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)

  Liason: *Rich Neale* (NCAR)
- 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

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

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

- Conservation of Tracers

$$\frac{\partial}{\partial t}(\pi q) + \nabla \cdot \left(\overrightarrow{V}\pi q\right) = 0,$$

FV Basic Equations

- Conservation of Heat

$$\frac{\partial}{\partial t}(\pi\Theta) + \nabla \cdot \left(\vec{V}\pi\Theta\right) = 0.$$

ΘPotential temperature

- Conservation of Momentum

$$\frac{\partial}{\partial t}u = \Omega v - \frac{1}{Acos\theta}\left[\frac{\partial}{\partial \lambda}(\kappa + \Phi - \nu D) + \frac{1}{\rho}\frac{\partial}{\partial \lambda}p\right] - \frac{d\zeta}{dt}\frac{\partial u}{\partial \zeta},$$

$$\frac{\partial}{\partial t}v = \underset{\substack{\downarrow \\ \text{Coriolis} \\ \text{Force}}}{-\Omega u} - \frac{1}{A}\left[\frac{\partial}{\partial \theta}(\underset{\substack{\downarrow \\ \text{Kinetic} \\ \text{energy}}}{\kappa} + \Phi - \underset{\substack{\downarrow \\ \text{Horizontal} \\ \text{divergence}}}{\nu D}) + \frac{1}{\rho}\underset{\substack{\downarrow \\ \text{P.G.F}}}{\frac{\partial}{\partial \theta}p}\right] - \frac{d\zeta}{dt}\frac{\partial v}{\partial \zeta},$$

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

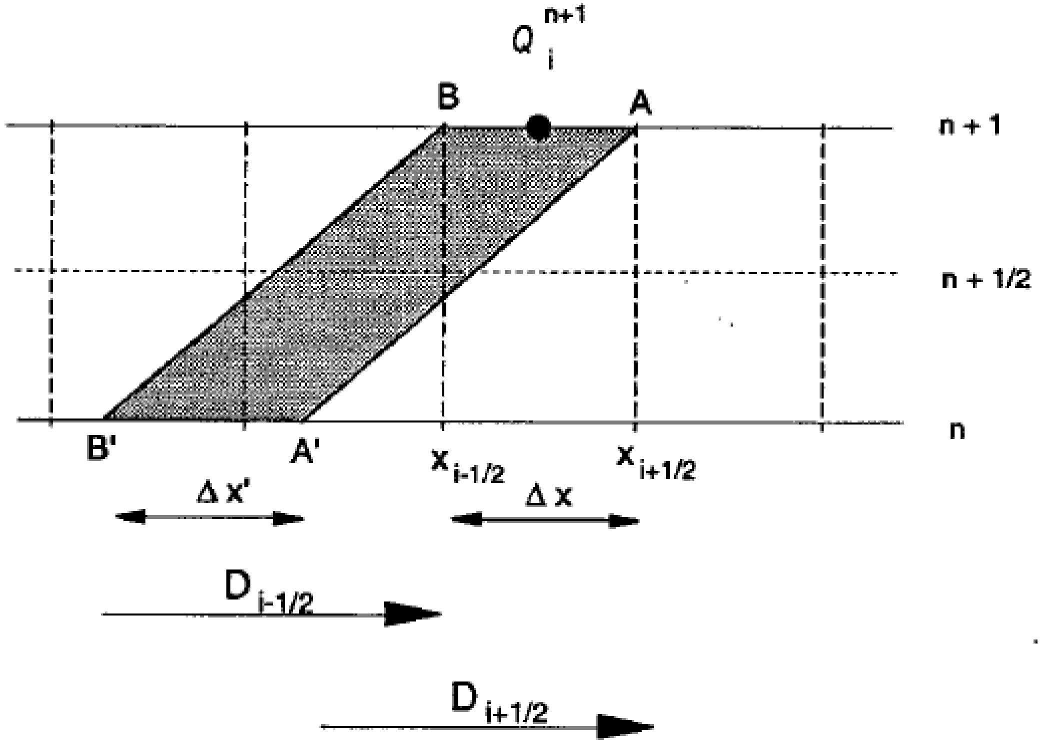
- Spectral transform method and centred finite-differencing method
- Semi-implicit semi-Lagrangian methods

  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



Mass is conserved in the shaded area.

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:

what is $\Delta x'$?

Horizontal discretization of the transport process

- Finite volume (integral) representation

$$\widetilde{\pi}(t) \equiv \frac{1}{A^2\Delta\theta\Delta\lambda cos\theta}\iint \pi(t;\lambda,\theta)A^2 cos\theta \, d\theta d\lambda.$$

- Mass conservation equation

Exact $$\underline{\widetilde{\pi}^{n+1} = \widetilde{\pi}^{n}} - \boxed{\frac{1}{A^2\Delta\theta\Delta\lambda cos\theta}\int_{t}^{t+\Delta t}\boxed{\left[\oint \pi(t;\lambda,\theta)\overrightarrow{V}\cdot\overrightarrow{n}\, dl\right]}\, dt.}$$

Contour integral

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

Splitting error

Forward-in-time

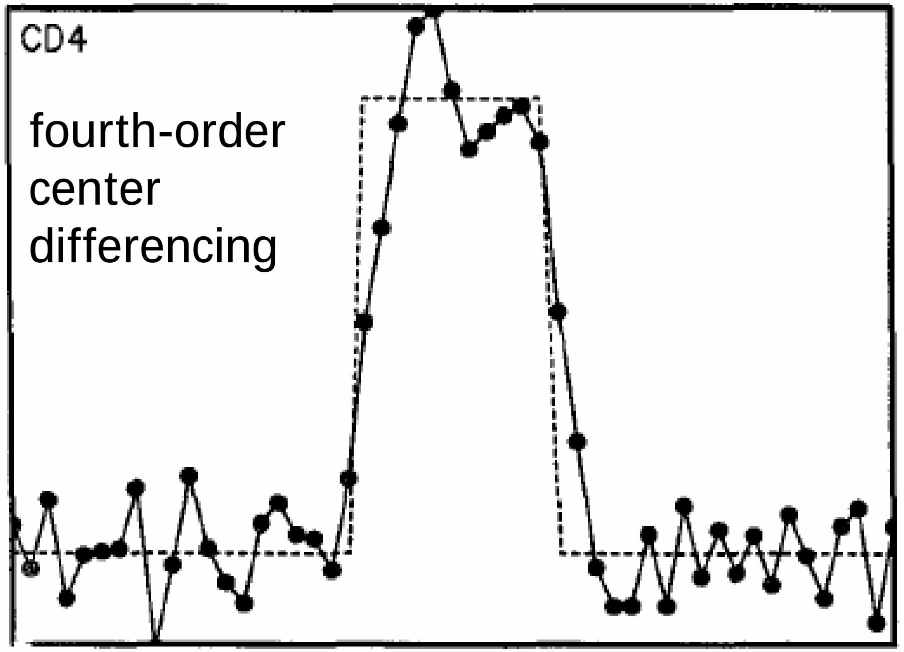
Flux-form transport operator=
“increments” of one time step

