



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.cesm.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

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

$\pi = \frac{\partial p}{\partial \zeta}$ “*pseudo-density*” § 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

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

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

Coriolis
Force

Kinetic
energy

Horizontal
divergence

P.G.F



Flux-form Semi-Lagrangian scheme

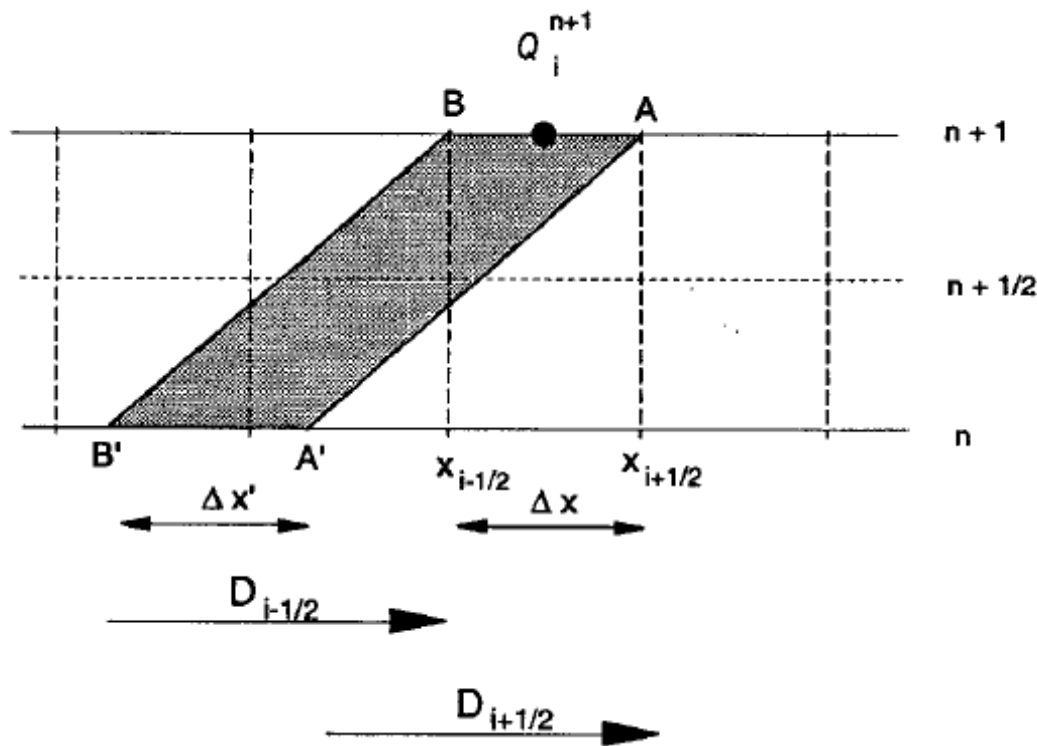
- Advection of tracer transport [Lin and Rood, 1996]
- Apply to dynamics of the hydrostatic flow [Lin and Rood, 1997]
Pressure gradient force [Lin, 1997]
- A vertically Lagrangian FV dynamical core [Lin, 2004]



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



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

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

- Mass conservation equation

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

Contour integral

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

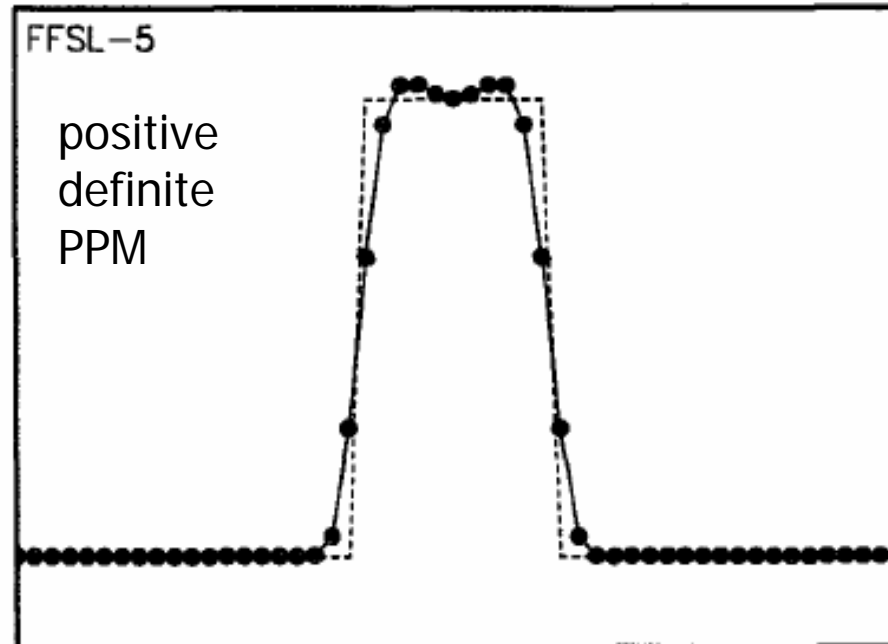
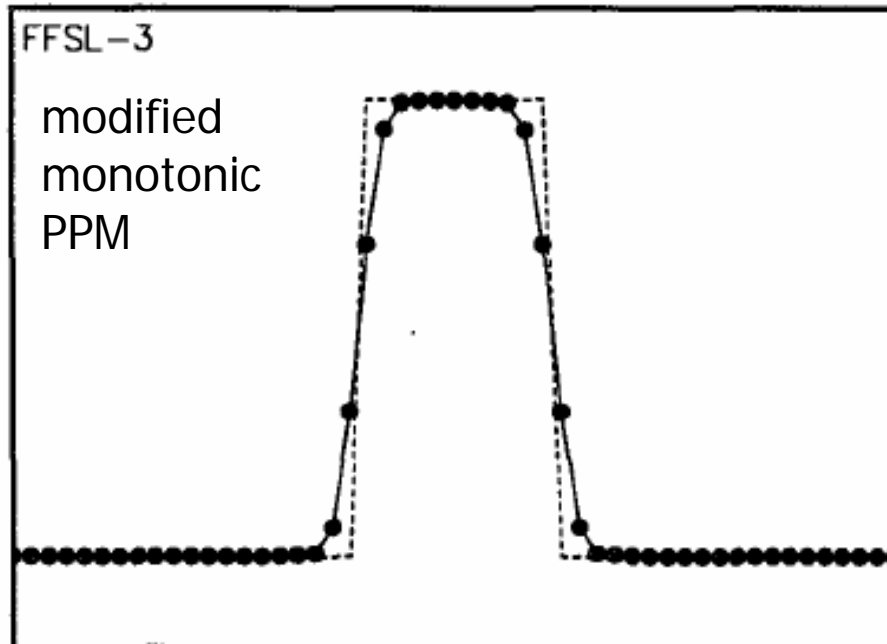
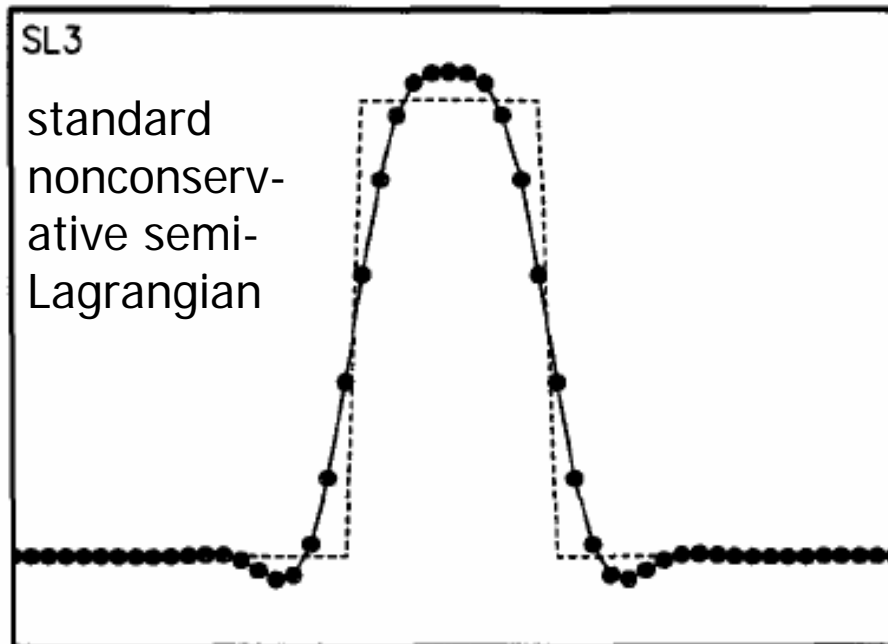
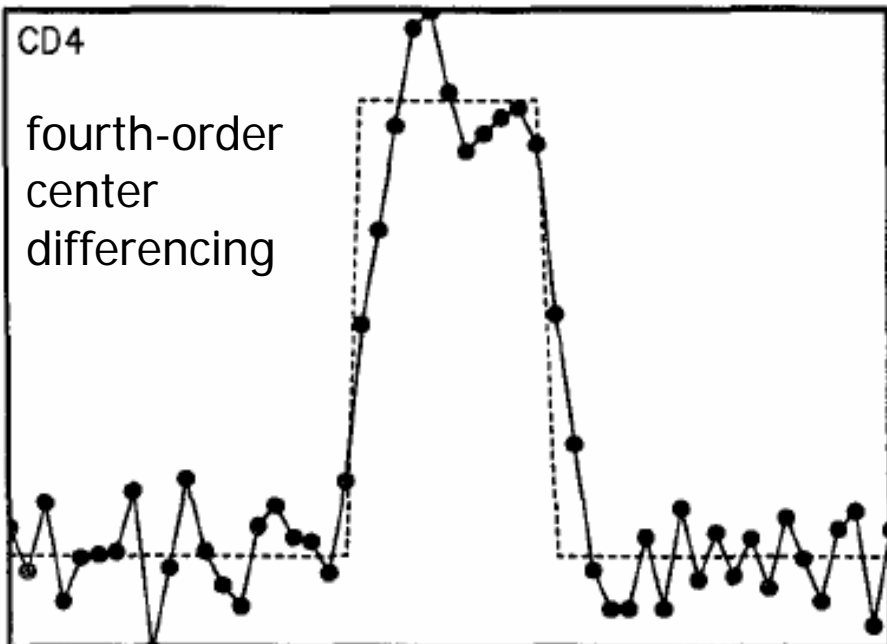
Splitting error

