SIMA dynamical core update

Peter Hjort Lauritzen and John Truesdale (CGD, NCAR)

Thanks to AMP software engineering group for code reviews etc. (Goldhaber, Craig, Nusbaumer, ...)
Thanks to Mariana Vertenstein and Jim Edwards for CIME/CESM support

MPAS part of this talk: Miles Curry, Michael Duda and Bill Skamarock (MMM, NCAR)
Spectral-element part of this talk: Mark Taylor and Oksana Guba (SNL, DOE), Francis Vitt and Hanli Liu (HAO, NCAR)
FV3 part of this talk: C. Jablonowski (UMICH) and Lukas Harris (GFDL)

June 15, 2021
SIMA is a set of interoperable modeling components and infrastructure.

Slide courtesy of SIMA leads
Finite-volume cubed-sphere (FV3) dynamical core update

- Released with CESM2.2; in the process of updating FV3 dynamical core from GFDL
- Working with Lukas Harris and Christiane Jablonowski (NOAA funded effort evaluating CAM-FV3) on “final” configuration for the CESM dynamical core evaluation effort

Impact of the FV3 Divergence Damping on the Circulation

- Insufficient explicit diffusion with FV3’s 8th-order divergence damping (nord=3):
  - Lots of numerical noise
- Enhanced diffusion in advection scheme (hord=10) cannot control this noise
- Slightly more explicit diffusion (6th-order div damping, nord=2) restores smooth solution
- Effect independent of moisture (dry/moist irrelevant)

Slide courtesy of C. Jablonowski (UMICH)

Ullrich et al. (2014) baroclinic wave test case (dry and moist) without topography
Spectral-element (SE) dynamical core updates

- Switched to FV3 vertical remapping algorithm in SE (improved QBO simulation!)

Having several dynamical cores in SIMA and gaining experience with them has significant synergetic effects! (e.g., assess structural uncertainty, algorithm research etc.)

Less diffusive vertical remapping significantly improves QBO; that said, slightly higher vertical resolution needed in both models for “good” QBO ...
Spectral-element (SE) dynamical core updates

- Changes to pressure-gradient force discretization and hyperviscosity

**Modified Pressure Gradient Term**

Using this identity: 

\[ c_p \theta_v \nabla \Pi + \nabla \phi = 0 \]

The pressure gradient term in the momentum equation can then be written:

\[ c_p \theta_v \nabla \Pi + \nabla \phi = c_p \left( \theta_v - \bar{\theta} \right) \nabla \Pi + \nabla \left( \phi - \bar{\phi} \right) \]

In the continuum, the two formulations are identical. But under discretization, the second formulation can have much less truncation error.

**Approximate Laplacian on pressure surfaces**

Motivated by approximation used in CAM-EUL (global spectral model)

\[ \frac{\partial \theta}{\partial t} + \cdots = \nu \Delta \Delta_p \theta \]

Laplacian on model surfaces: \( \Delta \)

Laplacian on pressure surfaces: \( \Delta_p \)

\[ \Delta_p \theta \approx \Delta \theta - \frac{\partial \theta}{\partial \bar{p}} \Delta \bar{p} \]

Limit the \( \Delta_p \) coefficient: preserve behavior for small values, gradually thresholding at alpha:

\[ \Delta_p \theta \approx \Delta \theta - \frac{\partial \theta / \partial \bar{p}}{1 + \| \partial \theta / \partial \bar{p} \| / \alpha} \Delta \bar{p} \]

Slides courtesy of M. Taylor (SNL, DOE); note CAM-SE uses \( T \) and not theta!

