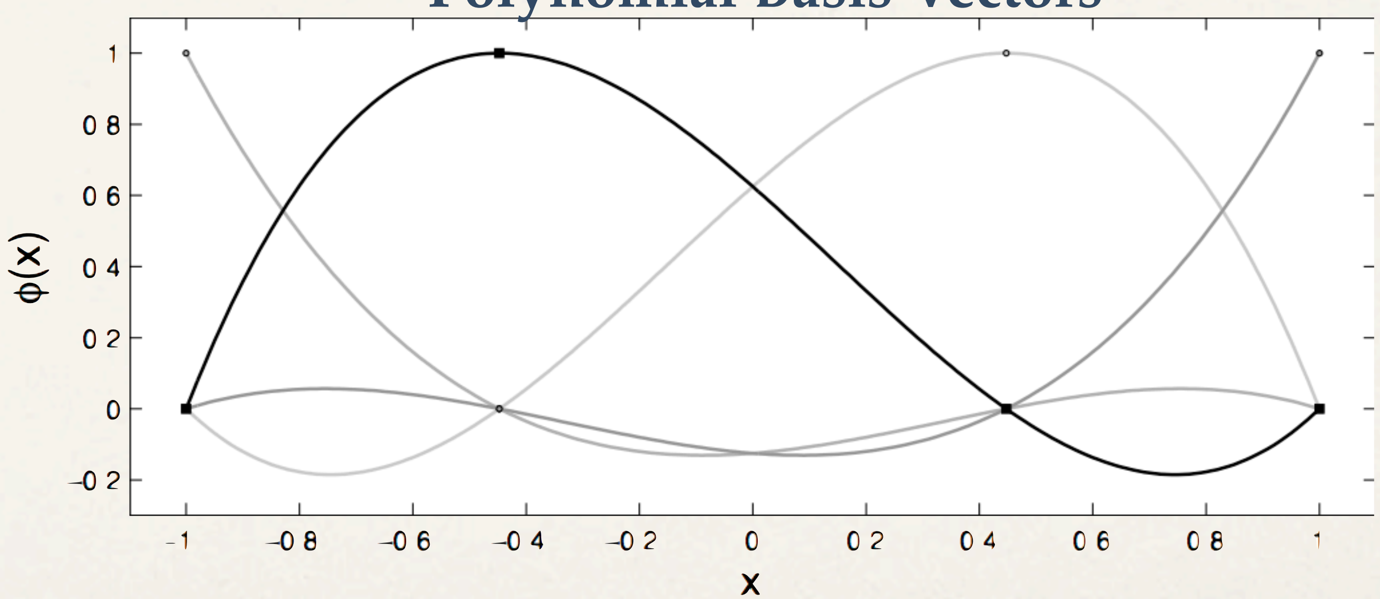
4 node points per element edge

4th order Lagrange interpolating polynomials

Nodes located at GLL quadrature points

All fields co-located at the same horizontal node points

Polynomial Basis Vectors

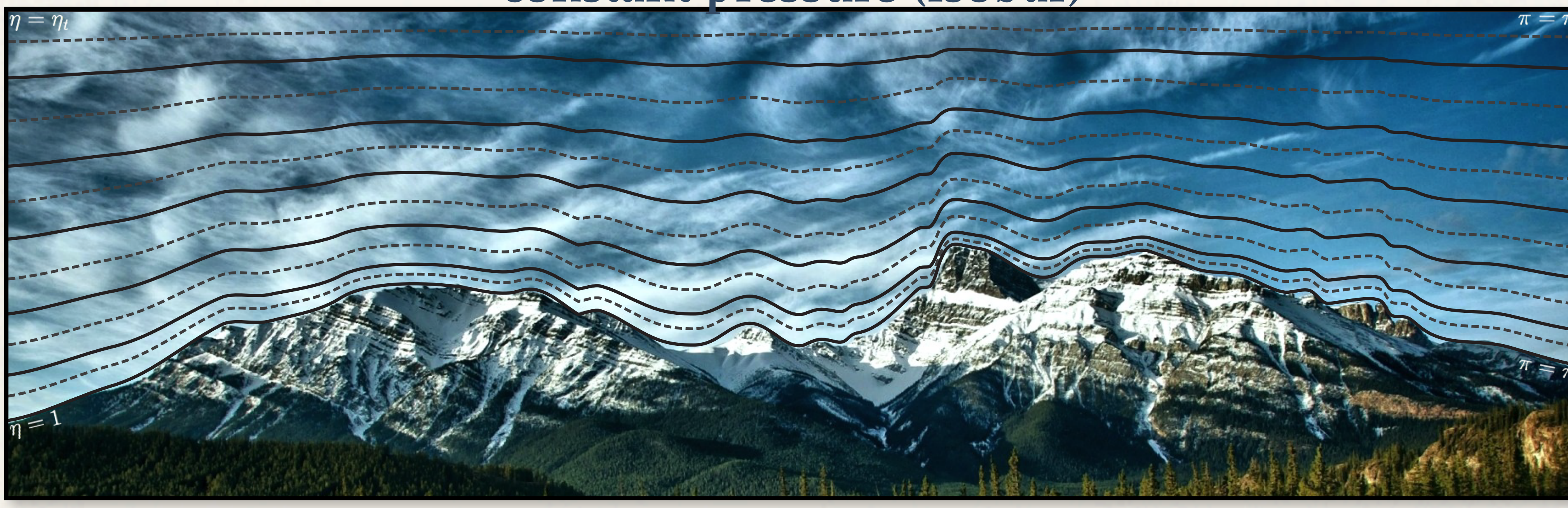


In the cubed sphere configuration, there are **NE elements per cube edge** and **4 nodes per element edge**. Within an element, prognostic and diagnostic **fields are approximated** by **4th order** interpolating **polynomials**. In the horizontal, all **fields are co-located** in the sense that they all use the same nodal polynomial basis vectors.

Vertical Mesh: 30 Hybrid Pressure/Terrain-Following Levels

constant pressure (isobar)

