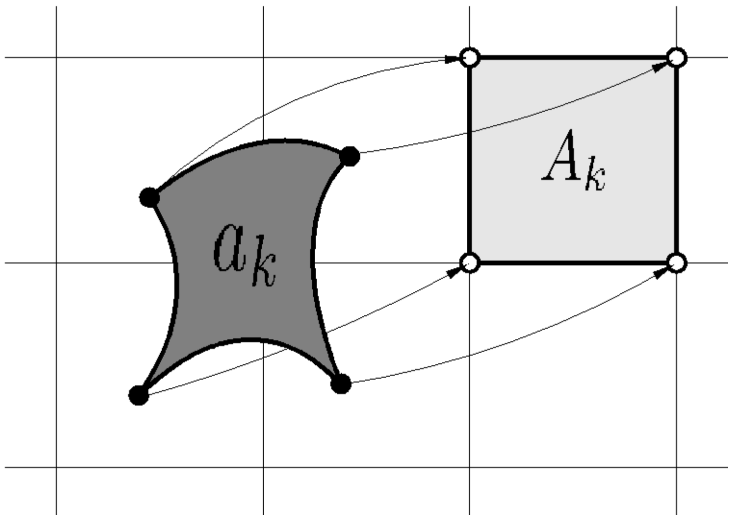
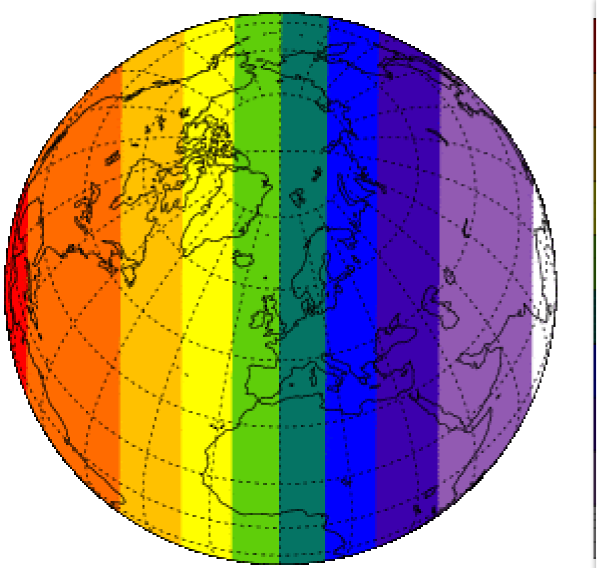
Tracer advection in CAM: new scheme and evaluation

Peter Hjort Lauritzen[§], J.-F. Lamarque[§], M.J. Prather[#], Mark Taylor[*],
A. Conley[§], S. Goldhaber[§], C. Erath[§]





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What's going on?

- Finite-volume transport in CAM-SE
- Specified dynamics option in CAM-SE
  (PI: J.-F. Lamarque)
- Idealized testing to assess accuracy:

  - 2D: prescribed winds, passive transport (large community involvement)

    Prescribed 2D passive linear advection option in CAM-SE/FV
    (PI: J.-F. Lamarque)

  - 3D: Transport and mixing of chemical air masses in idealized baroclinic life cycles
    (L. Polvani); Evaluating CAM-SE and CAM-FV (PI: J.-F. Lamarque)