Forward-in-time Flux-form transport operator=
"increments" of one time step

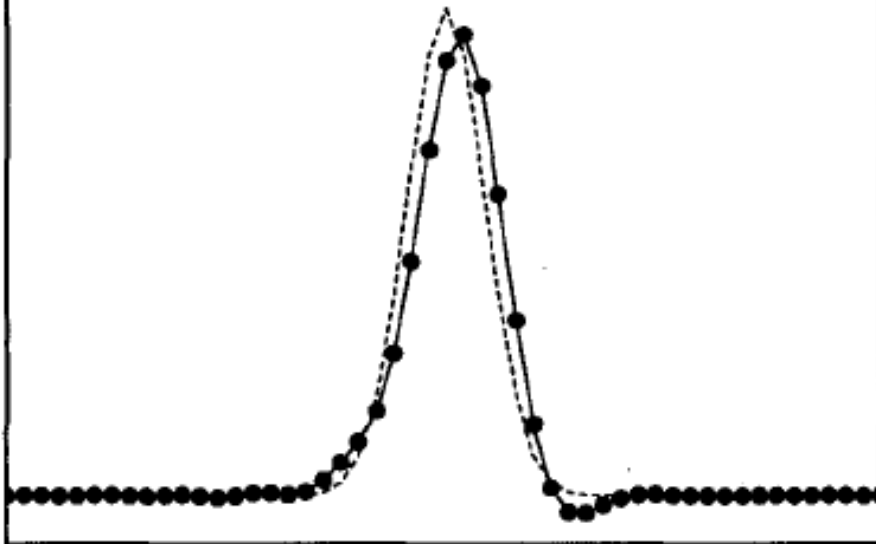


Subgrid distribution

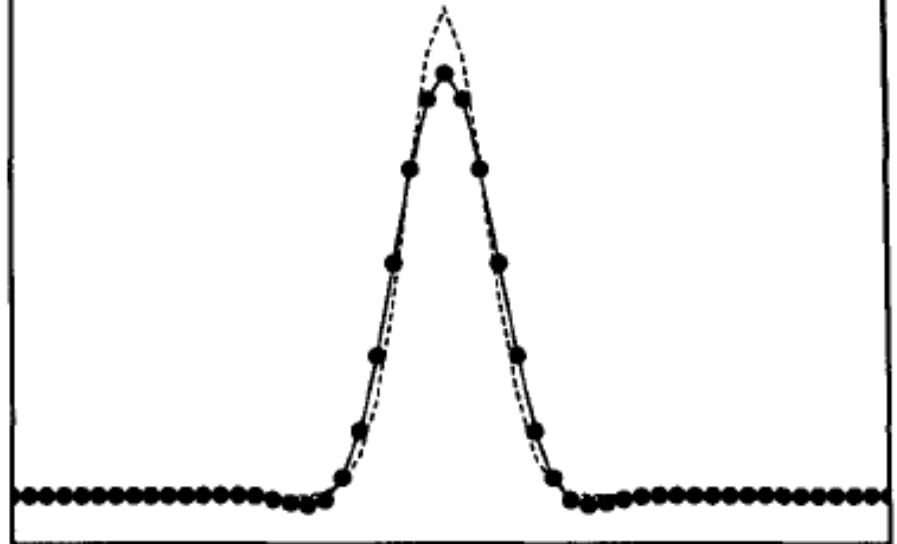
- Constant
- Piece-wise linear
- PPM – piece-wise parabolic Method
accurate and computational efficient, mass
conserving, monotonicity preserving
monotonic constraint works as a subgrid
mixing smoother