30 - 72 levels



terrain-following surface pressure

pressure at constant eta

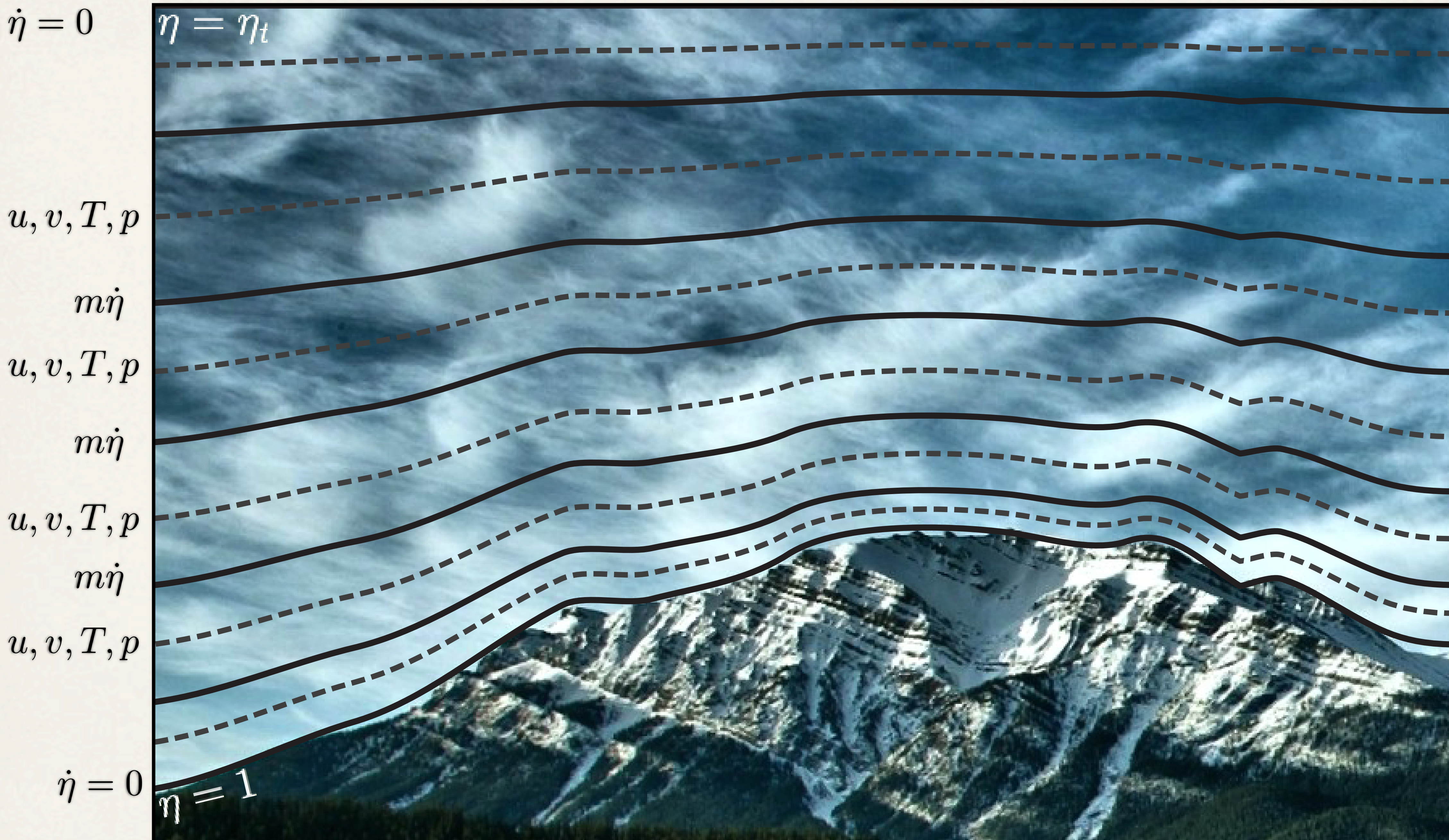
$$p = A(\eta)p_0 + B(\eta)p_s$$

pressure at top and bottom

$$p(1) = p_s \quad p(\eta_t) = A_t p_0$$

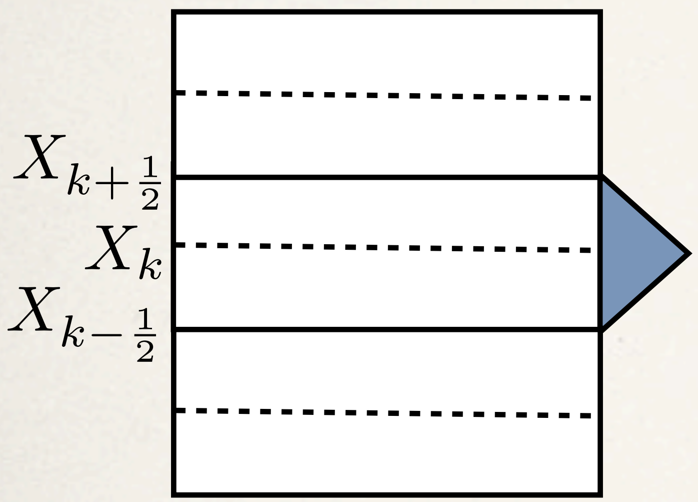
Each element contains ~**30 vertical layers** spaced **unevenly** in **η coordinates**.
η is a **hybrid vertical coordinate** that transforms smoothly from a **pure pressure coordinate at the top** (η~0) to a **terrain-following** surface pressure coordinate at the **bottom** (η=1).

Vertical Discretization: 2nd Order FD, Lorenz Staggering



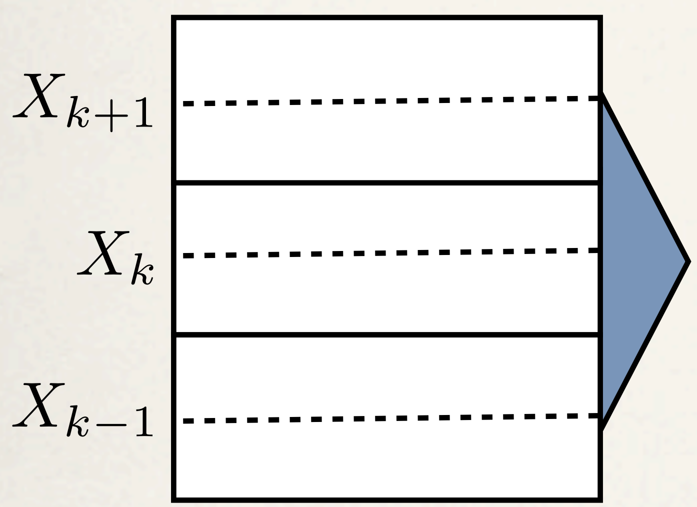
In CAM-SE, vertical terms are discretized using **2nd order mimetic finite differences**, as described in [**Simmons and Burridge 1981**]. **Lorenz staggering** is used, with all variables co-located on layer midpoints, except for the **vertical mass flux** which is defined **on layer interfaces**.

Vertical Discretization: Mimetic FD Operators



centered differences: interfaces to midpoints

$$\delta_\eta(X)_k = (X_{k+1/2} - X_{k-1/2})/(\eta_{k+1/2} - \eta_{k-1/2})$$



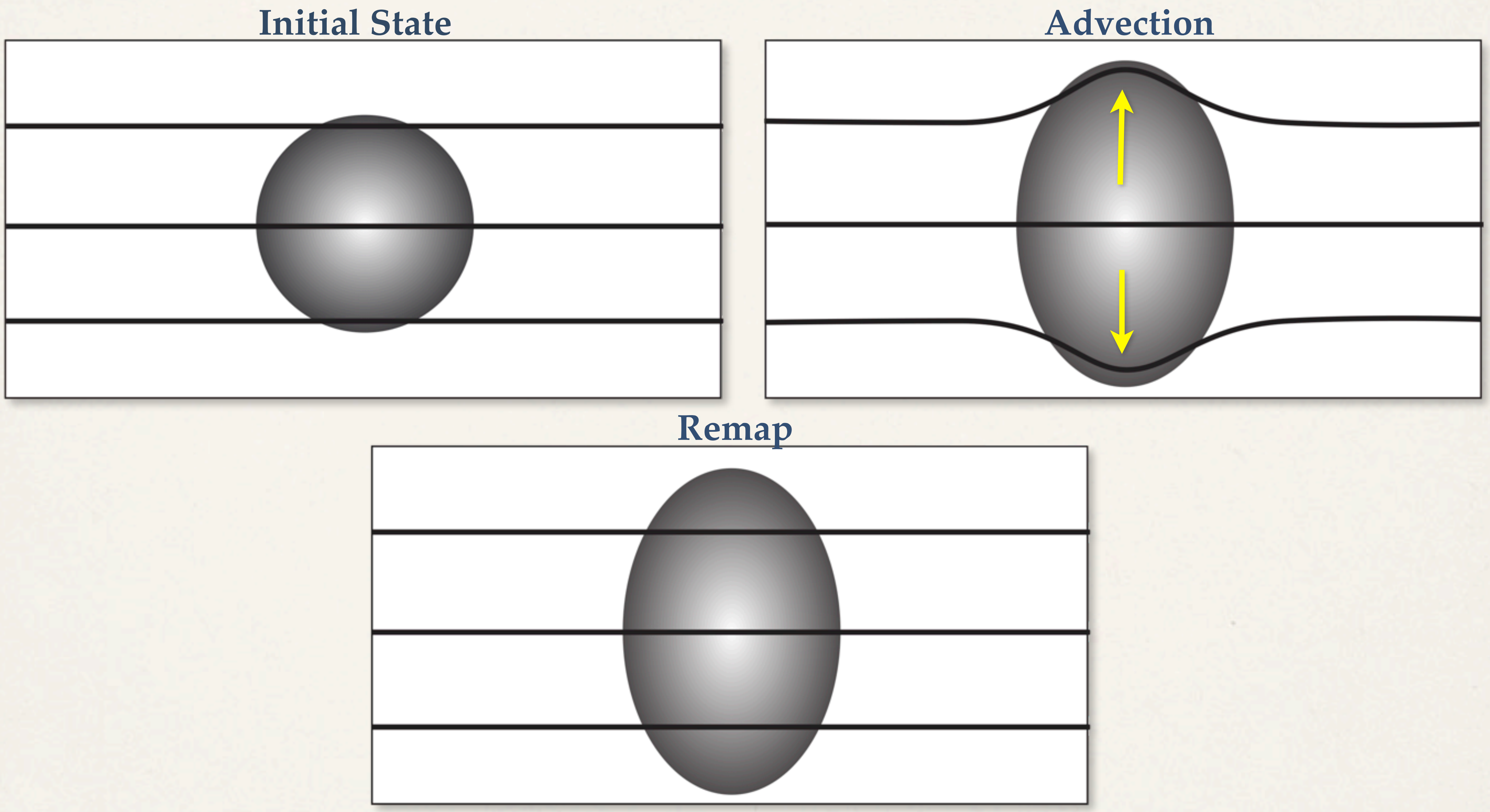
mimetic centered differences: midpoints to midpoints