Subgrid distribution

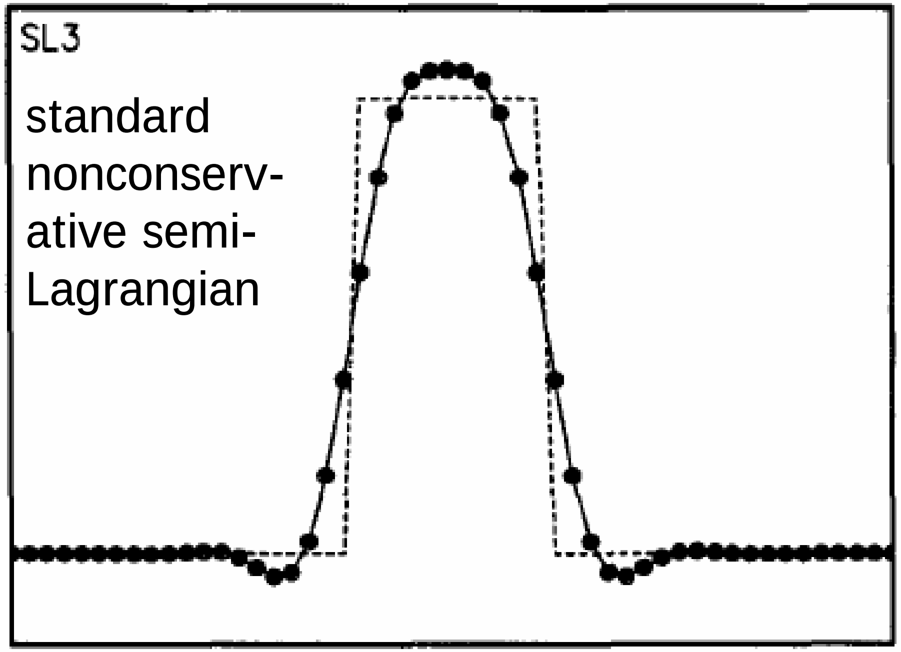
- Constant
- Piece-wise linear
- PPM – piece-wise parabolic Method

  accurate and computational efficient, mass conserving, monotonicity preserving

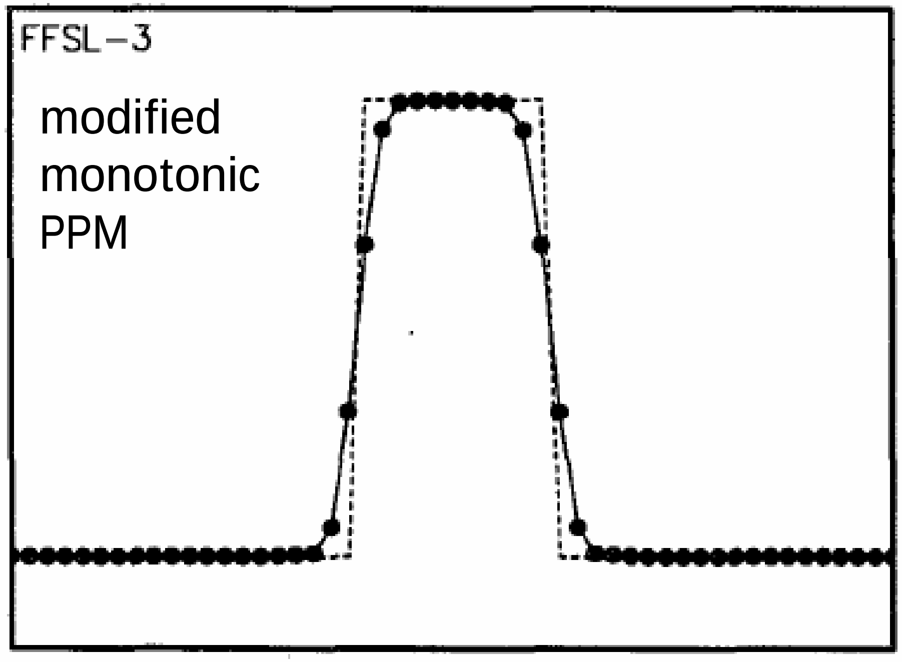
  <u>monotonic constraint works as a subgrid mixing smoother</u>



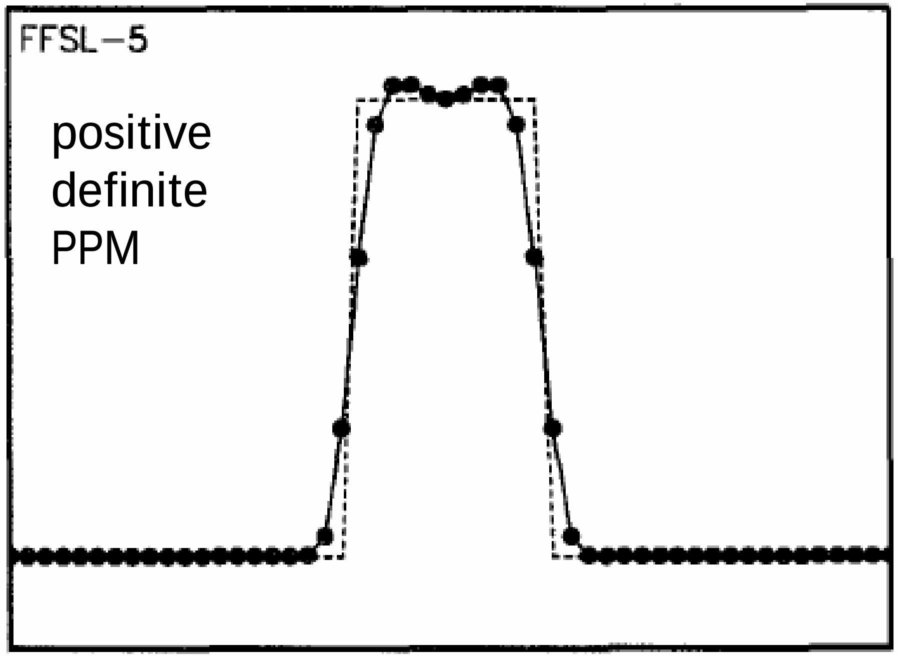
fourth-order
center
differencing



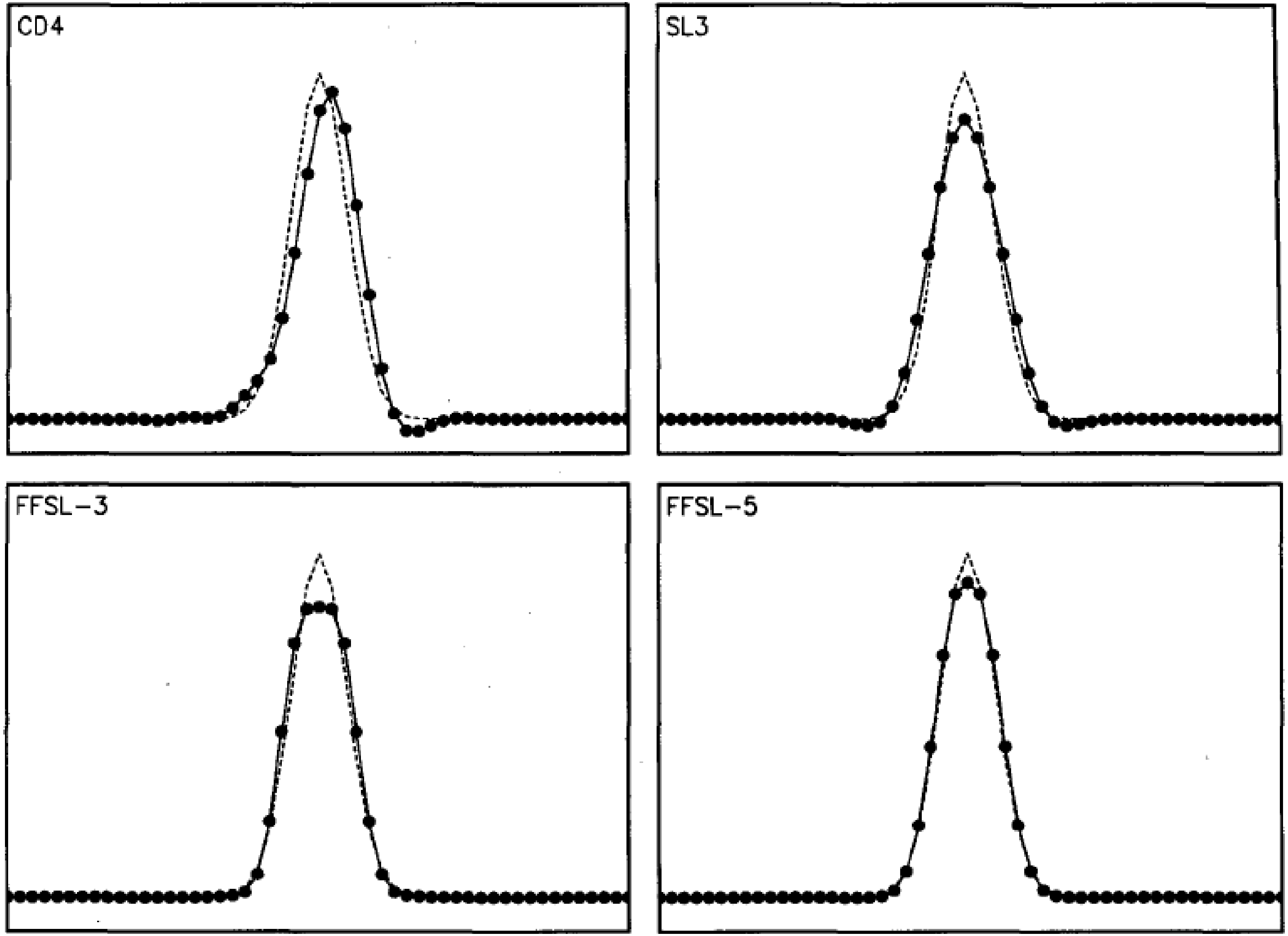
standard
nonconserv-
ative semi-
Lagrangian