  - Idealized non-linear chemistry test case

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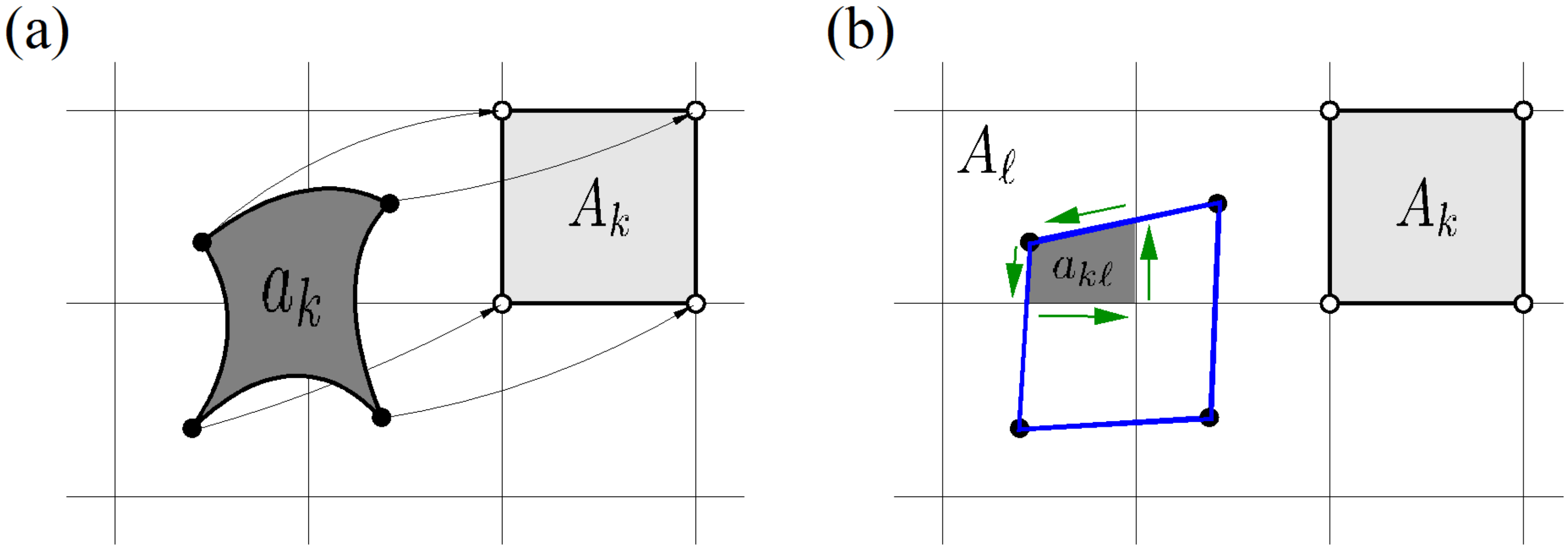
- Idealized non-linear chemistry test case

Conservative Semi-LAgrangian Multi-tracer transport scheme (CSLAM; Lauritzen et al., 2010)

- Passive and inert tracer transport with CSLAM is now working in HOMME* (Erath et al., 2012) using spectral element winds.



* HOMME is "providing" the spectral element dynamical core to CAM-SE

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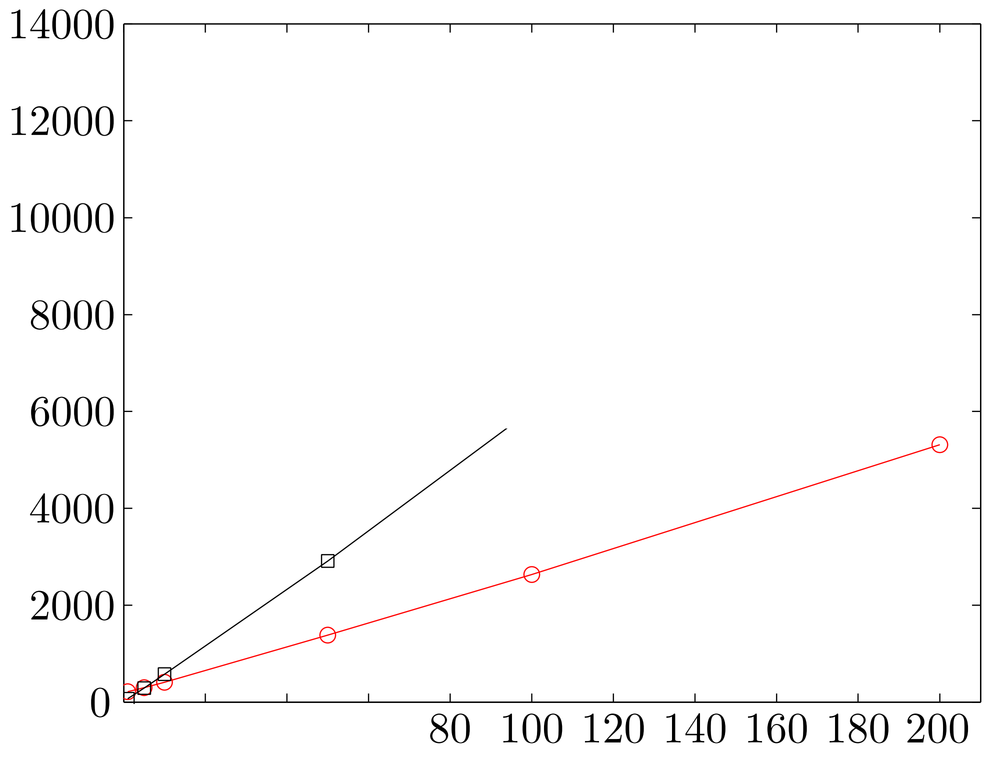