- WACCM-x: Species dependent thermodynamics, “horizontal” thermal conductivity and molecular viscosity operators in the dynamical core + sponge layer modifications.
Improvement of flow over topography

1 year average, AMIP-like (F2000CLIMO): (left) CESM2.2 version of SE, (right) CESM2.2 + topo mods

M.A. Taylor (DOE) and P.H. Lauritzen (NCAR)
Spectral-element (SE) dynamical core updates

- Changes to pressure-gradient force discretization and hyperviscosity

Modified Pressure Gradient Term

Using this identity: \( c_p \bar{\theta} \nabla \| + \nabla \phi = 0 \)

The pressure gradient term in the momentum equation can then be written:

\[
c_p \theta_v \nabla \| + \nabla \phi = c_p (\theta_v - \bar{\theta}) \nabla \| + \nabla (\phi - \bar{\phi})
\]

In the continuum, the two formulations are identical. But under discretization, the second formulation can have much less truncation error.

Approximate Laplacian on pressure surfaces

Motivated by approximation used in CAM-EUL (global spectral model)

\[
\frac{\partial \theta}{\partial t} + \cdots = \nu \Delta \Delta_p \theta
\]

Laplacian on model surfaces: \( \Delta \)

Laplacian on pressure surfaces: \( \Delta_p \)

\[
\Delta_p \theta \approx \Delta \theta - \frac{\partial \theta}{\partial p} \Delta \bar{p}
\]

Limit the \( p \) coefficient: preserve behavior for small values, gradually thresholding at \( \alpha \):

\[
\Delta_p \theta \approx \Delta \theta - \frac{\partial \theta / \partial \bar{p}}{1 + \| \partial \theta / \partial \bar{p} \| / \alpha} \Delta \bar{p}
\]

Slides courtesy of M. Taylor (SNL, DOE); note CAM-SE uses \( T \) and not theta!

- WACCM-x: Species dependent thermodynamics, “horizontal” thermal conductivity and molecular viscosity operators in the dynamical core + sponge layer modifications.
A generalized implementation of thermodynamics for species dependent air (dry air composition and condensates) in CAM-WACCM

Namelist specification of the composition of air, i.e. one can “easily” change composition of air and thermodynamically active water species (note: also applicable to other planets)

SE dynamical core and CAM-WACCM physics call the same module to get molecular viscosity and thermal conductivity coefficients, generalized cp and R, pressure (incl. weight of condensates if applicable), etc.

P.H. Lauritzen (CGD, NCAR), Hanli Liu, and Francis Vitt (HAO, NCAR)
Vertical Winds from ~25km, 273 level WACCM-x using SE-CSLAM (Spectral-elements with CSLAM)

Hanli Liu (HAO), Francis Vitt (ACOM) and P.H. Lauritzen (CGD)
Model for Prediction Across Scales dynamical core (MPAS): Consistent coupling with the CAM physics package

\[ \theta_m, \vec{v}, \rho_k^{(d)}, m^{(\ell)} \rightarrow T, \vec{v}, \Delta p, q^{(\ell)} \]

2.2 MPAS prognostic variables

MPAS prognostic variables are (omitting horizontal index):

- \( \theta_k^{(m)} \): layer mean modified potential temperature
- \( \rho_k^{(d)} \): mid-level dry density
- \( z_k \): layer height; layer thickness is \( \Delta z_k = z_{k-1/2} - z_{k+1/2} \)
- \( m_k^{(\ell)} \): layer mean dry mixing ratio of constituent \( \ell \)
- velocity components at mid-level

where \( k \) is level index. It is furthermore assumed that the mid-level is located at

\[ z_k \equiv \frac{1}{2} \left( z_{k+1/2} + z_{k-1/2} \right). \tag{1} \]

The modified potential temperature in MPAS is defined as

\[ \theta_k^{(m)} = \left( 1 + \frac{1}{\epsilon} m_k^{(\ell)} \right) \theta_k, \quad \text{where} \quad \epsilon \equiv \frac{R^{(d)}}{R^{(weis)}}. \tag{2} \]

(Skamarock et al., 2012, see equation 2) where

\[ \theta_k = T_k \left( \frac{R}{\rho_k} \right)^{m}, \tag{3} \]

2.1 CAM physics state variables

Not including state variables in specific parameterization, the CAM physics prognostic state variables are (omitting horizontal index):

- \( T_k \): mid-level temperature
- \( \Delta p_k \): pressure level thickness
- \( q_k^{(\ell)} \): layer mean specific/moist mixing ratio of constituent \( \ell \)
- velocity components at mid-level

where \( k \) is level index.