$$\overline{\dot{\eta}\delta_\eta}(X)_k = \frac{1}{2m_k\Delta\eta_k}\left[(m\dot{\eta})_{k+1/2}(X_{k+1}-X_k) + (m\dot{\eta})_{k-1/2}(X_k-X_{k-1})\right]$$

Two vertical FD operators are defined. The first is a 2nd order central difference **from layer interfaces to layer midpoints**. The second is a **mimetic operator** that maps **midpoints values to layer midpoints**, with a form chosen to maintain discrete **conservation of mass and energy.**

Floating Lagrangian Coordinates with Remap

namelist parameters:rsplit, vert_remap_q_alg



Tracers advection is performed using vertical **floating Lagrangian coordinates** [Lin2004] that are periodically **remapped** back to **fixed eta levels**. Floating Lagrangian with remap is also the **default** for the **dynamics** prognostics. The remap frequency is adjustable.

Limiter options

`namelist parameters: se_limiter_option`

CAM dynamics limiter options

- **se_limiter_option = 0: no limiter**
- **se_limiter_option = 4: sign preserving limiter**
- **se_limiter_option = 8: monotone limiter**

`(Guba-2014-JCP: Optimization-based limiters for the spectral element method)`

A limiter may be applied at the same time as the vertical remap by setting the se_limiter_option to 0,4, or 8.
Limiter 8 is the **default**, **monotone limiter** described in the 2014 paper by Guba et. al

Dissipation: Hyperviscosity

`namelist parameters:nu, nu_s, nu_p, hypervis_order=2, nu_top`

hyperviscosity, vector field

$$\partial_t \mathbf{u} = -\nu \nabla^4 \mathbf{u}$$

hyperviscosity, 2 step expansion

$$\partial_t \mathbf{u} = -\nu \left(\nabla(\nabla \cdot \mathbf{f}) - \nabla \times (\nabla \times \mathbf{f}) \right)$$

$$\mathbf{f} = \nabla(\nabla \cdot \mathbf{u}) - \nabla \times (\nabla \times \mathbf{u})$$

Numerical noise and **oscillations** are **controlled** by applying high frequency dissipation **using hyperviscosity**.
A **vector identity** of the **Laplacian** is employed to **reduce** the number of **data communications** from 4 **to 2**.
One may choose to employ **ordinary viscosity** instead by setting hypervis_order=1.
An optional **top of the model viscosity** operator may also be used to reduce reflections.

Time Discretization

`namelist parameters:tstep_type, dtime`

tracer advection: RK2-SSP3

$$u^{(1)} = u^n + \Delta t/2L(u^n)$$
$$u^{(2)} = u^{(1)} + \Delta t/2L(u^{(1)})$$
$$u^{(3)} = u^{(2)} + \Delta t/2L(u^{(2)})$$
$$u^{n+1} = u^n/3 + 2/3u^{(3)}$$

dynamics time integration options

- **tstep_type = 1: RK2 followed by leapfrog (2nd order)**
- **tstep_type = 2: RK2-SSP3**
- **tstep_type = 3: RK3**
- **tstep_type = 4: Kinnmark and Gray RK4**
- **tstep_type = 5: Kinnmark and Gray RK5 (3rd order)**

Tracer advection is integrated in time using a 3 stage 2nd order accurate **SSP Runge Kutta** scheme, in order to maintain tracer **monotonicity**. Various explicit Runge-Kutta schemes are available for the dynamics routines, with a modified leap-frog method used as the default.

Physics-Dynamics Coupling

`namelist parameters:ftype, se_nsplit`

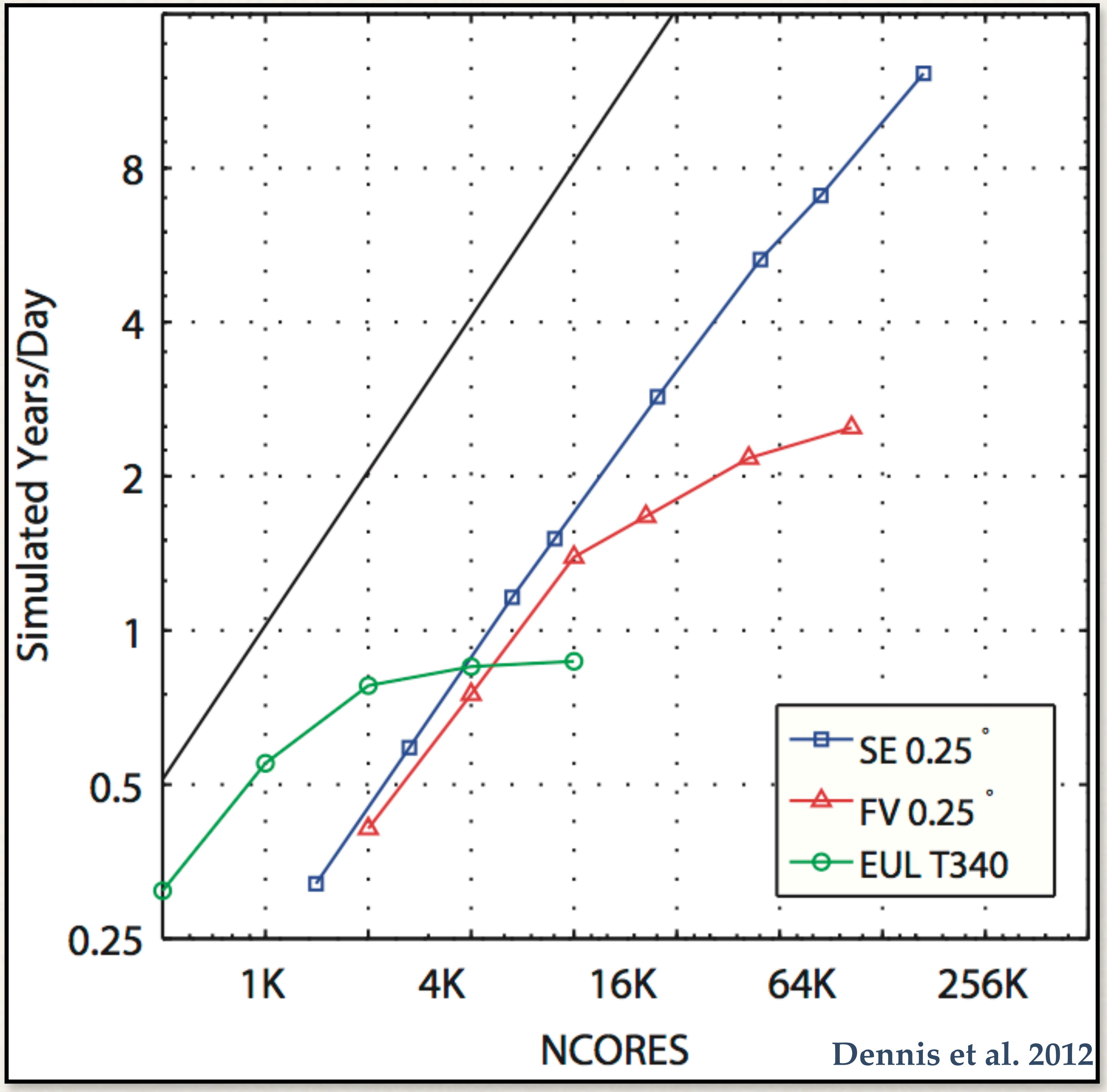
CAM physics forcing options

- **ftype = 0: tendencies applied to each dynamics timestep**
- **ftype = 1: adjustment at end of physics timestep**
- **ftype = 2: hybrid. (Q,ps) adjustment, (u,v,T) tendencies**

`se_nsplit = # dynamics steps to take per physics step`

The **physics and dynamics** are applied in a **time-split** manner, with the **dynamics sub-cycled** multiple times relative to the physics as controlled by the **se_nsplit** option. The forcing terms from the physics package may be applied as an **adjustment** at the end of each physics step, or divided into multiple smaller **tendencies** at the end of each dynamics step, or a **hybrid** of the two.