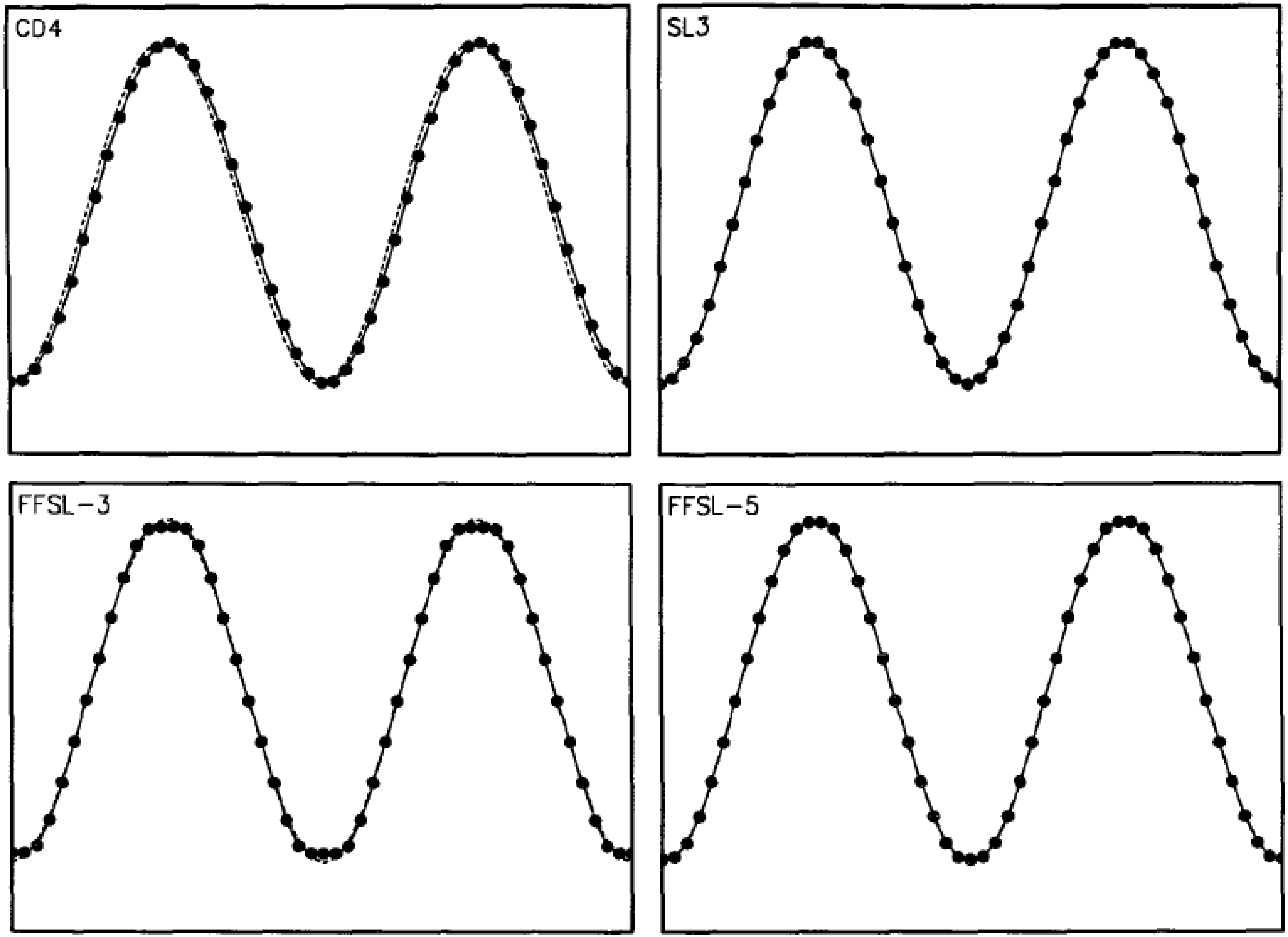


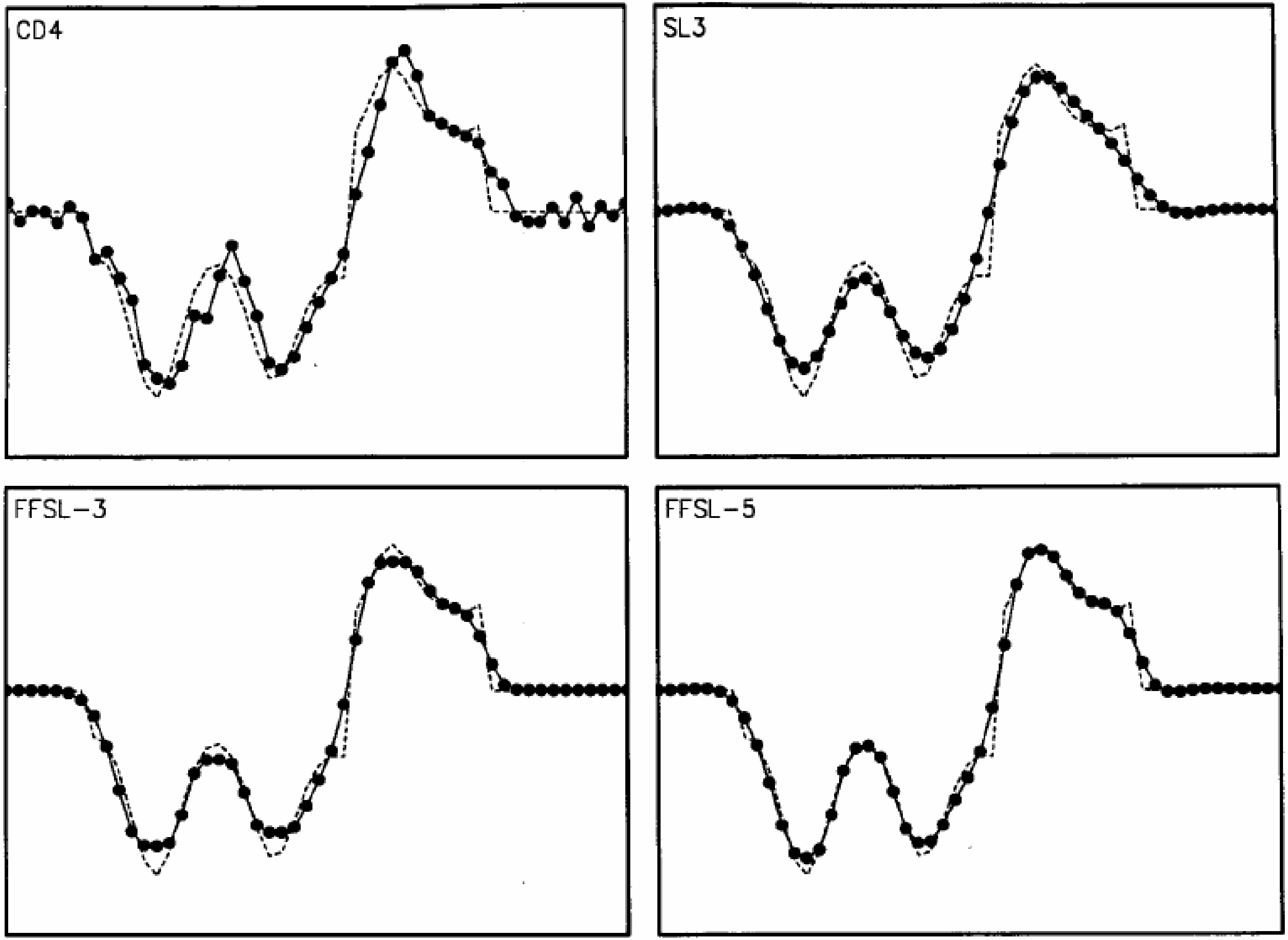
modified
monotonic
PPM



positive
definite
PPM


CD4
SL3
FFSL-3
FFSL-5


CD4
SL3
FFSL-3
FFSL-5


CD4
SL3
FFSL-3
FFSL-5

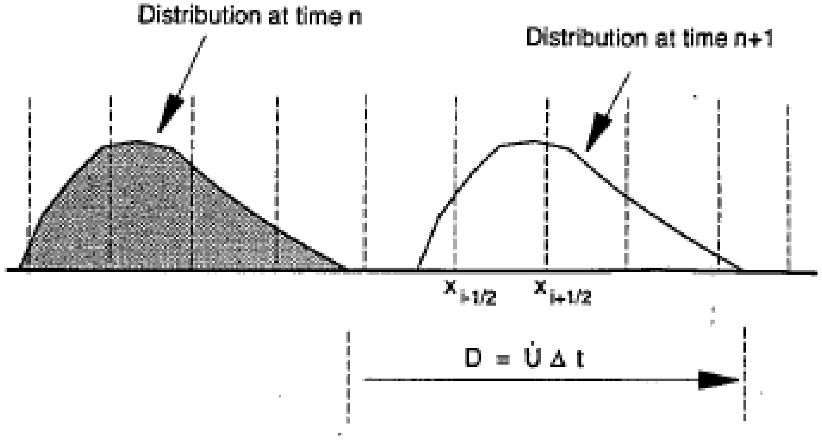
Comparison

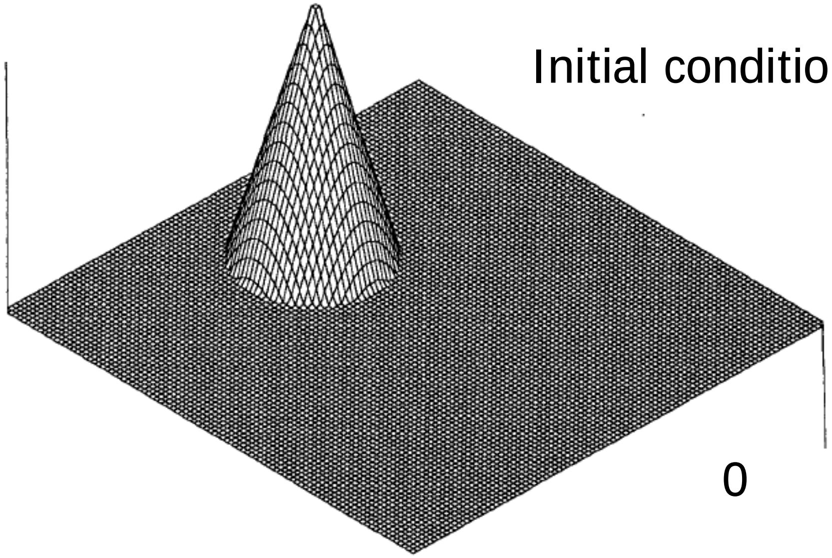
- SL3 is the most diffusive. CD4 is the most dispersive.
- CD4 has the largest errors by nearly all measures.