National Center for Atmospheric Research is a major facility sponsored by the NSF under Cooperative Agreement No. 1852977
Constraints:

- Mass conservation (straight forward assuming hydrostatic balance)

\[ \Delta p_k = g \Delta z_k \rho_k = g \Delta z_k \rho_k^{(d)} \sum_{\ell \in \mathcal{L}} m_k^{(\ell)} \]

\[ \mathcal{L} = \{ 'd', 'wv', 'cldice', 'cldliq', 'rain', 'snow' \} \]

\[ \Delta p_k = g \Delta z_k \rho_k^{(d)} \left( 1 + m_k^{(wv)} \right). \text{(CAM physics)} \]
Constraints:

- Energy conservation: as a first step assume MPAS hydrostatic for energy purposes, assume heat capacity of water vapor is that of dry air:

\[ \iiint \left( K + c_p^{(d)} T + \Phi_s \right) dA \frac{dp}{g} \]

Total energy CAM physics (not incl. latent heat terms)

\[ \iiint \left( K + c_v^{(d)} T + gz \right) \rho dA dz \]

Total energy MPAS (not incl. latent heat terms) assuming MPAS hydrostatic

\[ \theta_m, \bar{v}, \rho_k^{(d)}, m^{(\ell)} \rightarrow T, \bar{v}, \Delta p, q^{(\ell)} \]

Note: pressure diagnostic in MPAS (constant volume model); model top pressure not constant as in CAM physics
Half-level pressures are straight-forward to compute using MPAS prognostic state (assuming hydrostatic balance)

$$\Delta p_k = g \Delta z_k \rho_k = g \Delta z_k \rho_k^{(d)} \sum_{i \in \mathcal{L}} m_i^{(l)}$$

but full level pressure needs to be computed carefully for consistency. For example, choosing

$$p_k = \frac{1}{2} \left( p_{k+1/2} - p_{k-1/2} \right)$$

is NOT consistent with MPAS where mid-level is defined by

$$z_k = \frac{1}{2} \left( z_{k+1/2} + z_{k-1/2} \right)$$

Instead we use the equation of state to compute full-level pressure (and Exner pressure/function)

$$\left\langle \frac{1}{p_k} \right\rangle = \left( \frac{\theta_k^{(v)} \rho_k R_k^{(d)}}{P_0^{\kappa}} \right)^{(1-\kappa)}$$

$$\Pi_k = \left\{ \begin{array}{c} p_k \\ p_0 \end{array} \right\} \frac{R_k^{(a)}}{E_k^{(a)}}$$

$$= \left\{ \left[ \rho_k^{(m)} \frac{R_k^{(d)}}{p_0} \right] \frac{c_p^{(a)}}{c_v^{(a)}} \right\} \frac{R_k^{(d)}}{E_k^{(a)}}$$

$$= \left\{ \rho_k^{(d)} \frac{R_k^{(d)}}{p_0} \right\} \frac{R_k^{(a)}}{E_k^{(a)}}$$

$$\Rightarrow \text{height computed from CAM physics state (diagnostic) is consistent with MPAS height (fixed)}$$

$$\Delta z_k = \left\langle \frac{1}{p_k} \right\rangle \frac{R_k^{(d)} T_k^{(v)}}{g} \Delta p_k$$

$$z_k = z_{k+1/2} + \frac{1}{2} \Delta z_k = z_{k+1/2} + \frac{1}{2} \left\langle \frac{1}{p_k} \right\rangle \frac{R_k^{(d)} T_k^{(v)}}{g} \Delta p_k$$

National Center for Atmospheric Research is a major facility sponsored by the NSF under Cooperative Agreement No. 1852977
Temporal evolution of total energy

3.0.0.1 CAM energy equation  The total energy equation used in CAM physics (omitting surface fluxes and latent heat terms associated with phase transformations) is given by

$$\frac{\partial}{\partial t} \iiint \left( K + c_p^{(d)} T + \Phi_s \right) dA \frac{dp}{g} = \iiint \left[ Q + \vec{v} \cdot \vec{F} \right] dA \frac{dp}{g}$$ (30)

(Kasahara, 1974) where $Q$ is the heating rate per unit mass per unit time and $\vec{F}$ is the frictional force per unit mass. This energy equation assumes that the model top pressure is constant in time and that all water species use the same heat capacity $c_p^{(e)} = c_p^{(d)}$.