Parallel Scalability at Large Core Counts



CAM-SE exhibits **near-optimal scaling** on simulations using **100k's of processors**. This is enabling users to complete **high resolution** atmospheric simulations with **rapid turn-around times** on high-end machines. However **CAM-FV may be faster** for **lower resolution simulations**, or when using **fewer cores**.

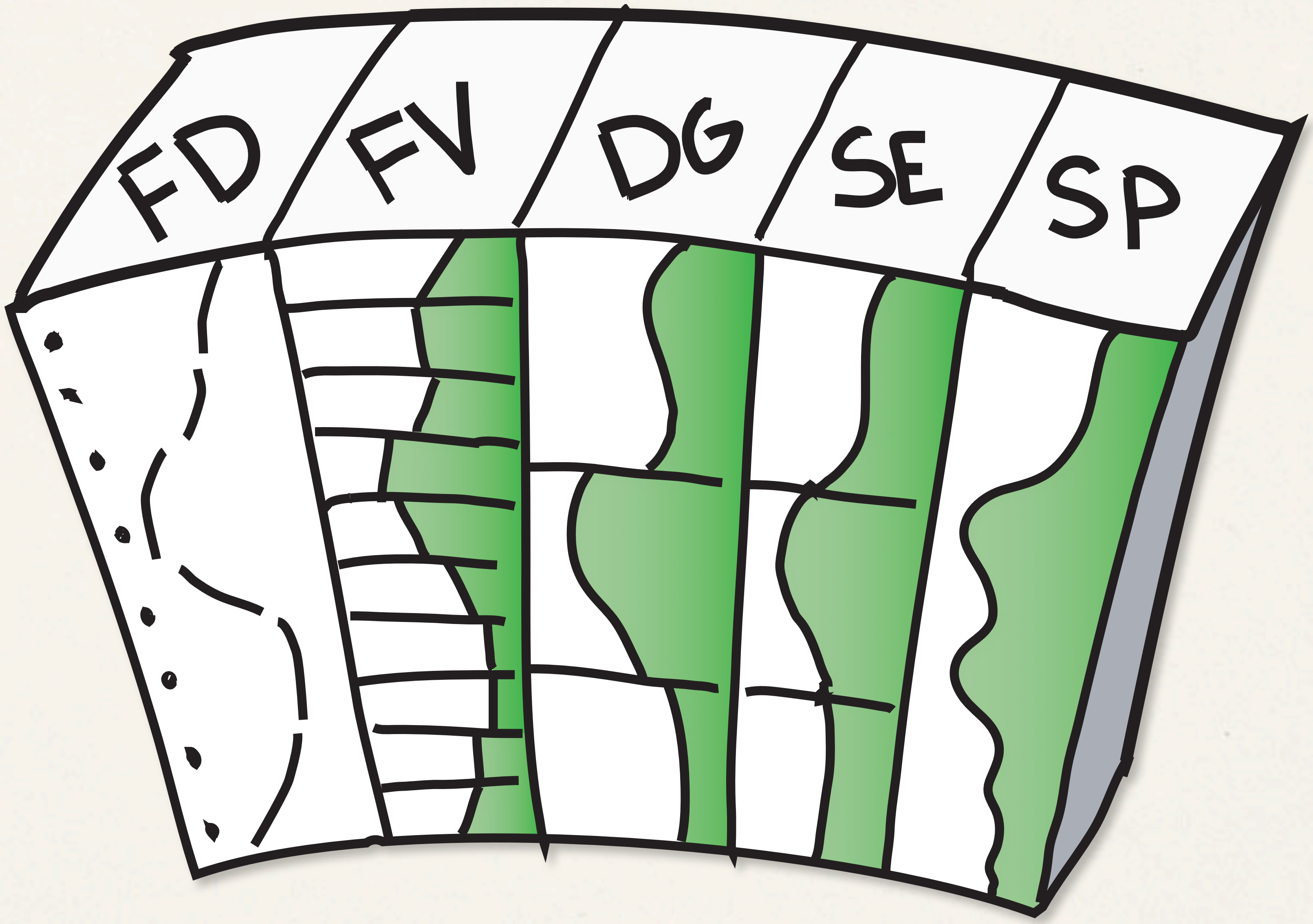
Experimental Targets in HOMME

My research focuses on the development of **experimental solvers** in the HOMME framework, including a **nonhydrostatic dynamical core**, and a primitive equation solver with a **high-order vertical discretization**.

Vertical Discretization at High Resolution

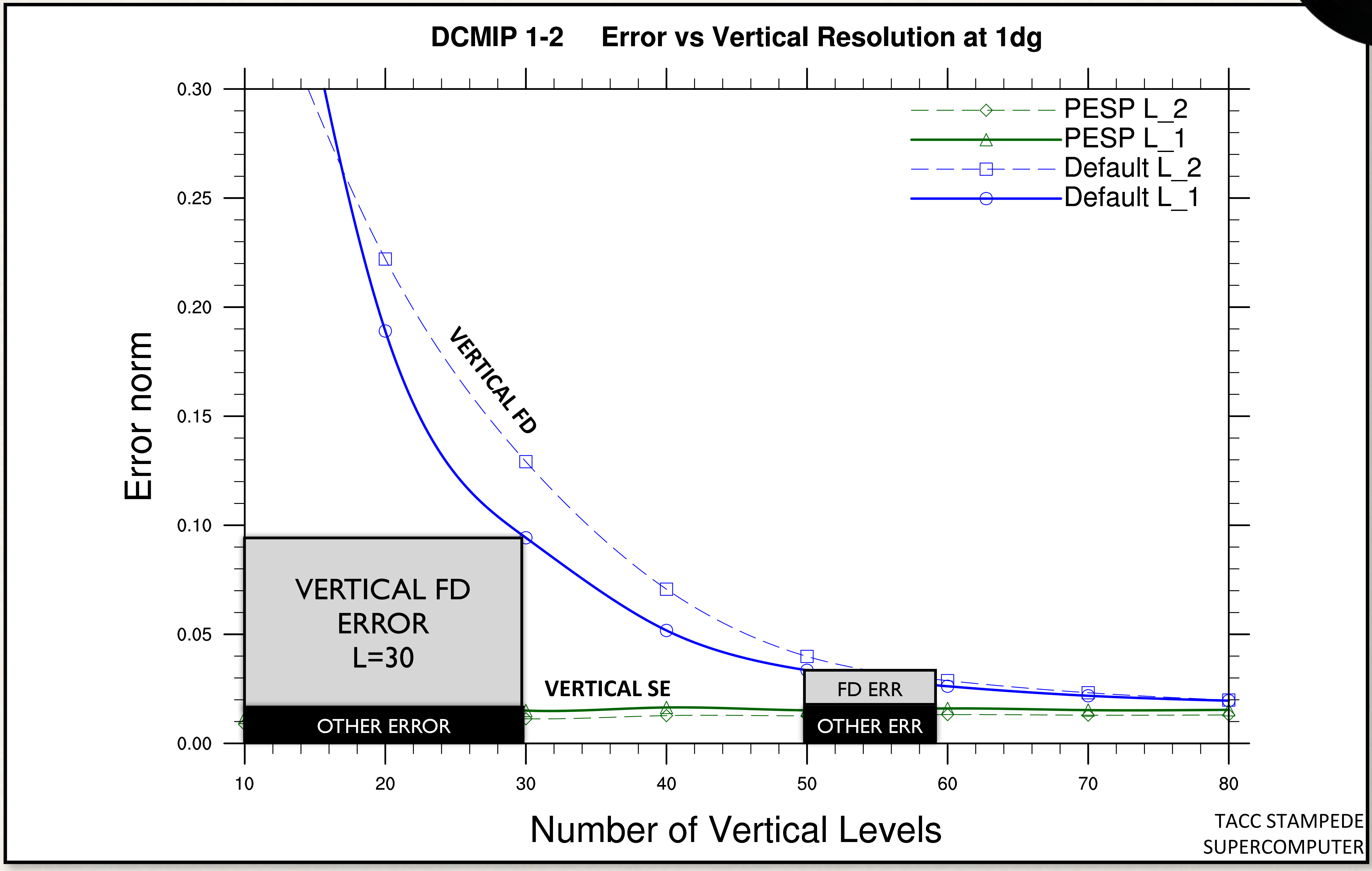
Recently a **debate** ensued at NCAR with some researchers calling for **doubling the vertical resolution** to **resolve** important **phenomena**, while others objected, as this would **double the cost** of their simulations. This debate inspired us to look for an **alternative**.