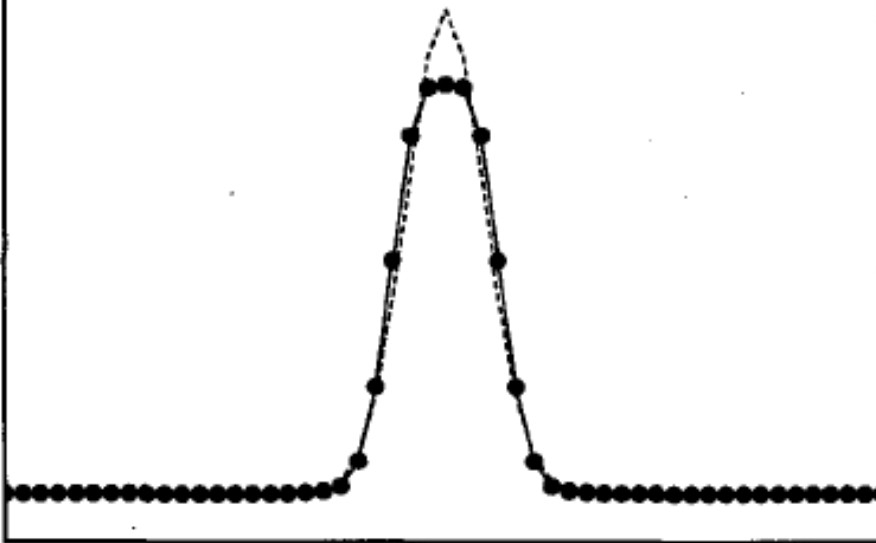
CD4



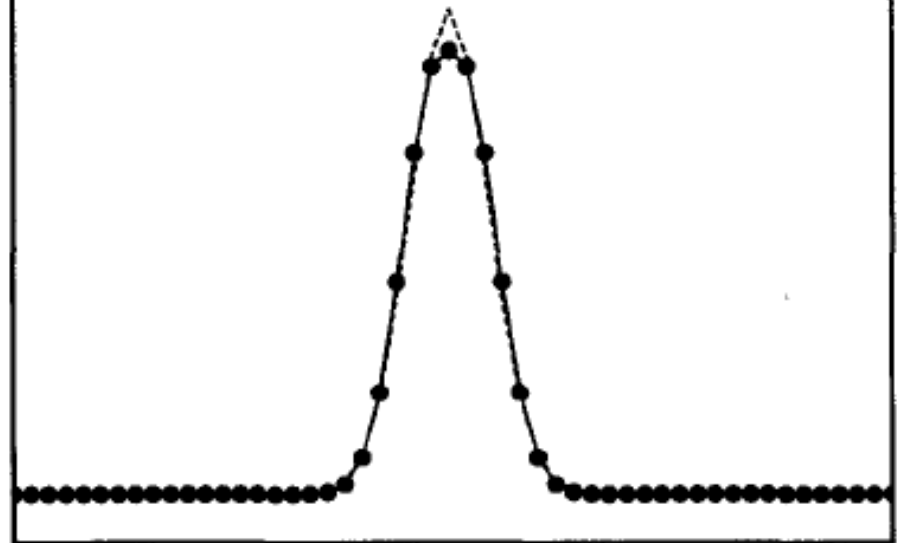
SL3

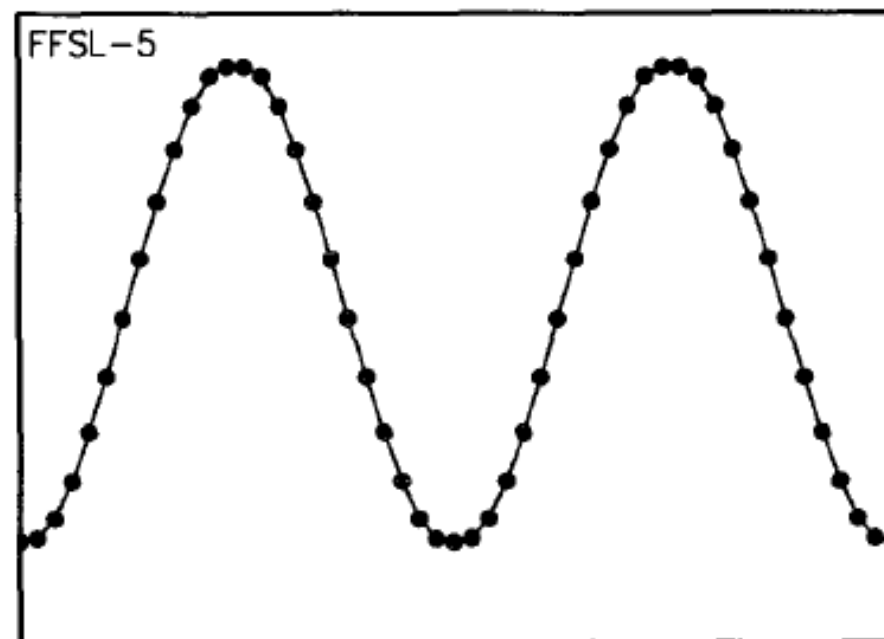
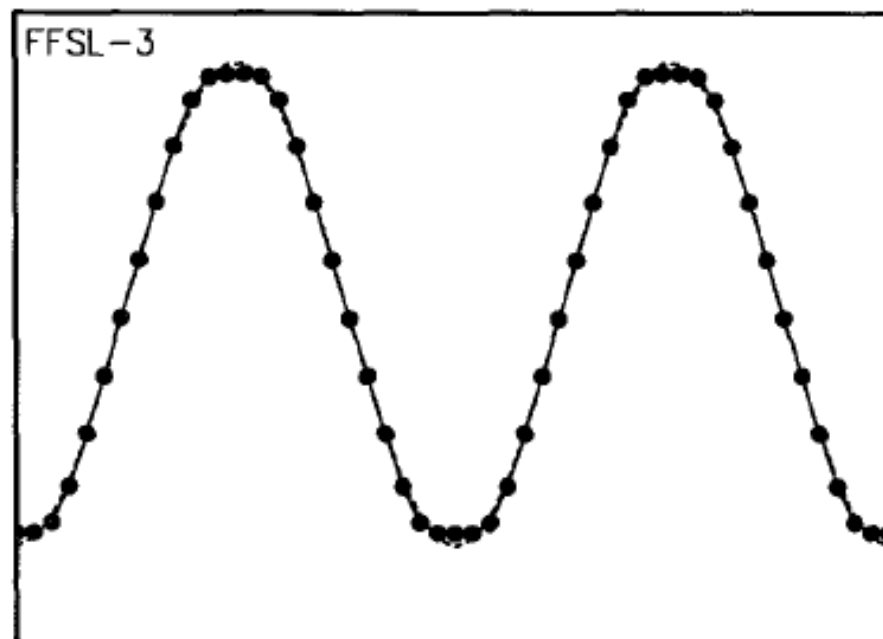
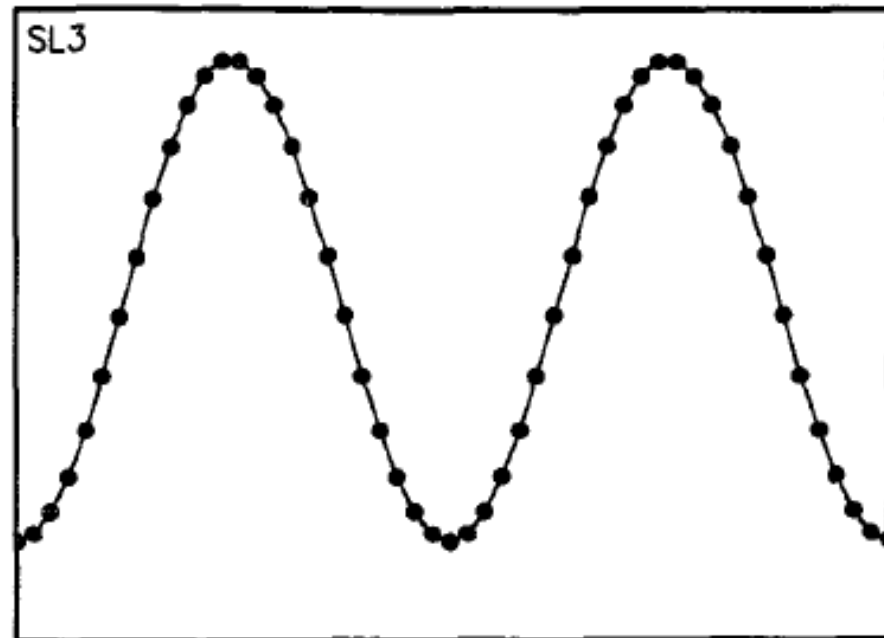
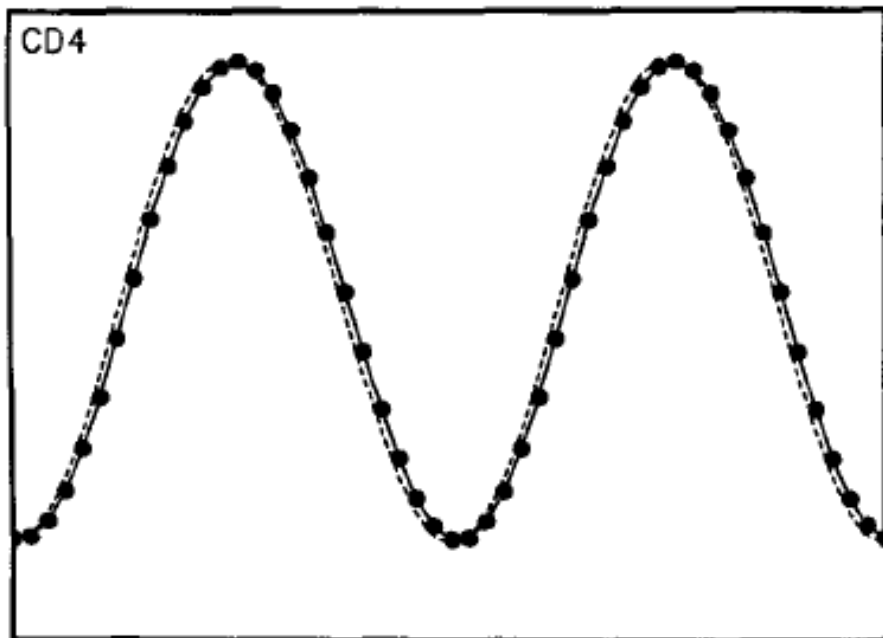