- PPM based schemes are more accurate than SL3 except for wave-2 test
- All FFSL schemes maintain positivity of the original distribution and conserve mass exactly.

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.

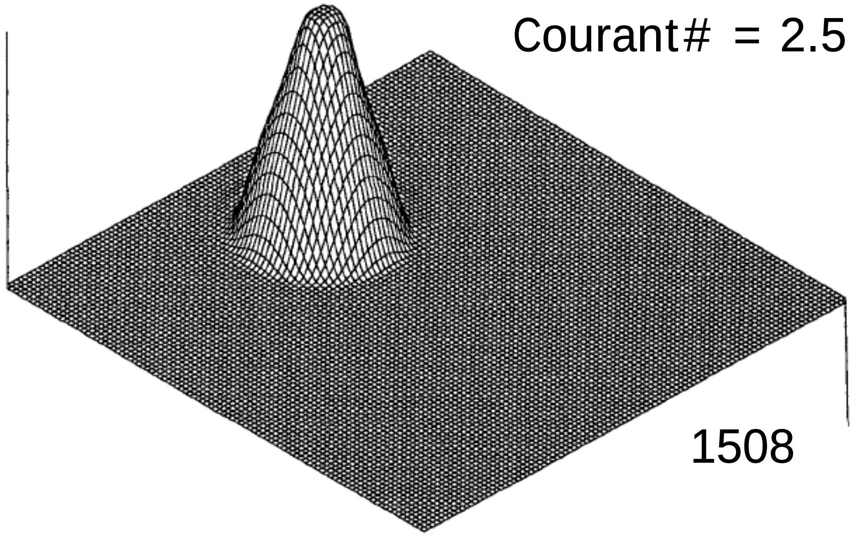
- Extension can be view as an integer shift of the tracer distribution followed by a normal Eulerian transport for the fractional part.