High Order Vertical Representation



In the long run as resolution grows, **2nd order** vertical accuracy can't keep up with the **4th order horizontal** representation. So, we are exploring alternative discretizations like **spectral elements** and DG **in the vertical.**

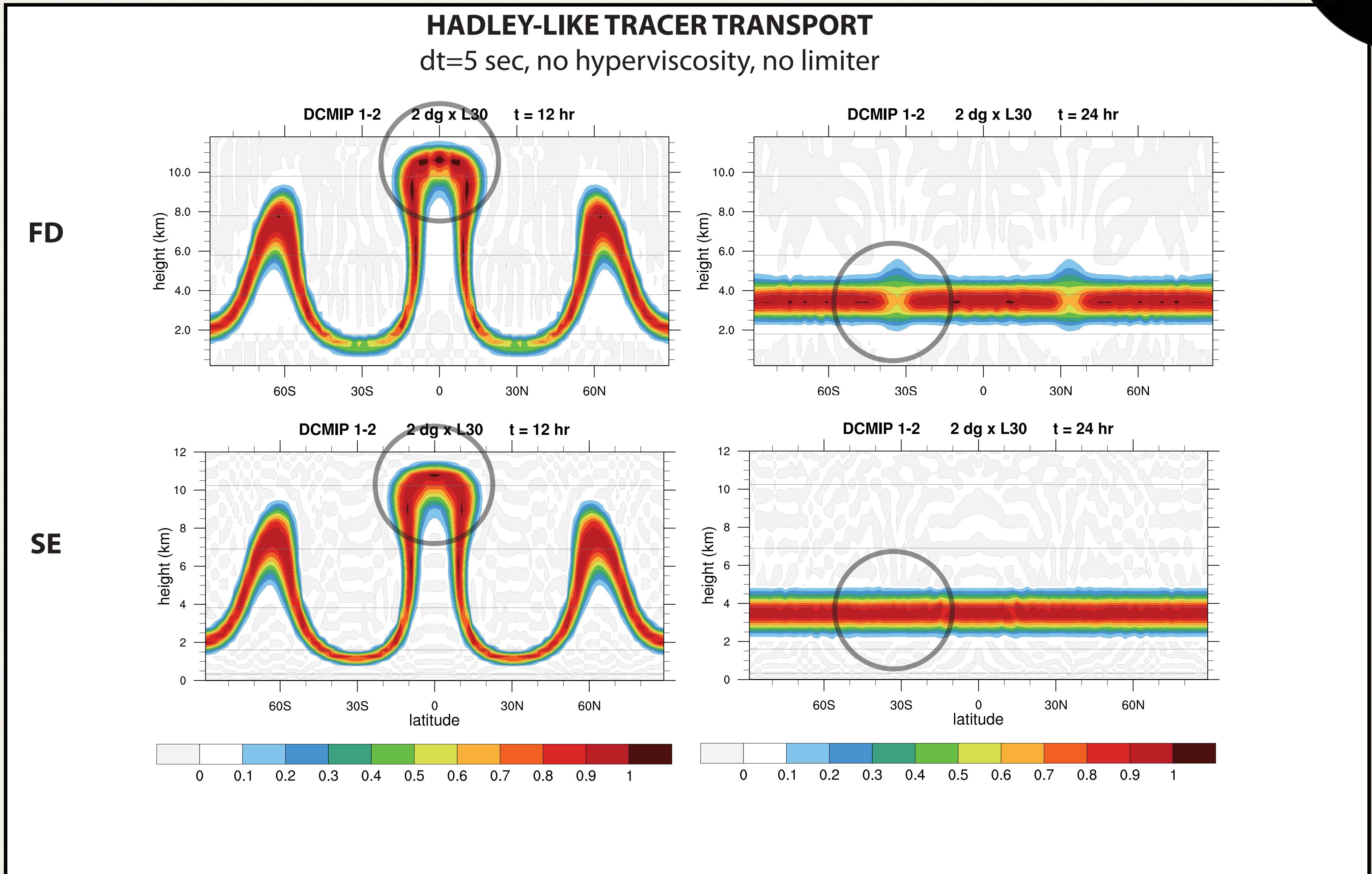
High Order Vertical Representation: dcmip1-2



The need for a high order vertical representation may be **quantified** using the dcmip 1-2 tracer transport test. Here we observe that the **vertical error** at the default resolution completely **dominates** the other error sources in the system. By **switching to a higher order representation**, we can use the same number of levels or use even fewer while greatly increasing the numerical accuracy.

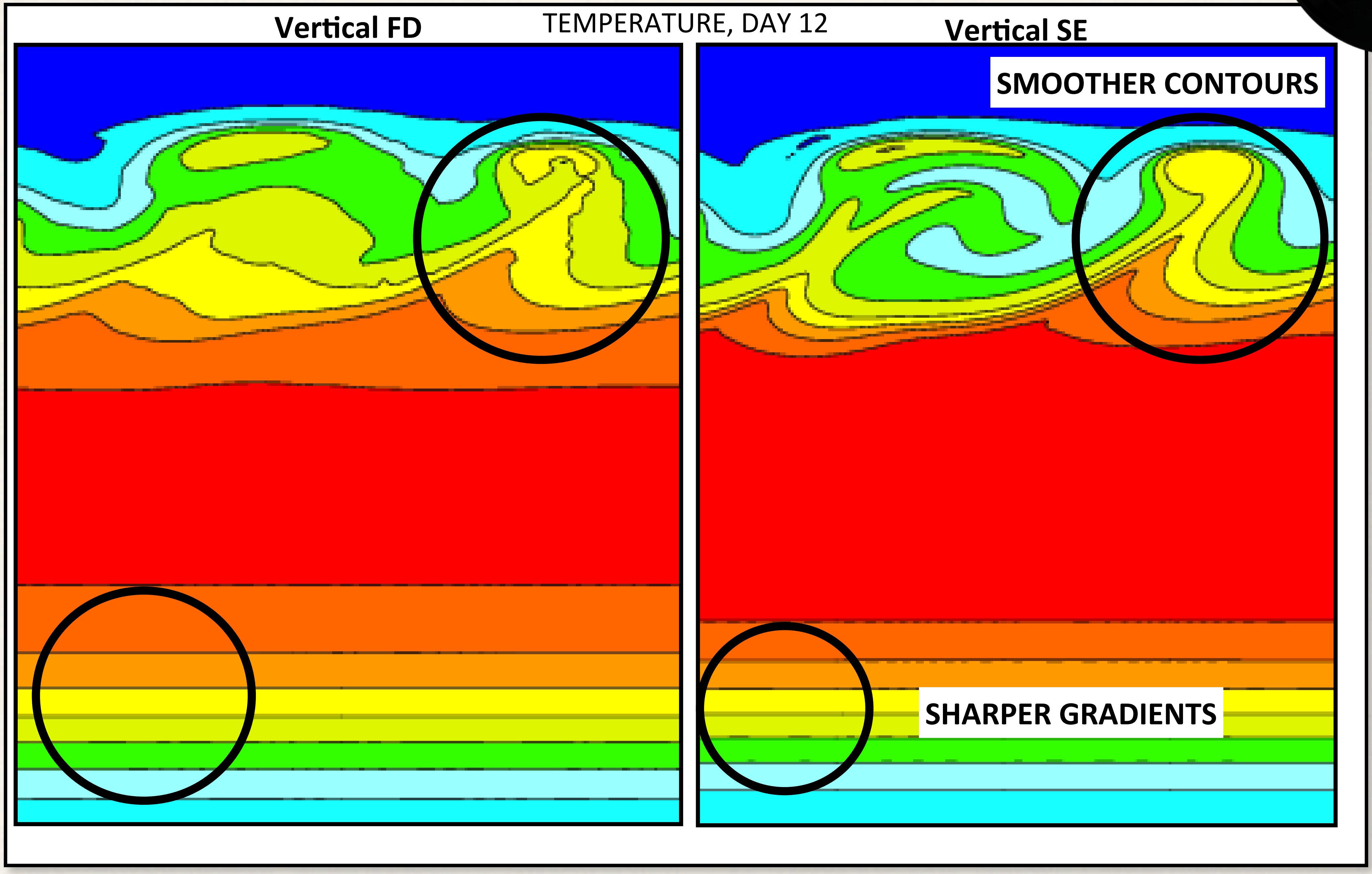
High Order Vertical Representation: DCMIP 1-2