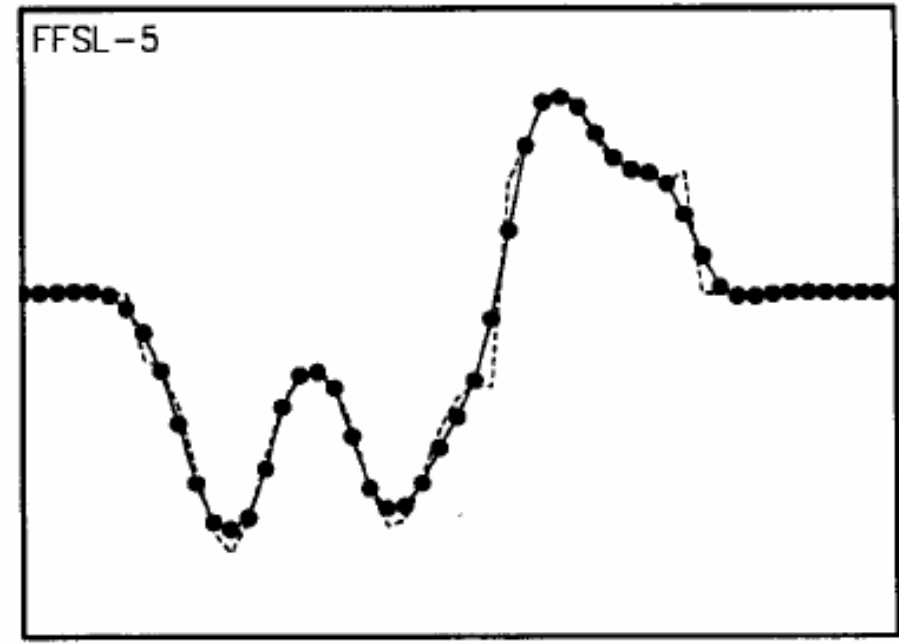
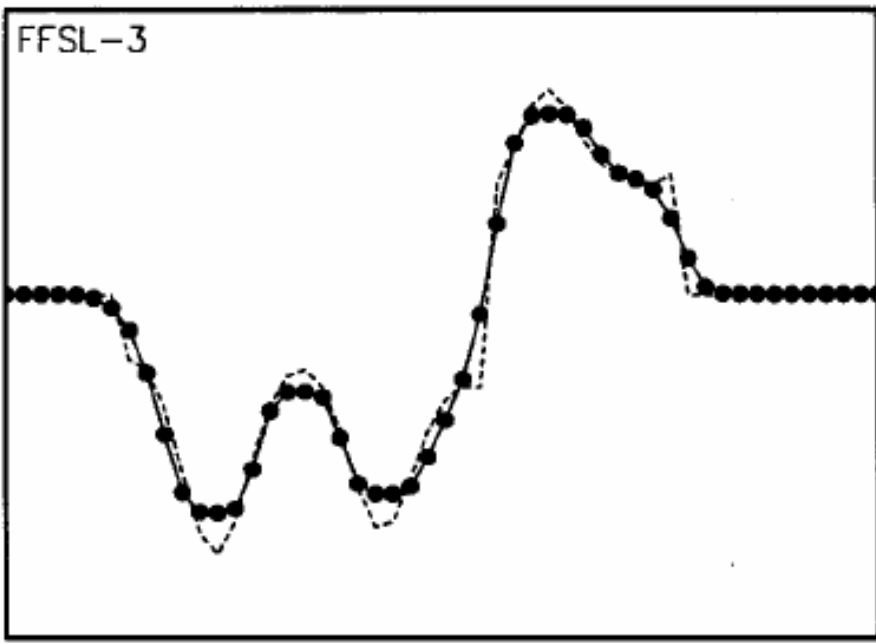
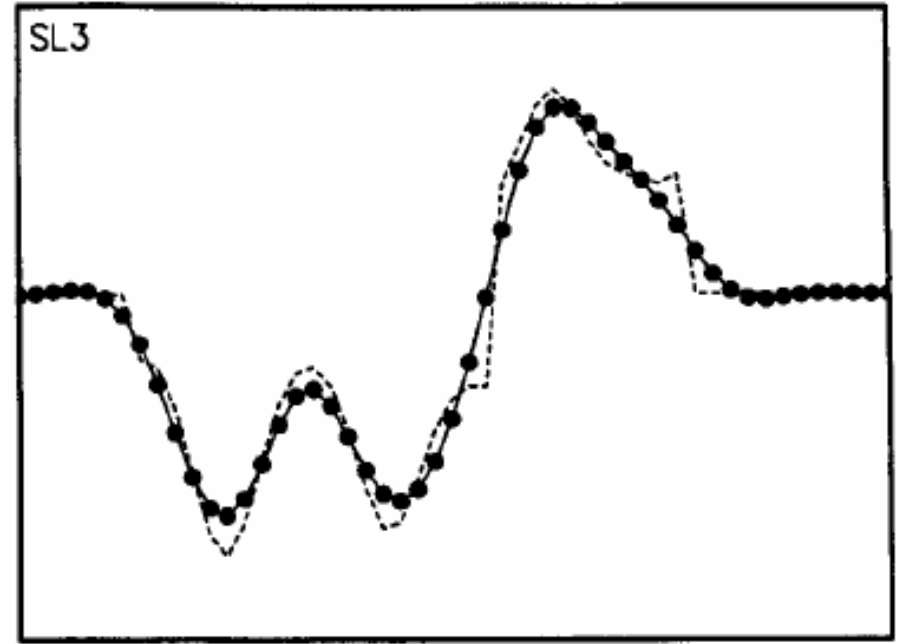
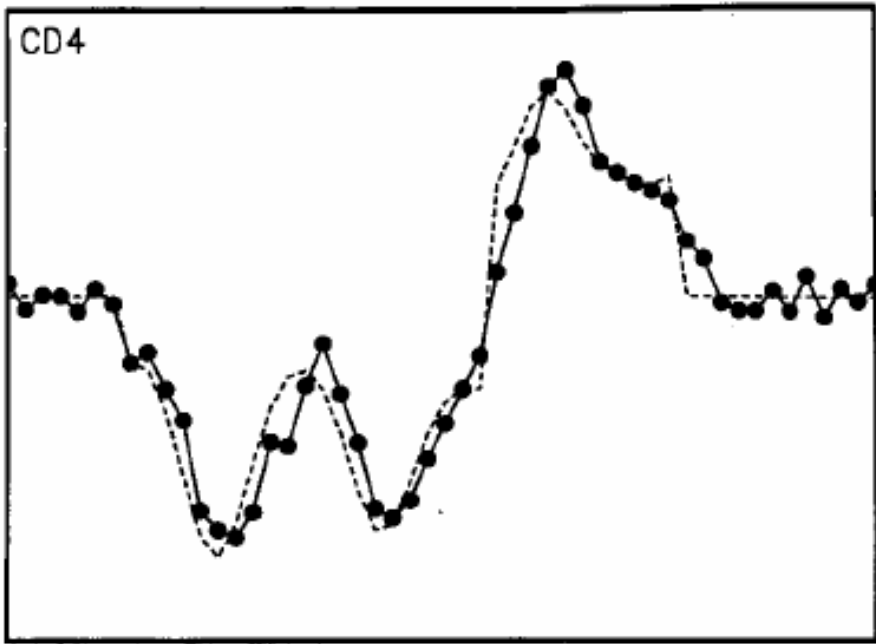
FFSL-3



