Community Atmosphere Model (CAM) --- A brief introduction

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General information

- 3D global atmosphere model
- A component of CCSM/Stand-alone
- Developed at NCAR, 19 years
- Atmosphere Model Working Group

**Co-Chair:** Phil Rasch (NCAR-CGD), Leo Donner (GFDL/NOAA), Minghua Zhang (Stony Brook)

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**Website:**
http://www.ccsm.ucar.edu/models/atm-cam/
Dynamical Cores

- Eulerian Dynamical Core
- Semi-Lagrangian Dynamical Core
- Finite Volume Dynamical Core
  - Horizontal discretization: a conservative "Flux-Form Semi-Lagrangian" (FFSL)
  - Vertical discretization: Lagrangian with a conservative re-mapping
FV Basic Equations

- Conservation of Mass

$$ \frac{\partial}{\partial t} \pi + \nabla \cdot (\vec{V} \pi) = 0, $$

$$ \pi = \frac{\partial p}{\partial \zeta} \quad \text{"pseudo-density"} \quad \zeta \quad \text{General vertical coordinate} $$

- Conservation of Tracers

$$ \frac{\partial}{\partial t} (\pi q) + \nabla \cdot (\vec{V} \pi q) = 0, $$
FV Basic Equations

- **Conservation of Heat**
  \[
  \frac{\partial}{\partial t}(\pi\Theta) + \nabla \cdot (\vec{V}\pi\Theta) = 0.
  \]
  Potential temperature

- **Conservation of Momentum**
  \[
  \frac{\partial}{\partial t}u = \Omega v - \frac{1}{A\cos\theta} \left[ \frac{\partial}{\partial \lambda} \left( \kappa + \Phi - \nu D \right) + \frac{1}{\rho} \frac{\partial}{\partial \lambda} p \right] - \frac{d\zeta}{dt} \frac{\partial u}{\partial \zeta},
  \]
  \[
  \frac{\partial}{\partial t}v = -\Omega u - \frac{1}{A} \left[ \frac{\partial}{\partial \theta} \left( \kappa + \Phi - \nu D \right) + \frac{1}{\rho} \frac{\partial}{\partial \theta} p \right] - \frac{d\zeta}{dt} \frac{\partial v}{\partial \zeta},
  \]
  Coriolis Force, Kinetic energy, Horizontal divergence, P.G.F.
Flux-form Semi-Lagrangian scheme

- Advection of tracer transport [Lin and Rood, 1996]
- Apply to dynamics of the hydrostatic flow [Lin and Rood, 1997]
- Pressure gradient force [Lin, 1997]
- A vertically Lagrangian FV dynamical core [Lin, 2004]
Advection schemes

- Spectral transform method and centred finite-differencing method
- Semi-implicit semi-Lagrangian methods
  better computational efficiency and accuracy
- Finite-volume schemes
  mass-conserving, 1D (M-D: splitting error)
- Flux-Form Semi-Lagrangian scheme
  automatic mass-conserving, reduced splitting error
Flux-Form Semi-Lagrangian

Eulerian scheme:
Mapping the field at time n (regular spacing), to time n +1 (irregular after deformation), remapping back to regular interval.

Usual semi-Lagrangian:
Where upstream does Point(i, n+1) come from?

FFSL:

Mass is conserved in the shaded area.

what is $\Delta x'$?
Horizontal discretization of the transport process

- Finite volume (integral) representation

\[ \tilde{\pi}(t) \equiv \frac{1}{A^2 \Delta \theta \Delta \lambda \cos \theta} \int \int \pi(t; \lambda, \theta) A^2 \cos \theta \, d\theta d\lambda. \]

- Mass conservation equation

Exact

\[ \tilde{\pi}^{n+1} = \tilde{\pi}^n - \frac{1}{A^2 \Delta \theta \Delta \lambda \cos \theta} \int_t^{t+\Delta t} \left[ \oint \pi(t; \lambda, \theta) \vec{V} \cdot n \, dl \right] \, dt. \]

Contour integral

\[ \tilde{\pi}^{n+1} = \tilde{\pi}^n + F \left[ u^*, \Delta t, \tilde{\pi}^\theta \right] + G \left[ v^*, \Delta t, \tilde{\pi}^\lambda \right] \]

Splitting error

Forward-in-time Flux-form transport operator=

"increments" of one time step
Subgrid distribution

- Constant
- Piece-wise linear
- PPM – piece-wise parabolic Method

accurate and computational efficient, mass conserving, monotonicity preserving
monotonic constraint works as a subgrid mixing smoother
fourth-order center differencing

standard nonconservative semi-Lagrangian

modified monotonic PPM

positive definite PPM
Comparison

- SL3 is the most diffusive. CD4 is the most dispersive.
- CD4 has the largest errors by nearly all measures.
- PPM based schemes are more accurate than SL3 except for wave-2 test.
- All FFSL schemes maintain positivity of the original distribution and conserve mass exactly.
Extend to large time step

- Eulerian schemes: strict stability limitations
- On equal angle spherical grids, the convergence of meridians at the pole
- If the stability is grid independent, then the time step can be chosen based on the physics and chemistry of the problem.
- Retain the characteristics of Lagrangian scheme which is independent of time step.