PESE
primtive eqns
vertical SE



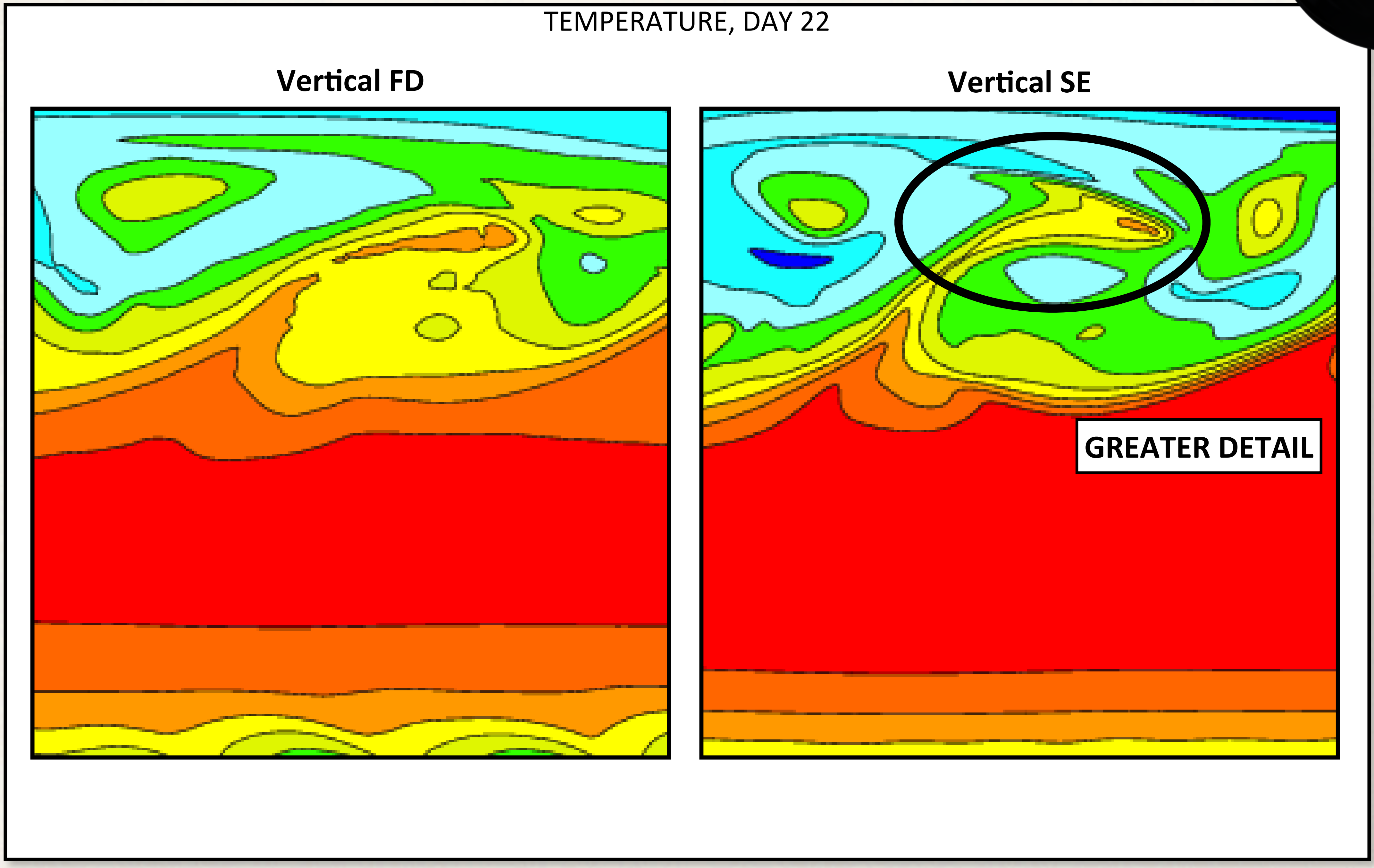
Using a **spectral-element vertical coordinate** greatly improved the **DCMIP-2012 tracer transport test results.** For example in DCMIP test 1-2, vertical SE produced **less gapping** and **less overshooting** in the thin tracer cloud with respect to the default method.

High Order Vertical Representation: DCMIP 4-1



Using a vertical SE representation also had a dramatic impact on dcmip test 4-1, the **dry baroclinic instability test**. Using the same horizontal and vertical resolution, the SE version demonstrated **smoother contours** and **sharper gradients** throughout the temperature field.

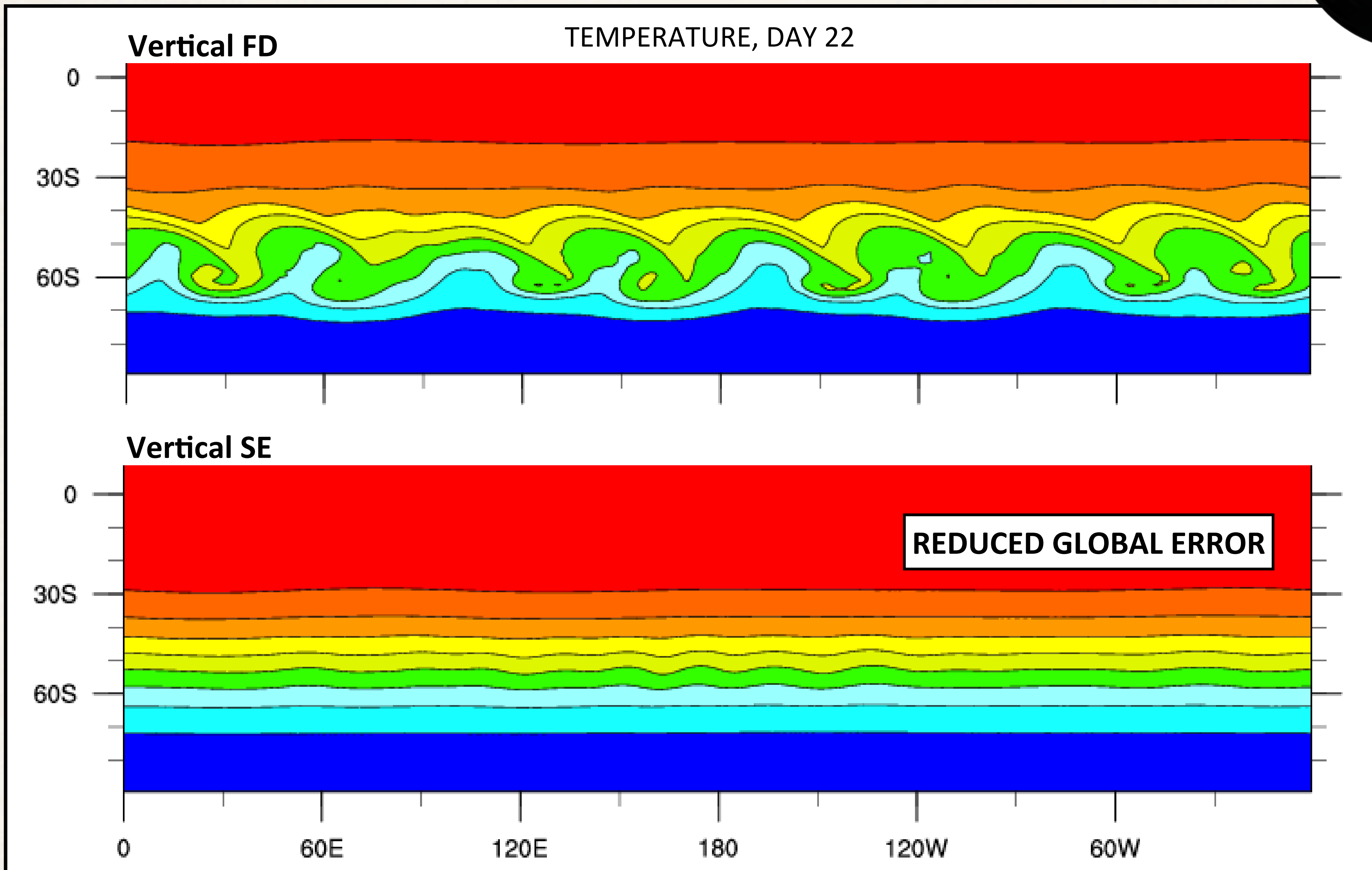
High Order Vertical Representation: DCMIP 4-1