FFSL-5







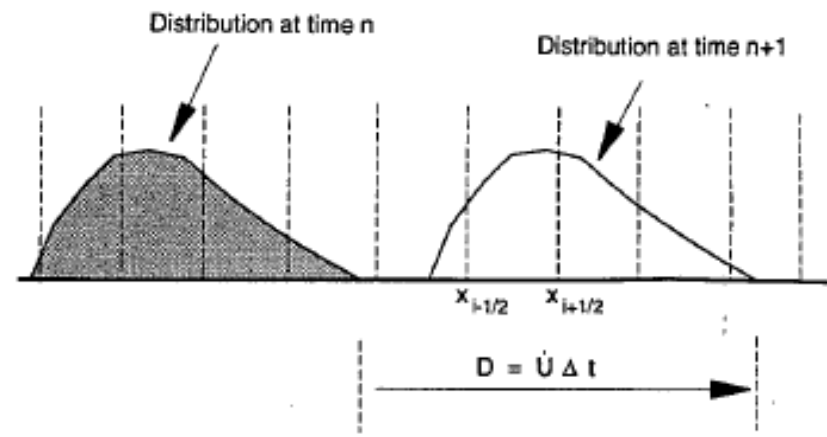


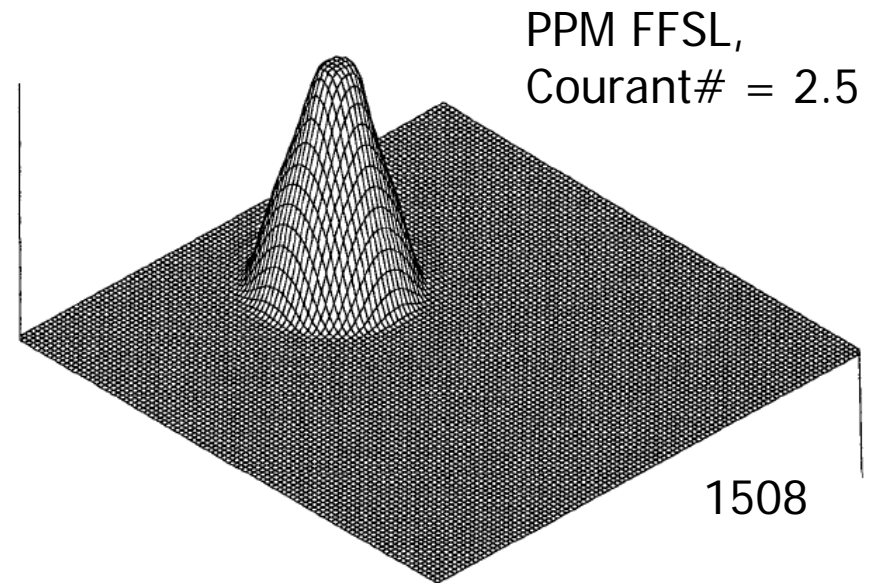
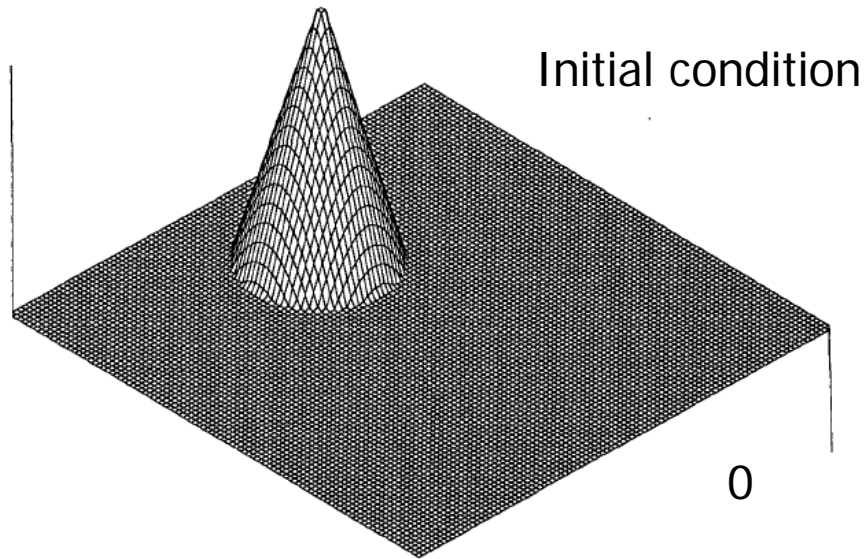
Comparison

- 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.

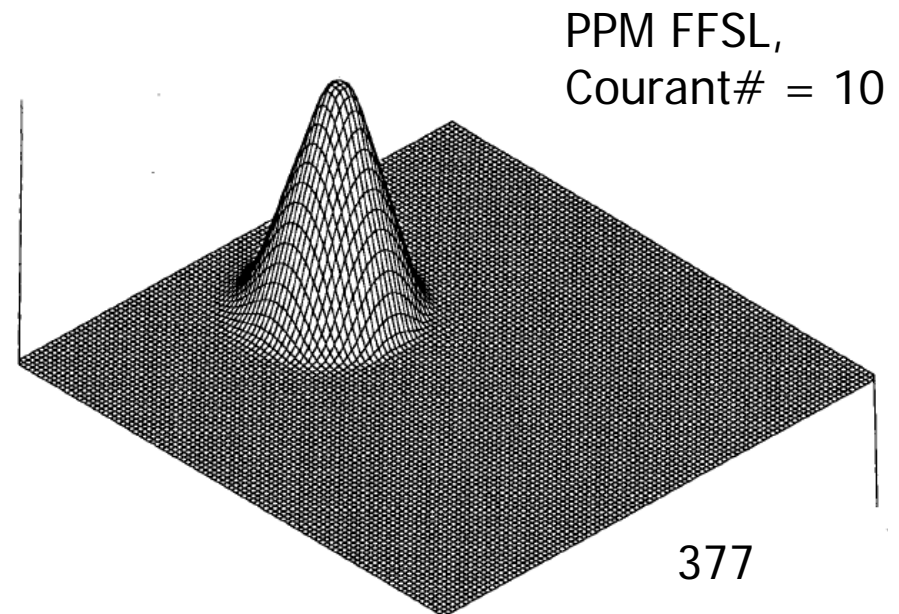
Extend to large time step

- 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.





- 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:

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

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

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



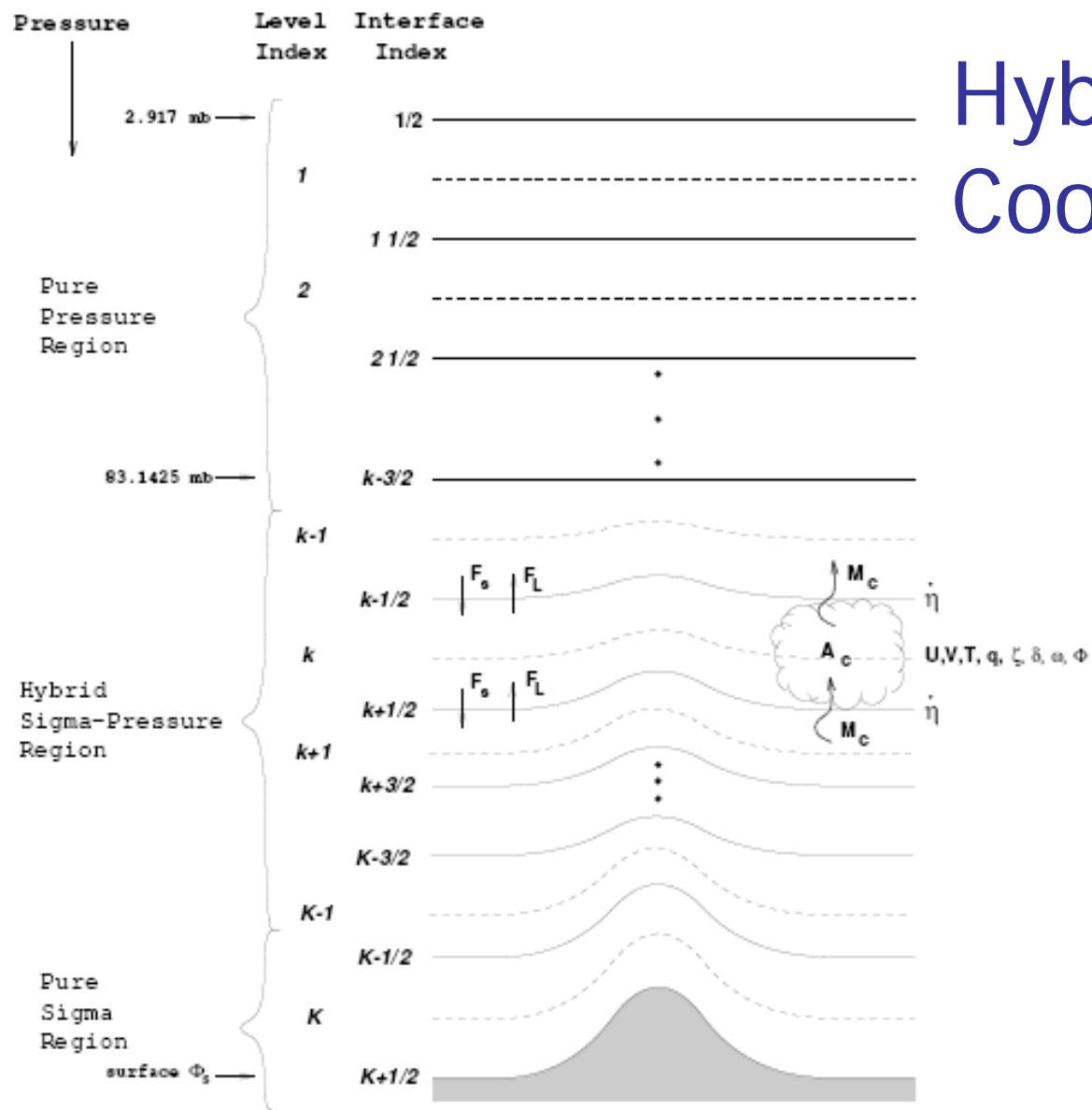
Time-splitting

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

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

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

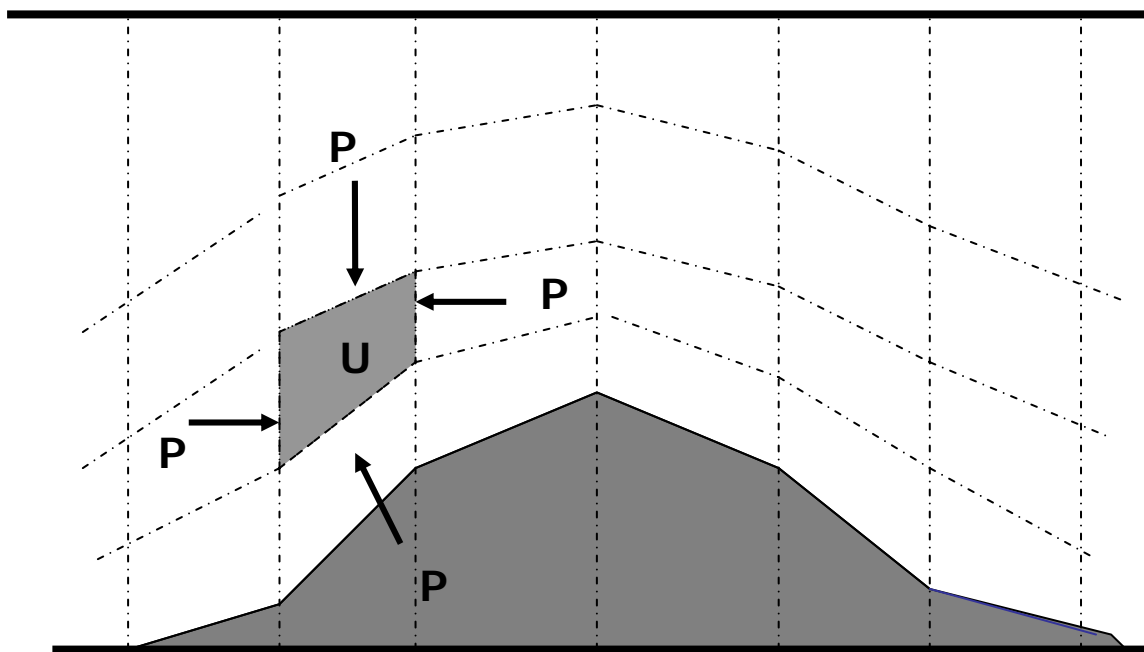
$$(\lambda)_i^n = (\lambda)_i^{n+(i-1)/m} + \frac{1}{2} f[u_i^*, \Delta t, (\lambda)_i^{n+(i-1)/m}]$$



Hybrid $-p$ Coordinate

Figure 3.1: Vertical level structure of CAM 3.0

Pressure gradient term



$$\sum F = \int_C p n ds$$

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

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

π is a function of P

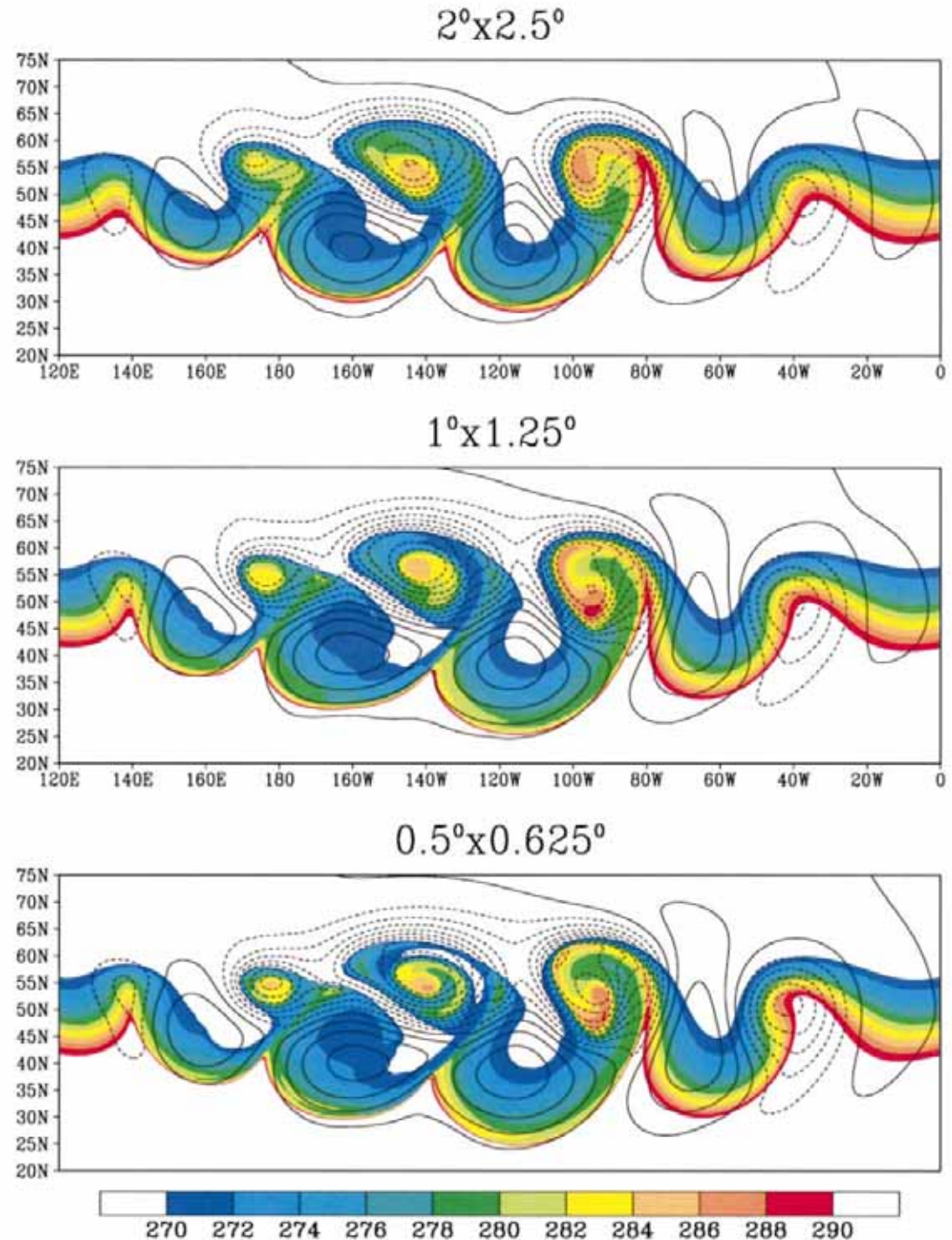
$$\delta \phi = -C_p \theta_0 \delta P^k$$