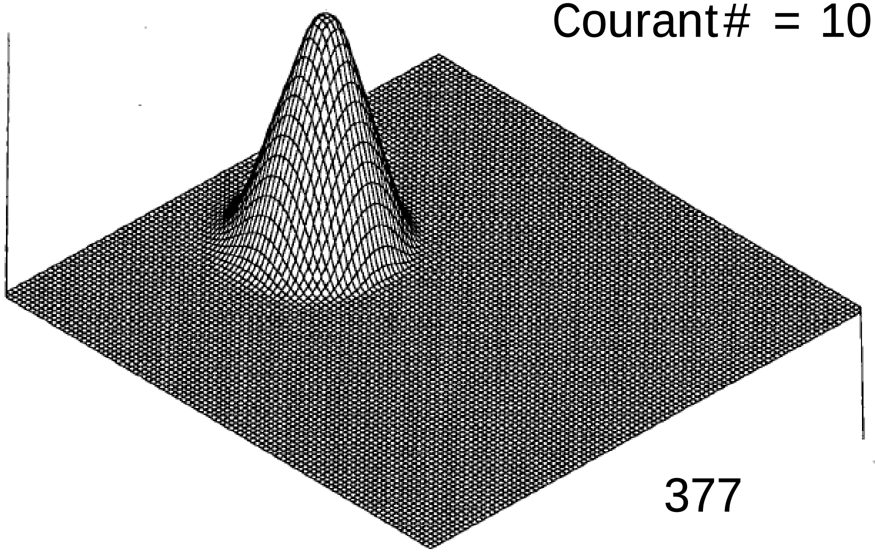


Initial condition

PPM FFSL,
Courant# = 2.5



PPM FFSL,
Courant# = 10



- Mass is exactly conserved
- Adding a constant background value does NOT change the finial 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

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

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:

$$\frac{\partial}{\partial t}\delta p + \frac{1}{A\ \cos\theta}\left[\frac{\partial}{\partial \lambda}(u\delta p) + \frac{\partial}{\partial \theta}(v\delta p\ \cos\theta)\right] = 0,$$

$$\frac{\partial}{\partial t}u = \Omega v - \frac{1}{A\ \cos\theta}\left[\frac{\partial}{\partial \lambda}(\kappa + \phi - \nu D) + \frac{1}{\rho}\frac{\partial}{\partial \lambda}p\right]$$

$$\frac{\partial}{\partial t}v = -\Omega u - \frac{1}{A}\left[\frac{\partial}{\partial \theta}(\kappa + \phi - \nu D) + \frac{1}{\rho}\frac{\partial}{\partial \theta}p\right]$$

Time-splitting

- Take advantage of the large time step (Δt) of the transport scheme.
- The dynamics uses a relative small time step (Δ τ) to stabilize the fast wave

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

$$()_i^{\theta} = ()^{n+(i-1)/m} + \frac{1}{2} g[\upsilon_i^{*}, \Delta\tau, ()^{n+(i-1)/m}],$$

$$()_i^{\lambda} = ()^{n+(i-1)/m} + \frac{1}{2} f[u_i^{*}, \Delta t, ()^{n+(i-1)/m}]$$

Hybrid σ-p Coordinate

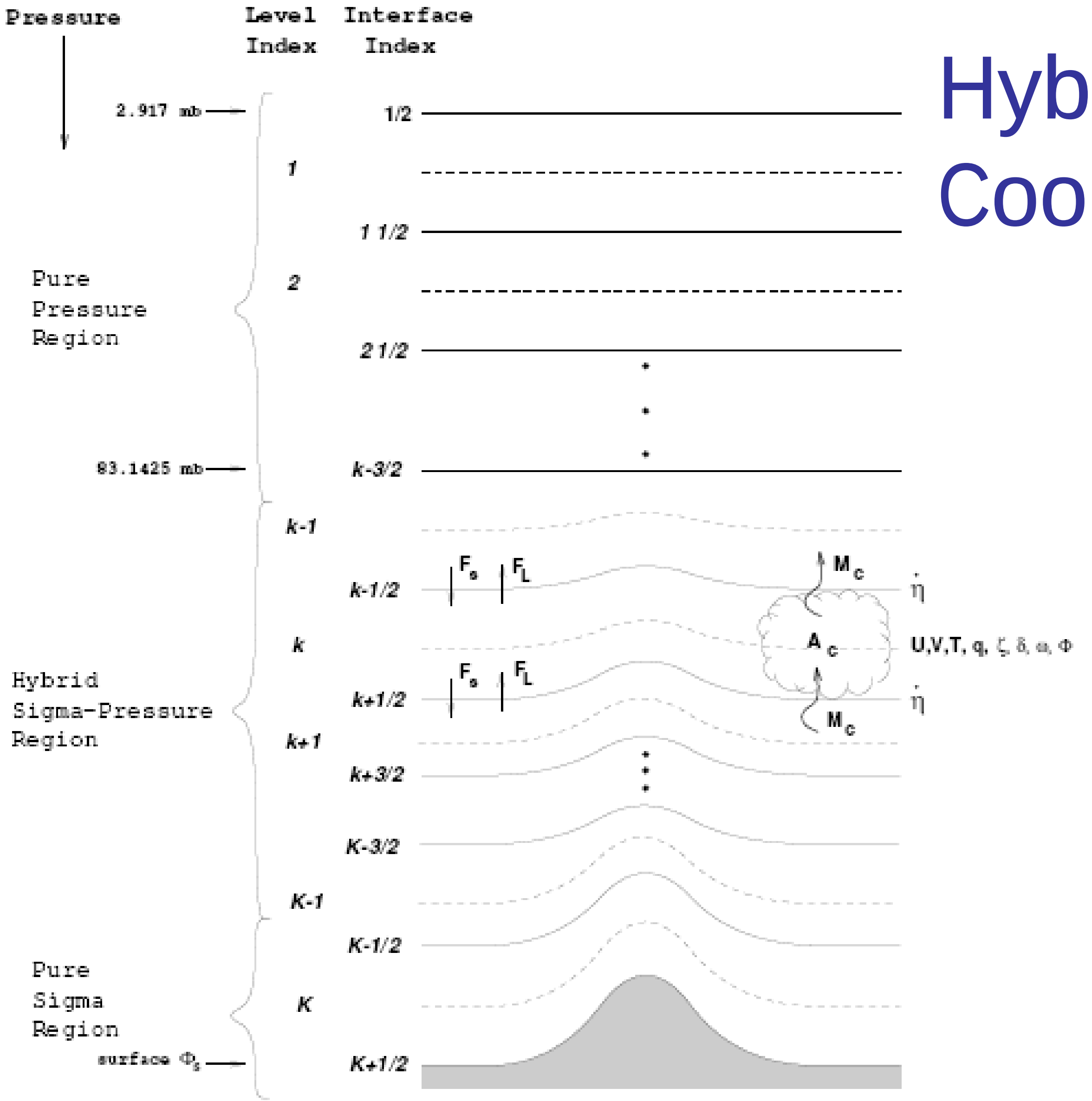
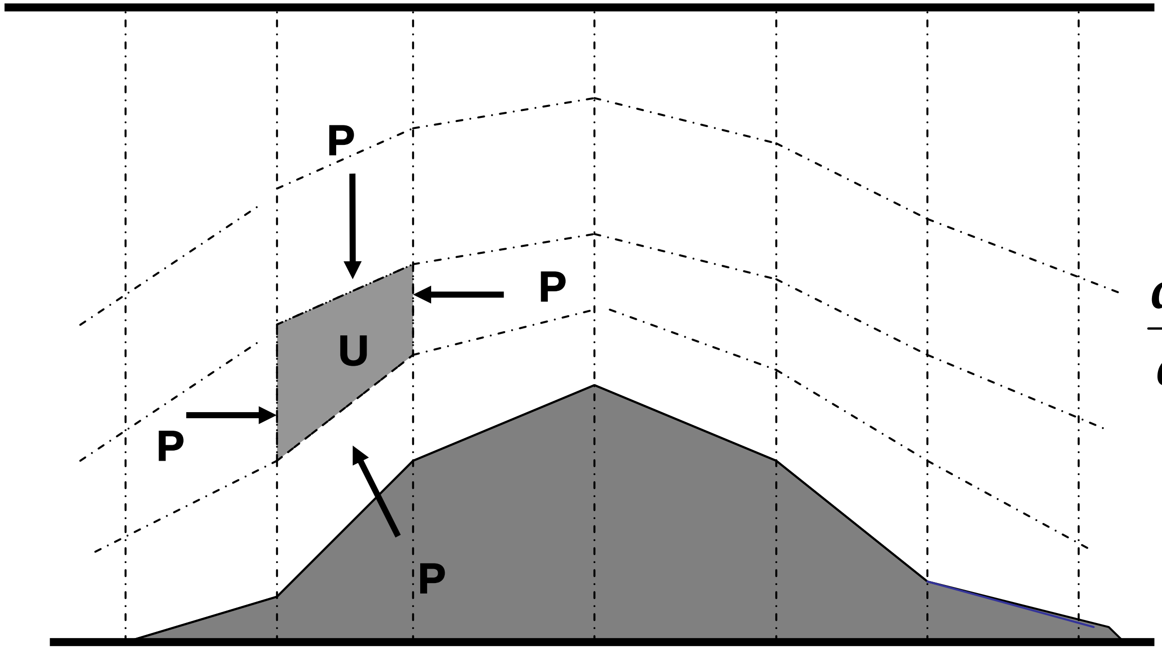