Greater detail was observed through the simulation.

High Order Vertical Representation: DCMIP 4-1

PESE
primtive eqns
vertical SE



And overall, the **global error is reduced** as indicated by a
delayed onset of a second baroclinic instability in the souther hemisphere.

Nonhydrostatic Model: DCMIP-2012 Tests

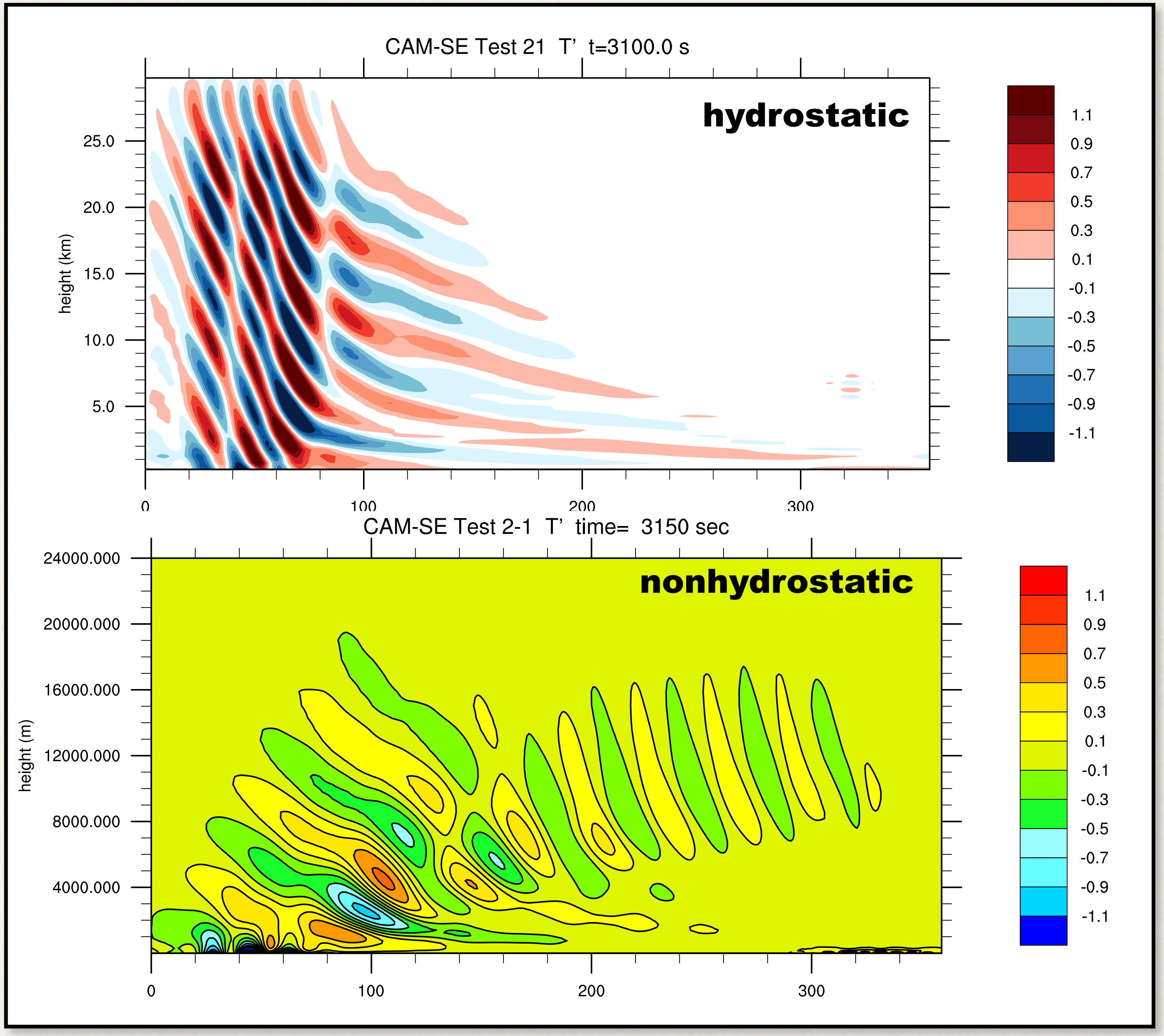
NHSE
nonhydrostatic
vertical SE

- **Tracer transport**
  - dcmip 1-1 ✔
  - dcmip 1-2 ✔
  - dcmip 1-3 ✔
- **Orography**
  - dcmip 2-0 ✔
  - dcmip 2-1 ✔
  - dcmip 2-2 ✔
- **Gravity waves**
  - dcmip 3-1 ✔
- **Dry dynamics**
  - Dry Baroclinic wave ✔
- **Moisture, p/d coupling**
  - Moist Baroclinic wave ✘
  - Tropical Cyclone ✘
  - Supercell Storm ✘