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

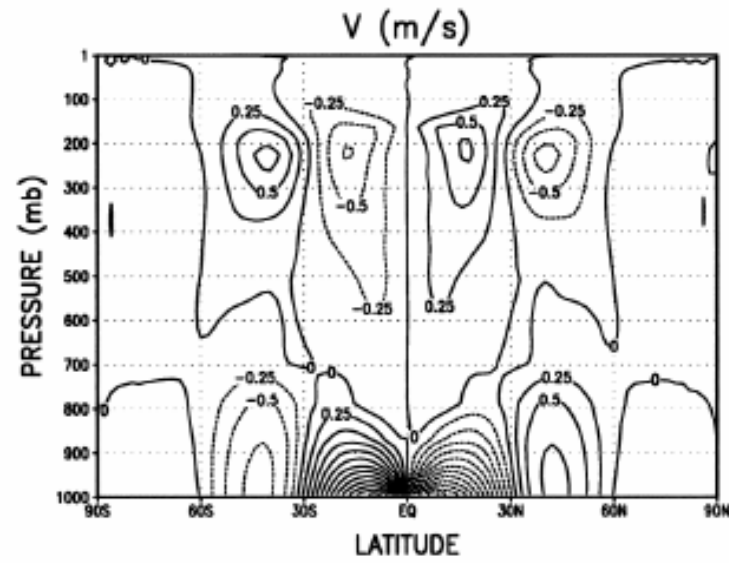
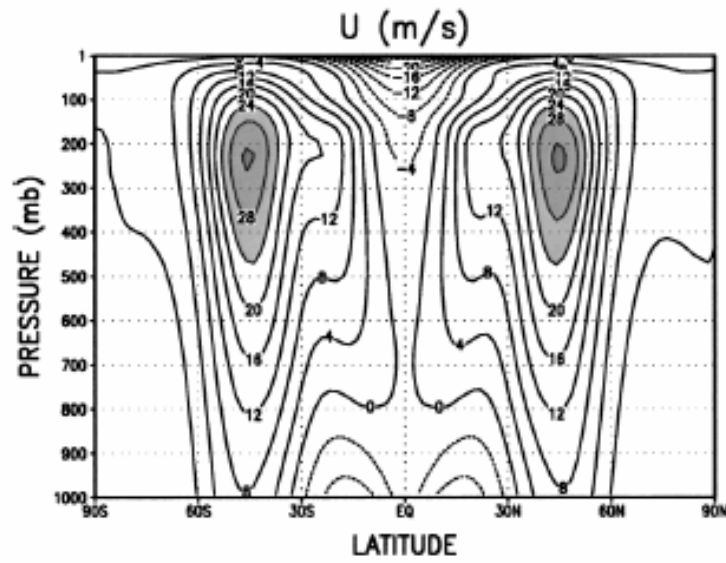
The absolute PG error reduce dramatically when over 20 levels

Perturbation test

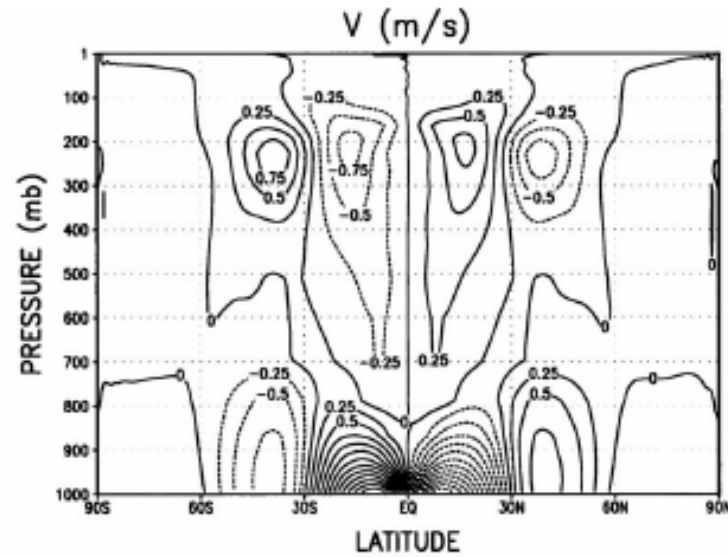
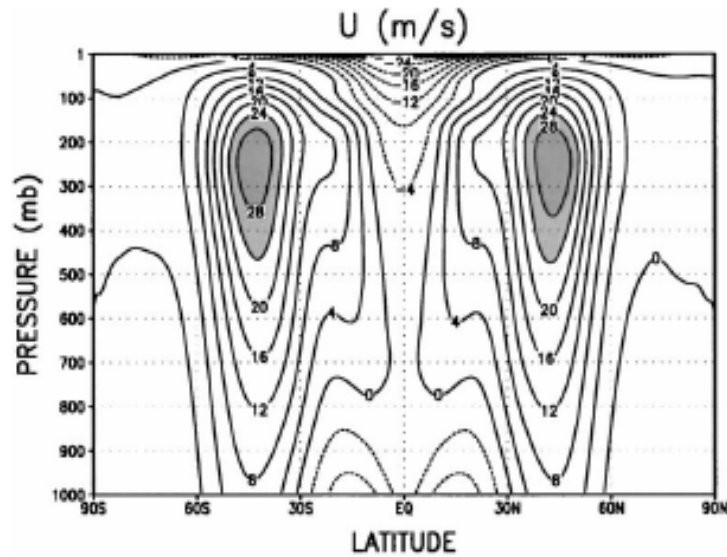
- Trigger the baroclinic instability by a T perturbation at 45N, 90E
- Surface pressure perturbation and T at the lowest model layer at day 10.
- Weaker amplitude for 2x2.5
- Detailed feature unresolved in 0.5x0.625
- Monotonic constrain damps strongly on the two-grid-scale structure



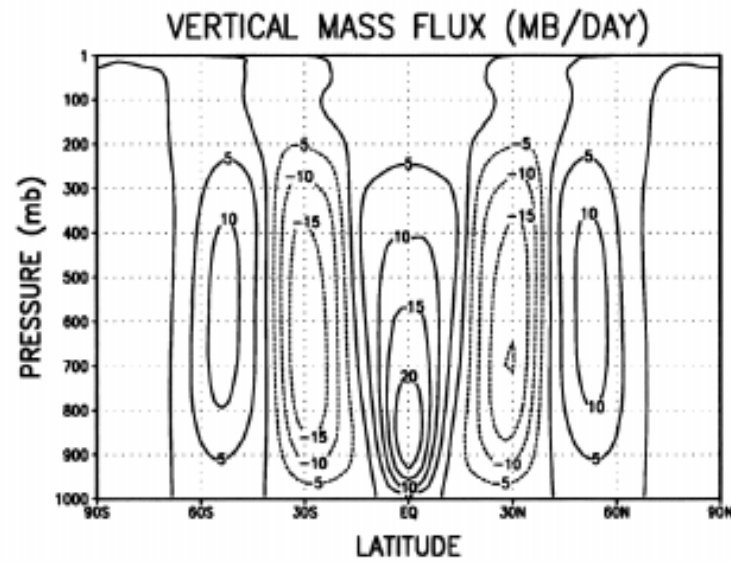
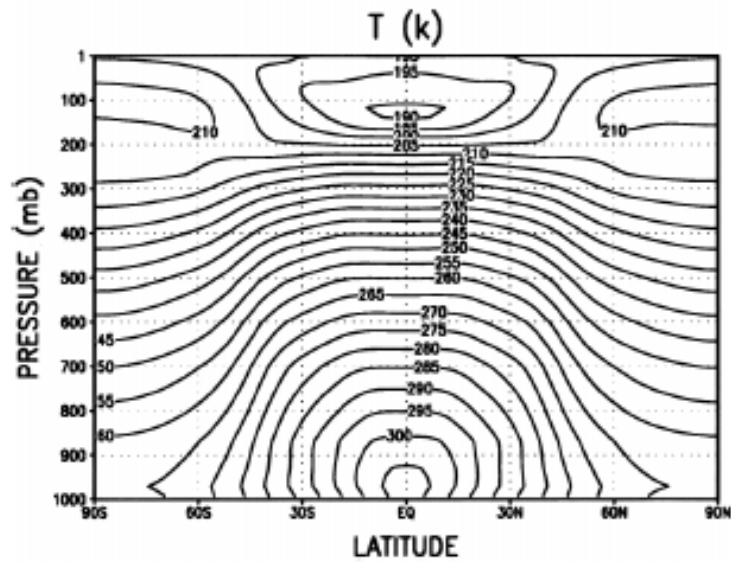
Held and Suarez's forcing