Figure 3.1: Vertical level structure of CAM 3.0

Pressure gradient term



The absolute PG error reduce dramatically when over 20 levels

$$\sum F = \int_C pnds$$

$$\frac{du}{dt} = \frac{\sum F_x}{\Delta m}$$

$$\frac{du}{dt} = -\frac{\iint \frac{\partial \phi}{\partial x} dxd\pi}{\iint dxd\pi} = \frac{\int_C \phi d\pi}{\int_C \pi dx}$$

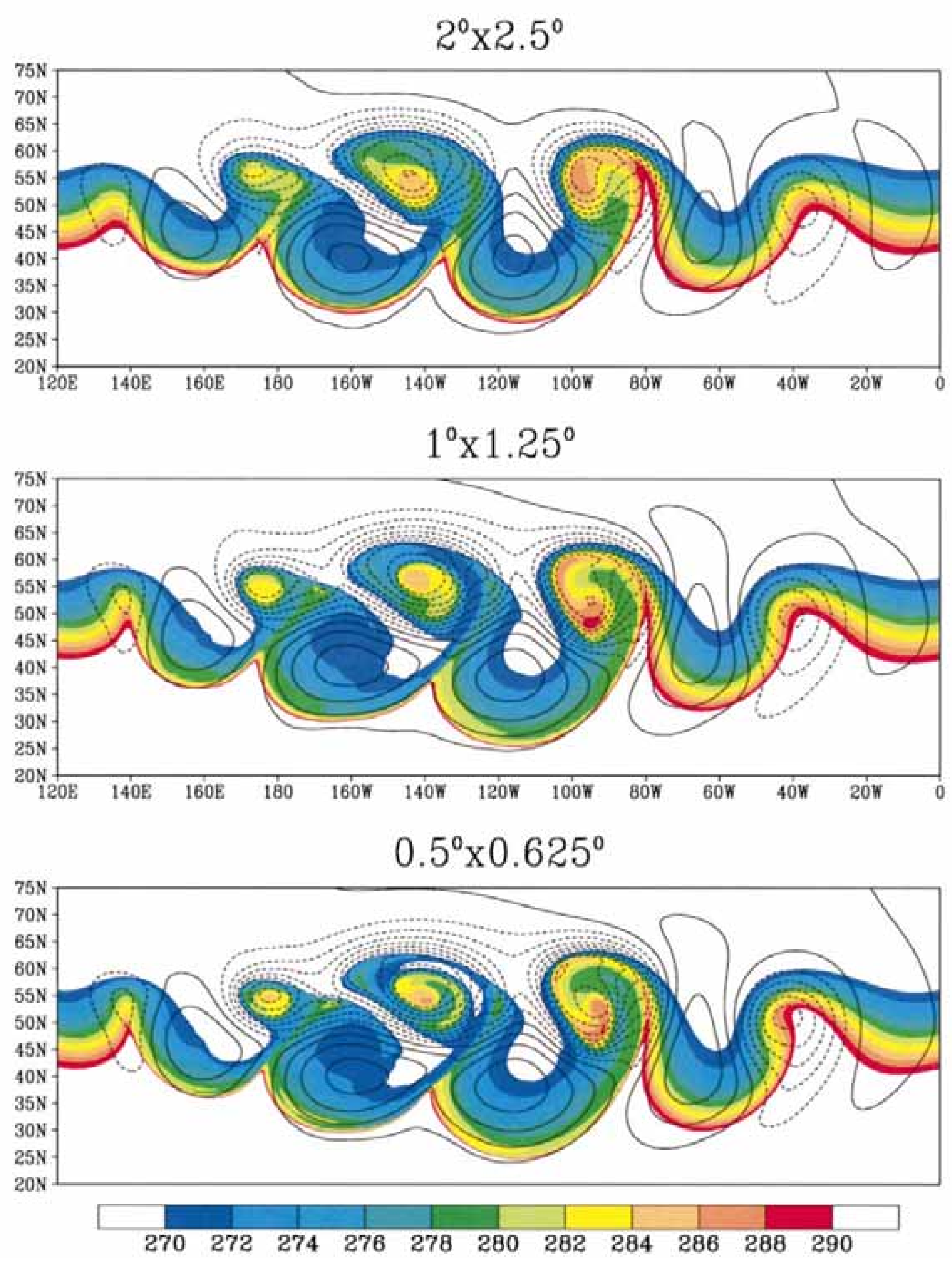
π is a function of P

$$\delta\phi = -C_p \theta_0 \delta P^k$$

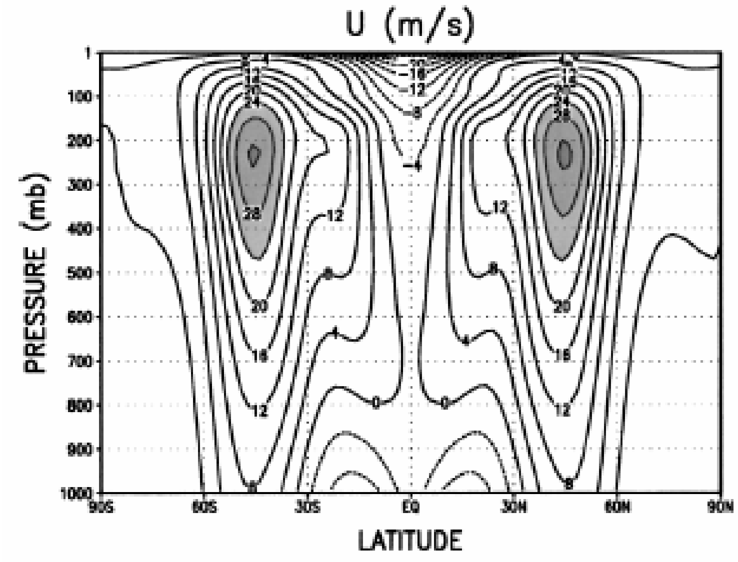
$$\pi = P^k \quad k = R/C_p$$

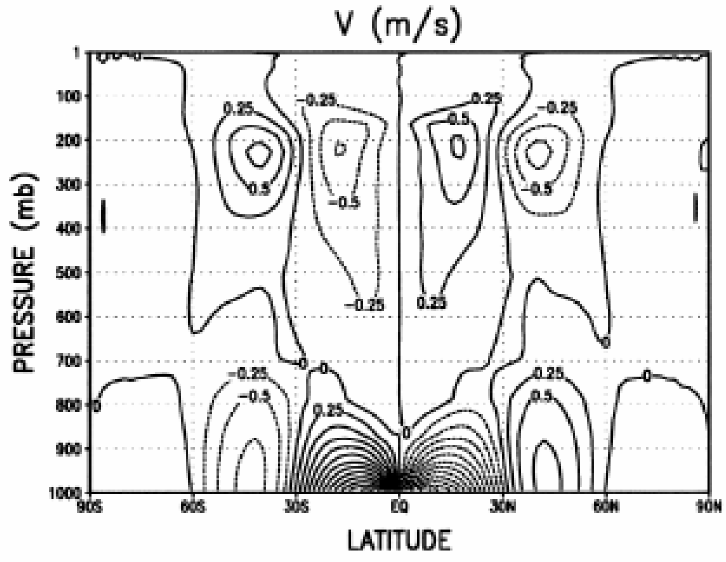
Perturbation test

- 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