- Extension can be view as an integer shift of the tracer distribution followed by a normal Eulerian transport for the fractional part.
- Mass is exactly conserved
- Adding a constant background value does NOT change the final results.
- Results are NOT overly sensitive to the size of the time step.
Stability analysis

- Nondeformational flows: unconditional stable
- Deformational flows: Time step only limited by

$$\frac{\Delta t \delta_x u^{n+1/2}}{\Delta x} \leq 1$$

the left and right interfaces of a cell do not cross each other
Vertically Lagrangian control-volume discretization

- Apply the FFSL scheme to hydrostatic flow
- Shallow-water equations:

\[
\frac{\partial}{\partial t} \delta p + \frac{1}{A \cos \theta} \left[ \frac{\partial}{\partial \lambda} (u \delta p) + \frac{\partial}{\partial \theta} (v \delta p \cos \theta) \right] = 0, \\
\frac{\partial}{\partial t} u = \Omega v - \frac{1}{A \cos \theta} \left[ \frac{\partial}{\partial \lambda} (k + \phi - vD) + \frac{1}{\rho} \frac{\partial}{\partial \lambda} p \right] \\
\frac{\partial}{\partial t} v = -\Omega u - \frac{1}{A} \left[ \frac{\partial}{\partial \theta} (k + \phi - vD) + \frac{1}{\rho} \frac{\partial}{\partial \theta} p \right]
\]
Time-splitting

- Take advantage of the large time step ($\Delta t$) of the transport scheme.
- The dynamics uses a relative small time step ($\Delta \tau$) to stabilize the fast wave

$$\Delta \tau = \Delta t / m$$

$$\left(\phi^\sigma\right)_i = \left(\phi\right)^{n+(i-1)/m} + \frac{1}{2} g\left[u^*_i, \Delta \tau, \left(\phi\right)^{n+(i-1)/m}\right]$$

$$\left(\phi^\lambda\right)_i = \left(\phi\right)^{n+(i-1)/m} + \frac{1}{2} f\left[u^*_i, \Delta t, \left(\phi\right)^{n+(i-1)/m}\right]$$
Hybrid $\sigma - p$ Coordinate

Figure 3.1: Vertical level structure of CAM 3.0
Pressure gradient term

\[ \sum F = \int_C pnd s \]

\[ \frac{du}{dt} = \frac{\sum F_x}{\Delta m} \]

\[ \frac{du}{dt} = -\frac{\int \int \frac{\partial \phi}{\partial x} dxd\pi}{\int \int dxd\pi} = \frac{\int_C \phi d\pi}{\int_C \pi dx} \]

\( \pi \) is a function of \( P \)

\[ \delta \phi = -C_p \theta_0 \delta P^k \]

\[ \pi = P^k \quad k = R/C_p \]

The absolute PG error reduce dramatically when over 20 levels
Perturbation test

- Trigger the baroclinic instability by a T perturbation at 45N, 90E
- Surface pressure perturbation and T at the lowest model layer at day 10.
- Weaker amplitude for 2x2.5
- Detailed feature unresolved in 0.5x0.625
- Monotonic constrain damps strongly on the two-grid-scale structure
Held and Suarez’s forcing

2x2.5

1x1.25
Without Monotonicity constraint

2x2.5

1x1.25
The FV dynamical core based on FFSL transport scheme absolutely conserves mass and keeps a consistency between the air flow and tracer mixing ratio. It can apply to large time step for the advection. Time-splitting is needed for hydrostatic flow to stabilize the fast wave.

Both amplitude and phase is well preserved compared to centered-difference and usual semi-Lagrangian scheme.

The PPM subgrid distribution acts as a monotonicity constraint, which assure no negative tracer concentration while smooth out some small scale feature. Even at 55 km grid increment, the 2 delta x feature is unresolved.
Parameterizations

- **Deep convective clouds**
  - **Input**
    - boundary layer height, temperature perturbation, temperature, pressure...
  - **Output**
    - precipitation flux, snow flux, tendency of temperature, water vapor, cloud ice, cloud water; heating rate by ice and evaporation...
Parameterizations

- shallow clouds
  - Input
    - surface temperature, temperature, sea surface temperature, detrain rate from deep convection, vertical integral of liquid, land/ocean/sea ice fraction, snow depth...
  - Output
    - relative importance of all the process of phase change, rate of ice/liquid conversion, in-cloud water/ice mixing ratio, precipitation rate, heating rate...
Parameterizations

- Radiation
  - Input
    land/ocean/sea ice fraction, snow depth, surface absorbed solar flux, temperature and pressure, net column absorbed solar flux, surface quantities, net out going LW, cloud.
  - Output
    Total/clear sky column absorbed solar flux, surface absorbed solar flux, heating rate, LW flux at the top/surface, LW up/down flux, LW cloud forcing, surface absorbed solar flux, net out-going LW, surface downward solar flux.


Collins et al, 2004. CAM3.0 scientific description, Chapter 3. NCAR.
Thank you