DCMIP
Dynamical Core
Model
Intercomparison
Project

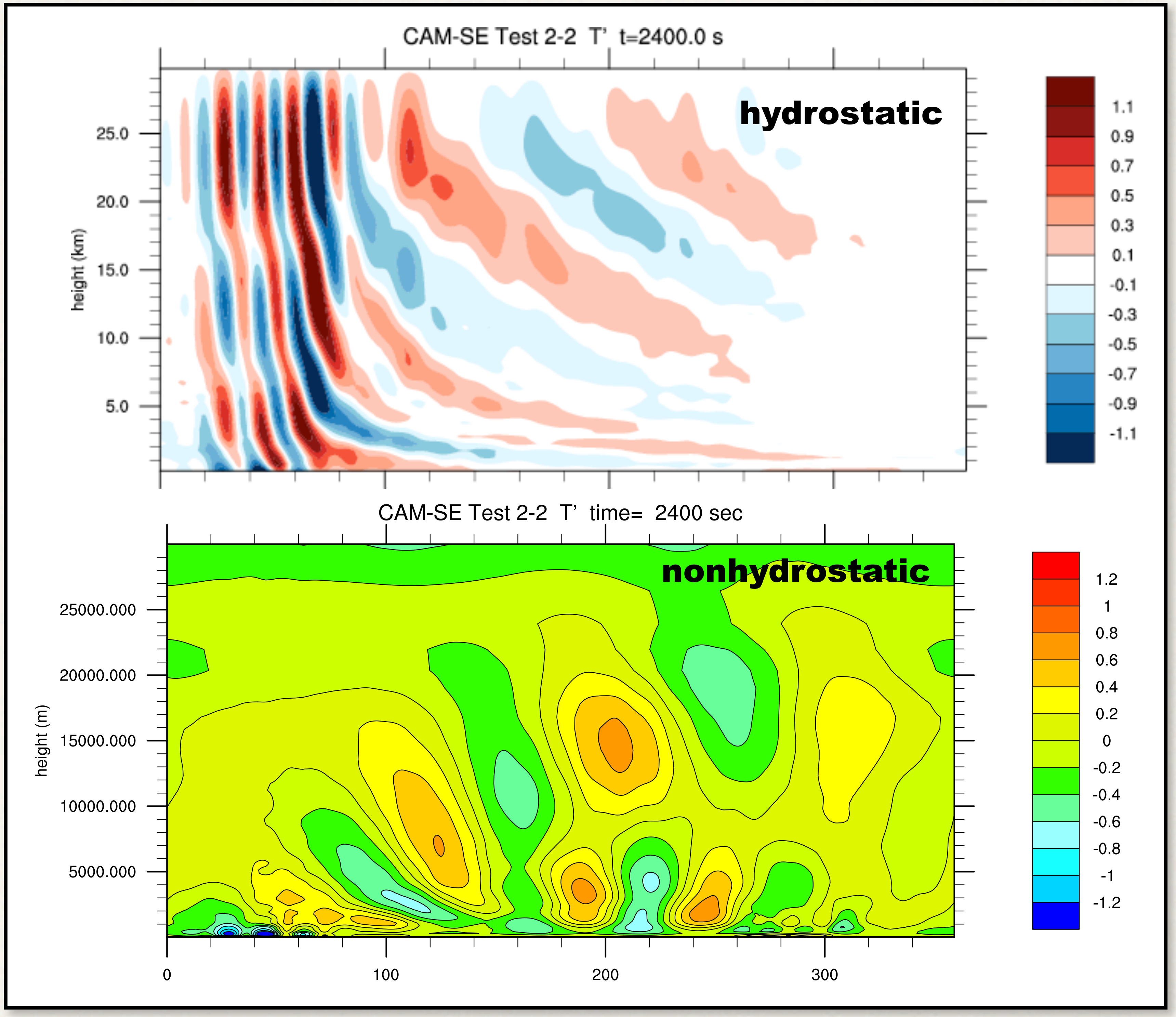
An experimental **nonhydrostatic** version of CAM-SE / HOMME is also under development, which has passed the **dry dcmip test cases** from 2012. However, moisture and physics coupling routines were not implemented in time for this summer school.

Hydrostatic vs Nonhydrostatic: dcmip2-1



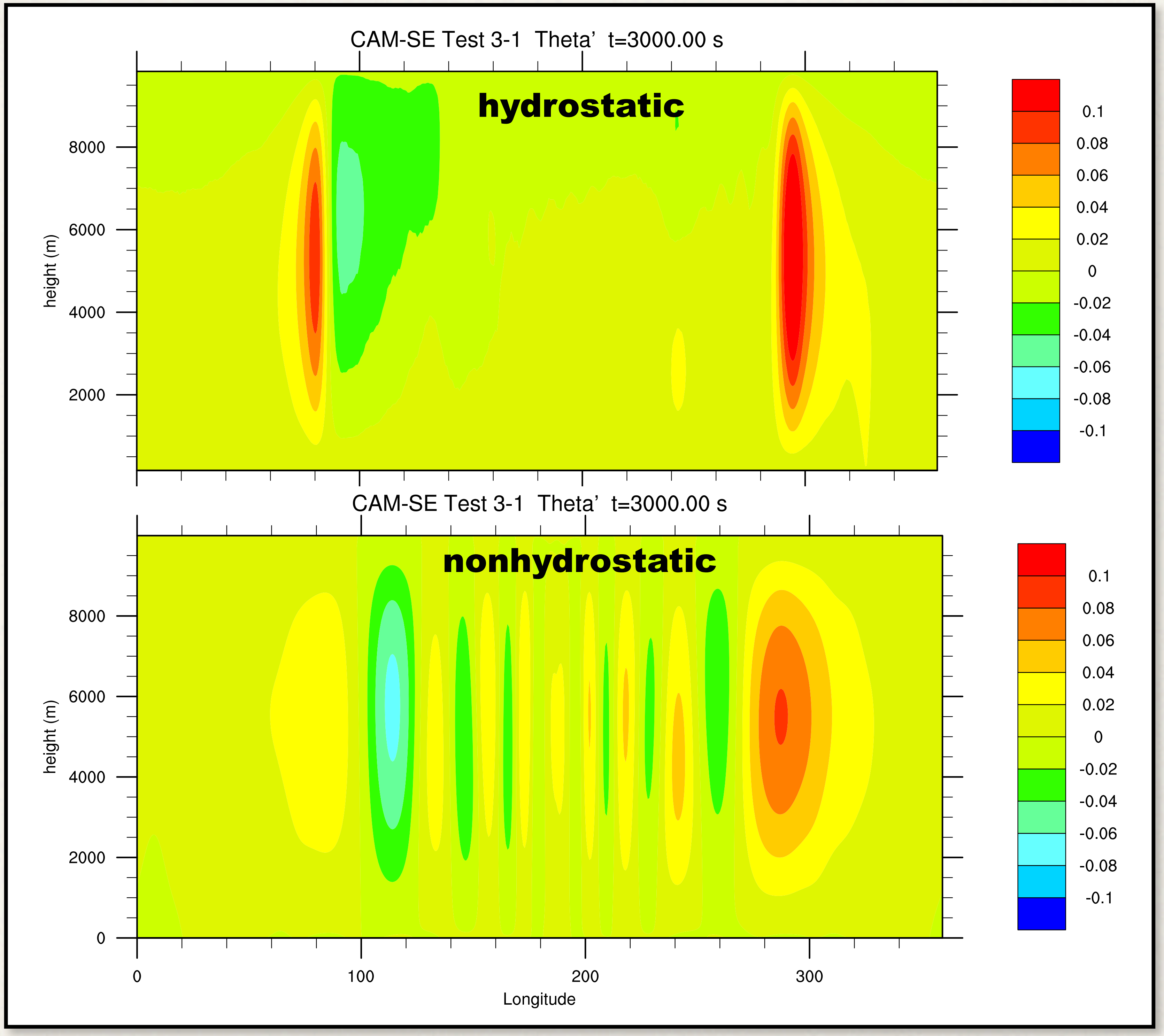
Here is a comparison of **hydrostatic** and **nonhydrostatic** temperature field in the dcmip 2-1 **orographic wave test.** The standing wave is observed to bend away from the mountain range in the nonhydrostatic case.

Hydrostatic vs Nonhydrostatic: dcmip2-2



Here is a comparison of hydrostatic and nonhydrostatic temperature field dcmip test 2-2: **orographic waves with vertical shear**. As before, the disturbance is primarily directly above the mountain range in the hydrostatic case, and **arcs away** from the mountains in the **nonhydrostatic** case.

Hydrostatic vs Nonhydrostatic: dcmip3-1



The thermally induced **gravity wave test** also demonstrates a large contrast between the hydrostatic and nonhydrostatic versions, producing a single large pulse in the hydrostatic case and a series of **inertial oscillations** in the **nonhydrostatic** case.

More Information

- CAM-5 scientific description
  - http://www.cesm.ucar.edu/models/cesm1.0/cam/docs/description/cam5_desc.pdf
- CAM-5 users guide
  - http://www.cesm.ucar.edu/models/cesm1.0/cam/
- CESM code, including CAM-SE
  - https://svn-ccsm-models.cgd.ucar.edu/cesm1/release_tags
- HOMME dcmip2016 test instructions
  - https://docs.google.com/document/d/1POzXwxpXqDkeqXqbHO9OLrhWMyB7TmFQkAiVEa7GyI0/edit?usp=sharing

For more information, please follow these links