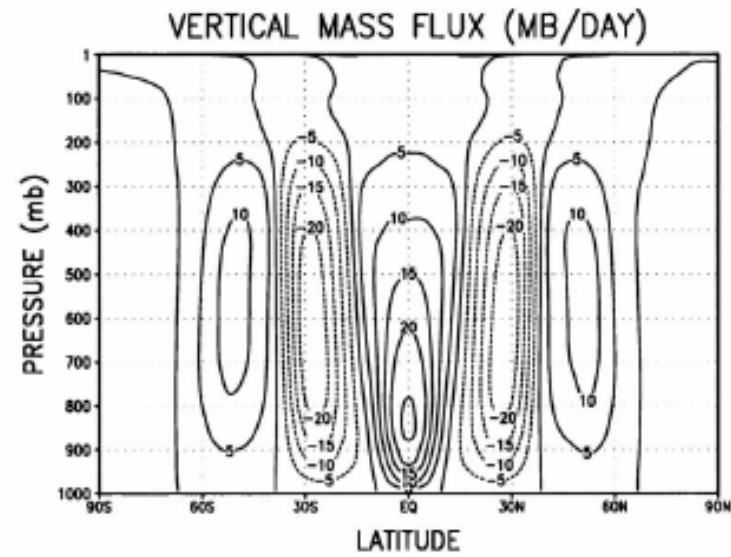
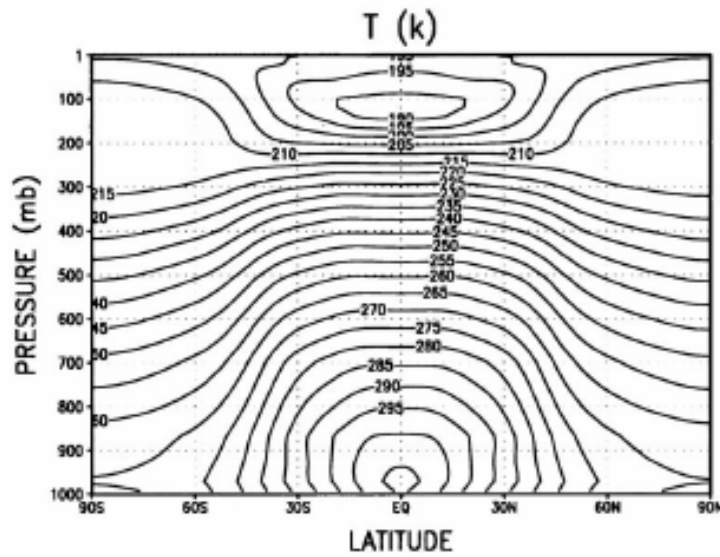
2x2.5



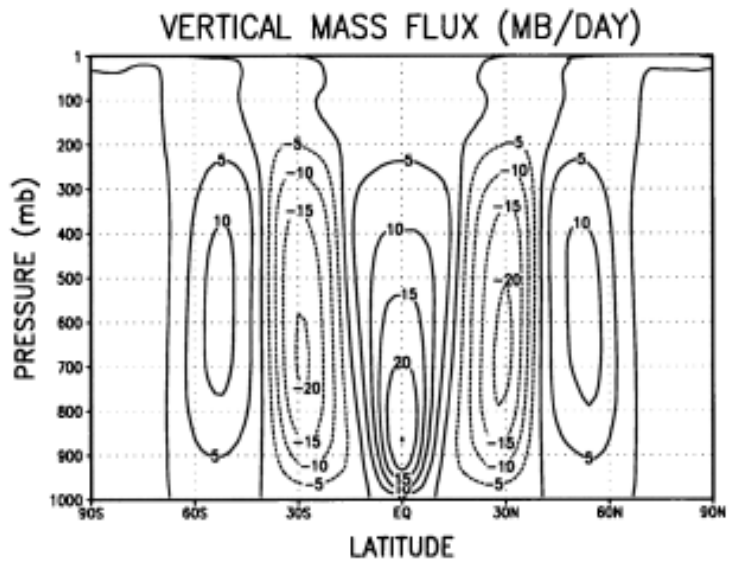
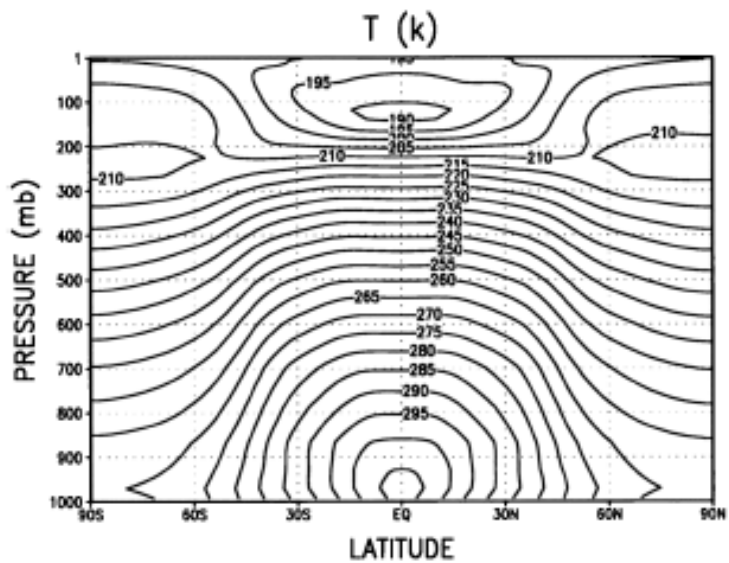
1x1.25



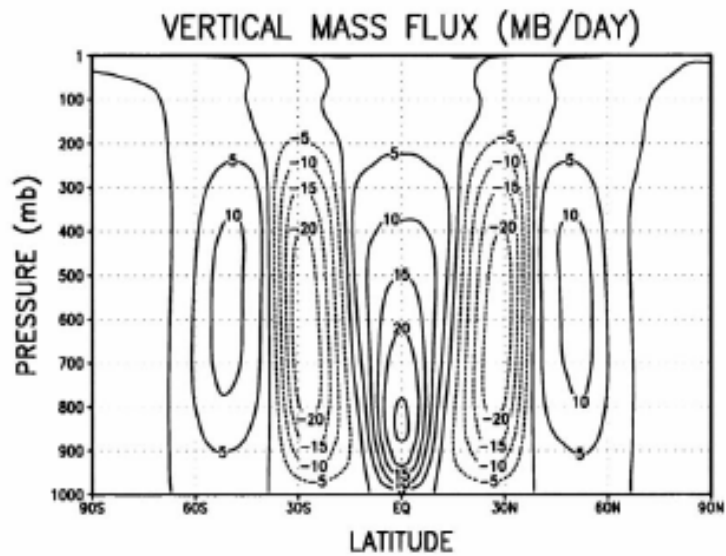
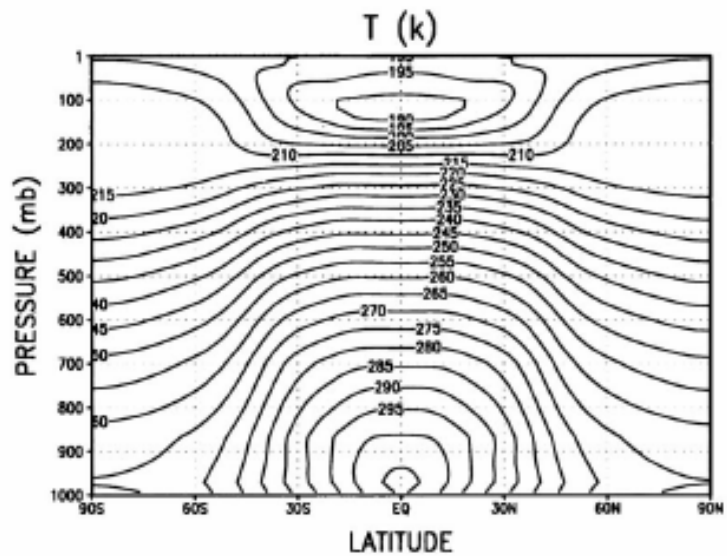
2x2.5



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.

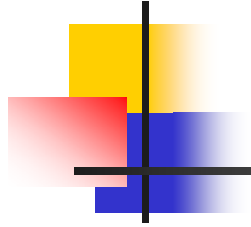
- Output

- 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