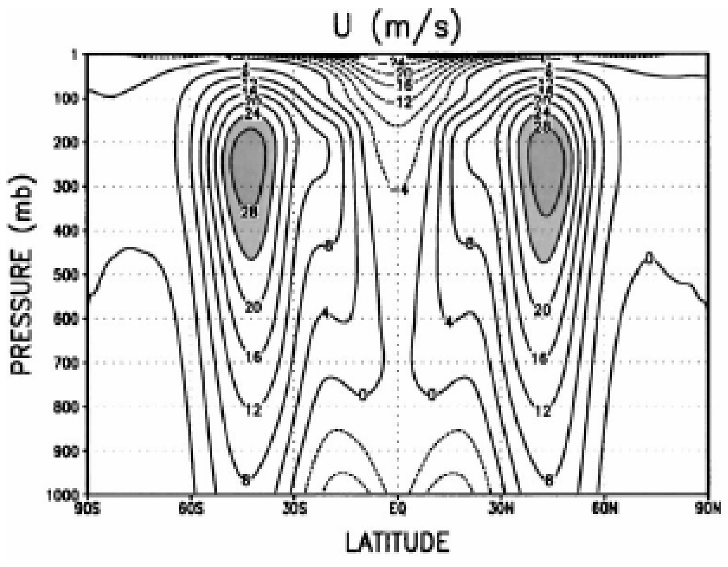


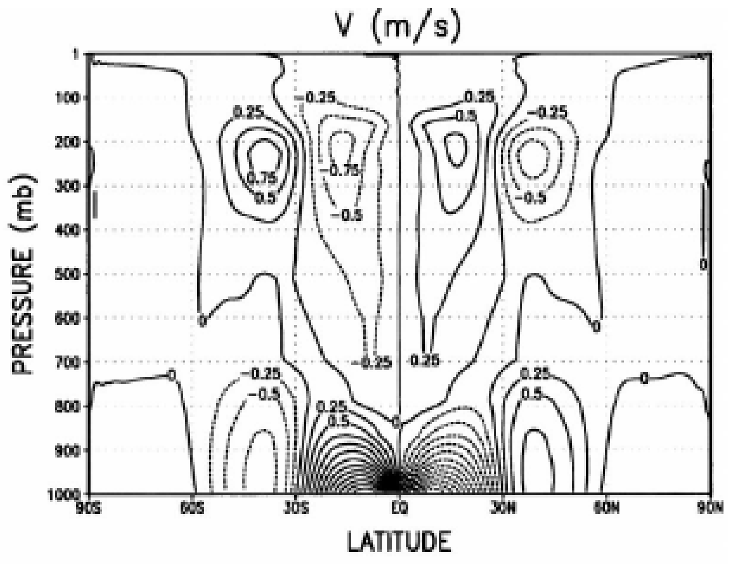
Held and Suarez's forcing



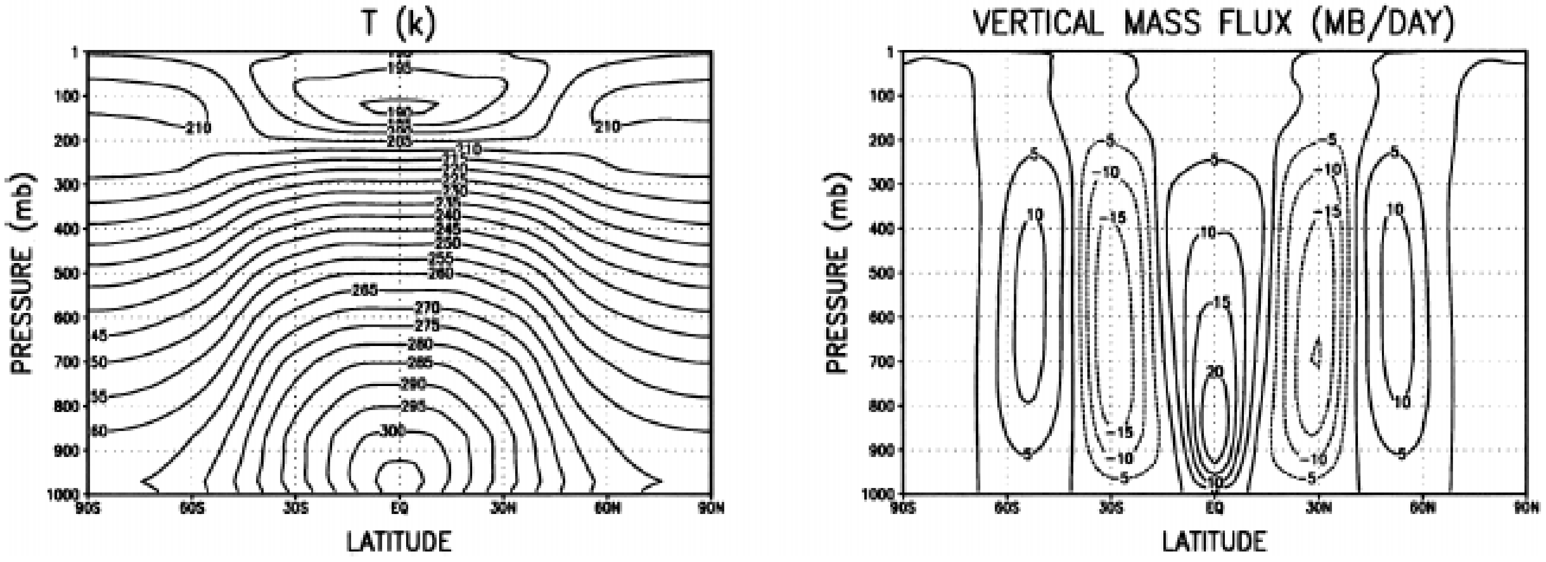


2x2.5

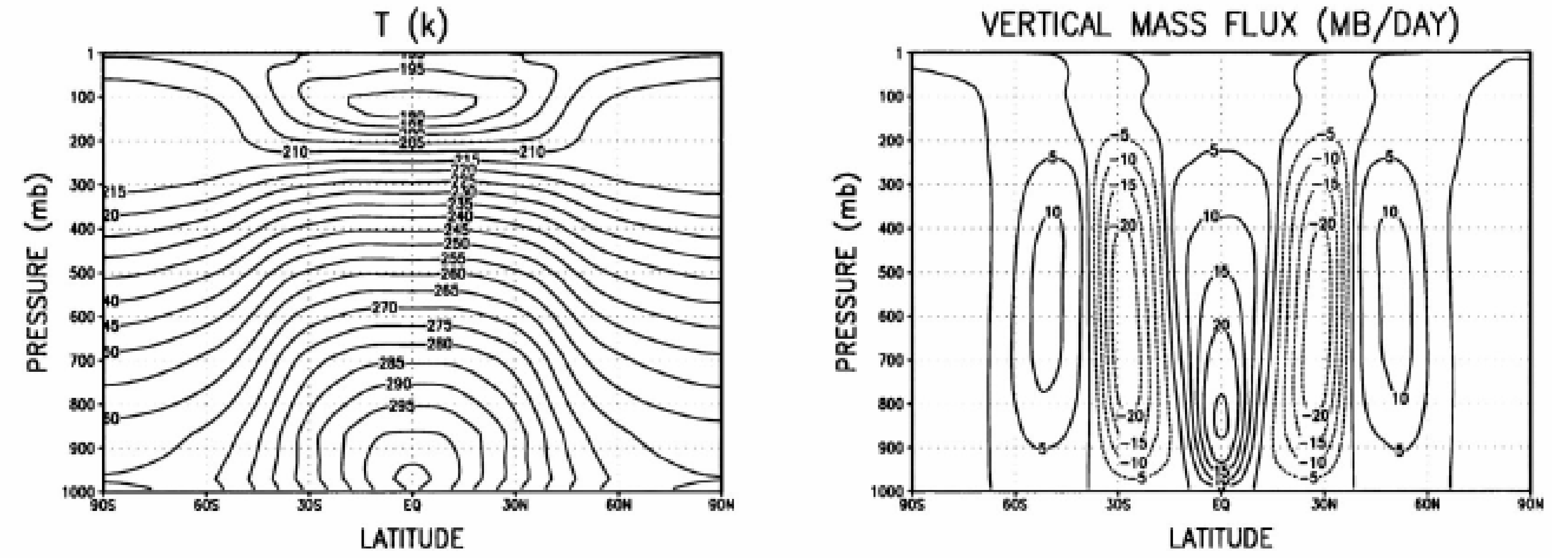




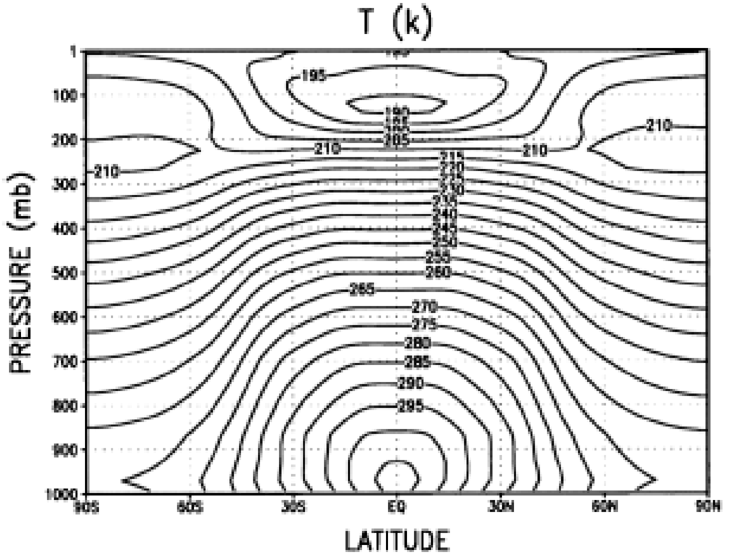
1x1.25

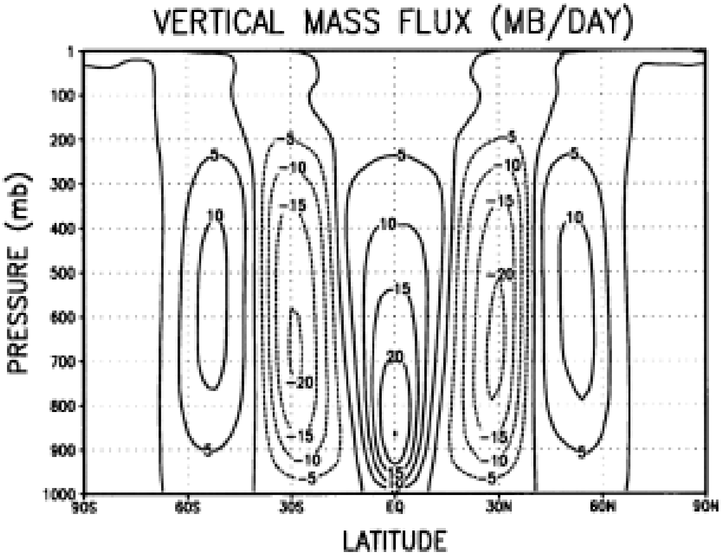

T (k)
VERTICAL MASS FLUX (MB/DAY)
PRESSURE (mb)
LATITUDE
1
100
200
300
400
500
600
700
800
900
1000
90S
60S
30S
EQ
30N
60N
90N

2x2.5

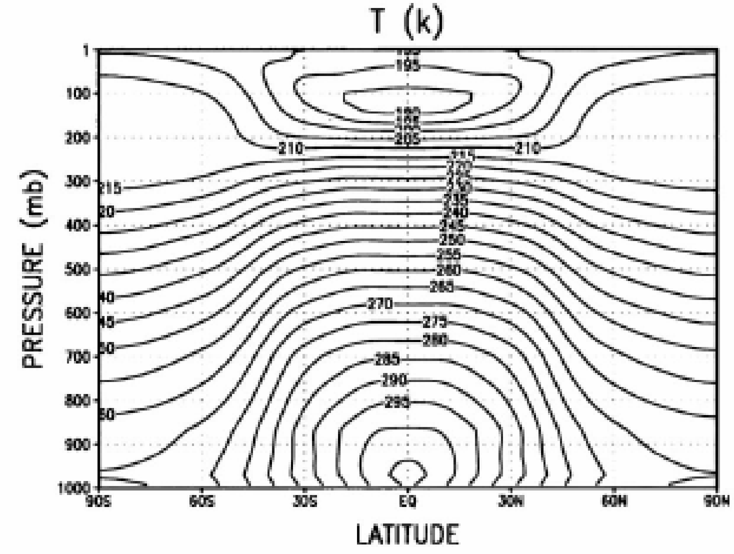

T (k)
VERTICAL MASS FLUX (MB/DAY)
PRESSURE (mb)
LATITUDE
1
100
200
300
400
500
600
700
800
900
1000
90S
60S
30S
EQ
30N
60N
90N

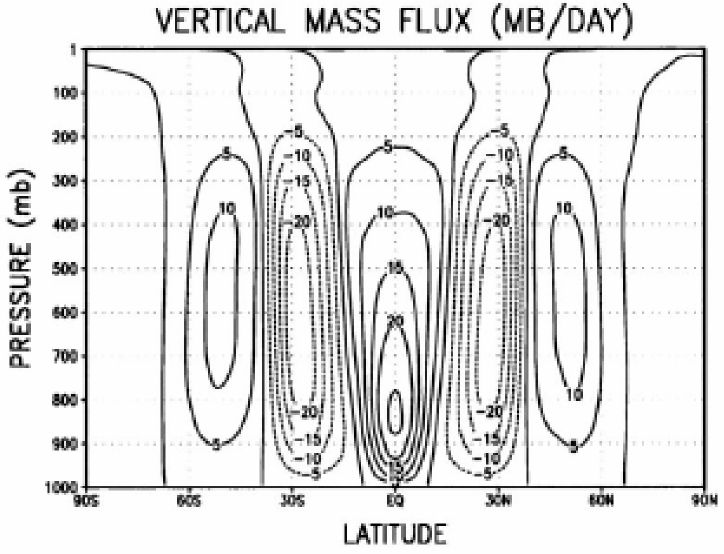
1x1.25





2x2.5
Without
Monotonicity
constraint





1x1.25

conclusion

- 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.

References

- Lin, S.-J., 1997: A finite-volume integration method for computing pressure gradient forces in general vertical coordinates. *Quart. J. Roy. Meteor. Soc.,* **123,** 1749–1762.
- Lin, and R. B. Rood, 1996: Multidimensional flux form semi-Lagrangian transport schemes. *Mon. Wea. Rev.,* **124,** 2046–2070.
- Lin, 2004. A ‘‘Vertically Lagrangian’’ Finite-Volume Dynamical Core for Global Models. *Mon. Wea. Rev.,* **132,** 2293–2307.
- Collins et al, 2004. CAM3.0 scientific description, Chapter 3. NCAR.

Thank you