3.0.0.2 MPAS energy equation  Assuming hydrostatic balance, constant $z$ model top and $c_p^{(e)} = c_p^{(d)}$, MPAS conserves

$$\frac{\partial}{\partial t} \iiint \left( K + c_v^{(d)} T + gz \right) \rho dA dz = \iiint \left[ Q + \vec{v} \cdot \vec{F} \right] dA \rho dz$$ (32)

(Kasahara, 1974) in the absence of surface fluxes and latent heat terms associated with phase transformations.
If the energy fixer uses a total energy formula different than the dynamical core’s energy formula then the energy fixer is not fixing what it is supposed to fix which is:

- **“Actual”** energy dissipation in dynamical core
- **“Actual”** energy errors in physics dynamics coupling
- Moisture adjustment as “seen” by dycore

Total energy fixer in CAM

2.5. A Few Observations Regarding the Energy Budget Terms

It is useful to note that the energy fixer “fixes” energy errors for the dynamical core, pressure work error, PDC, and TE discrepancy

\[
-\partial E^{\text{fix}}_{\text{phys}} = \partial E^{\text{pwork}}_{\text{phys}} + \partial E^{\text{rad}}_{\text{dyne}} + \partial E^{\text{pdc}} + \partial E^{\text{discre}}.
\]  

If the energy fixer uses a total energy formula different than the dynamical core’s energy formula then the energy fixer is not fixing what it is supposed to fix which is:

- **“Actual”** energy dissipation in dynamical core
- **“Actual”** energy errors in physics dynamics coupling
- Moisture adjustment as “seen” by dycore
Level 0 consistency:

Energy fixer that fixes dynamical core, physics-dynamics coupling and water adjustment energy errors, should use a total energy formula consistent with z-vertical coordinate, i.e. energy fixer should be using

\[
\frac{\partial}{\partial t} \iiint \left( K + c_v^{(d)} T + g z \right) \rho dA \, dz
\]

CAM physics parameterizations satisfy

\[
\frac{\partial}{\partial t} \iiint \left( K + c_p^{(d)} T + \Phi_s \right) dA \, \frac{dp}{g}
\]

Temperature increments in CAM physics are for constant pressure and are converted to heating increments under constant volume so that energy increments in the two coordinate systems are the same:

\[
\Delta T_k|_p = \frac{c_v^{(d)}}{c_p^{(d)}} \Delta T_k|_V
\]
Water adjustment energy tendency (dme_adjust)
Water adjustment energy tendency (dme_adjust)

Moisture adjustment (dmeadj); cv-cp

mean: -0.75 W/m^2

mean: -0.41 W/m^2

global min = -7.287  global max = 11.42

bal max = 19.76
Still inconsistencies:

1. **Static energy potential:**
   
   \[ S = gz + dp\cdot cp\cdot T + gz \]

   We made our heating increments consistent (equivalent to using \( dp\cdot cv\cdot T \) in static energy) but \( z \) varies in CAM physics (updated after each physics call so the parameterization”see” height changing whereas the MPAS vertical coordinate, height, stays fixed)

2. **Related:** Top boundary condition in CAM assumes constant pressure (with MPAS pressure at model top varies but not height)

3. **Assuming hydrostatic total energy formula** (i.e. vertical velocity term missing)

4. **Energy formula does not incl. condensates** (inconsistency with SE and FV3 as well)
National Center for Atmospheric Research is a major facility sponsored by the NSF under Cooperative Agreement No. 1852977