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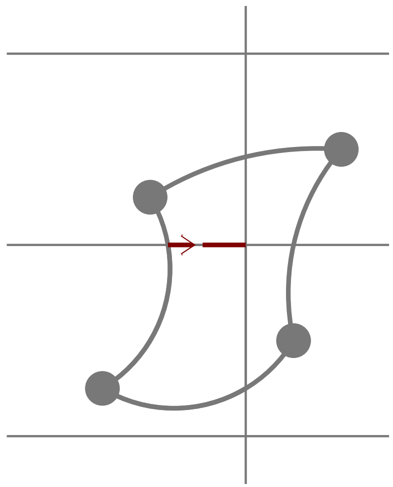
- High resolution ill-conditioning of analytical line-integrals

  -> change all line-integrals to Gaussian quadrature and locally enforce mass-consistency (Erath et al., 2013, revising)

  - change does not affect locality and accuracy, and scalability



on $\rightarrow$ mandatory for mass conservation:

e.g., antiderivative for high order weights:

$$-y\,\mathrm{arsinh}\left(\frac{x}{\sqrt{1+y^2}}\right) - \arccos\left(\frac{x}{\sqrt{1+x^2}}\frac{y}{\sqrt{1+y^2}}\right)$$

Stability problems!

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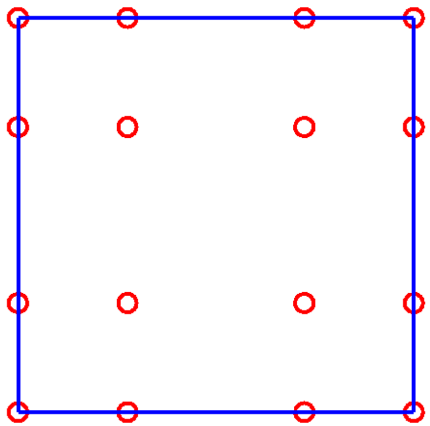
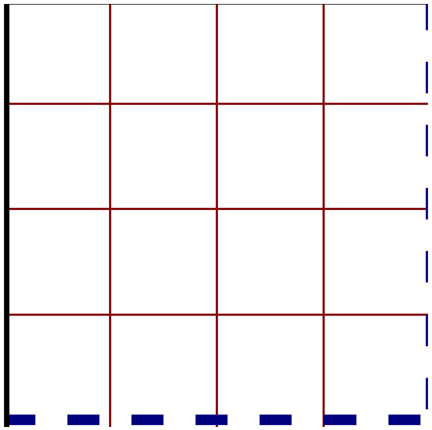
- So why are we not showing AMIP simulations with CSLAM?

CSLAM coupling with spectral element dynamics (1/2)

(work in progress)

- Equiangular finite-volume physics grid in CAM-SE





When I/O and physics on finite-volume grid is working in CAM-SE, CSLAM transport (without SE-CSLAM air density coupling) should be available.

- without SE-CSLAM air density coupling? CSLAM evolves its own density and CAM-SE evolves it own density
(this inconsistency appears when using different numerical methods and/or different time-steps for air and tracers)

CSLAM coupling with spectral element dynamics (2/2)

(and specified dynamics option in CAM-SE)

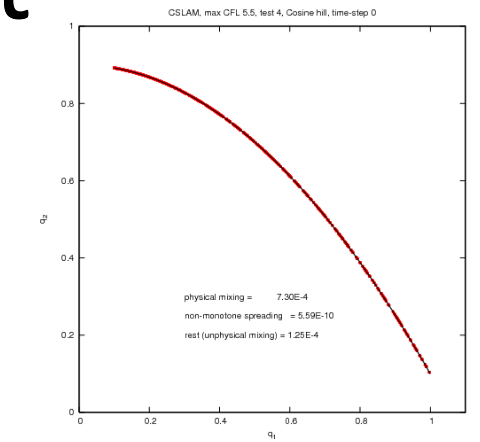
- Continuity equation for air and tracer (rho=density, phi=mixing ratio):

$$\frac{\partial \rho}{\partial t} + \nabla \cdot (\vec{v}\rho) = 0, \quad \text{CAM-SE}$$

$$\frac{\partial (\rho \phi)}{\partial t} + \nabla \cdot (\vec{v}\rho \phi) = 0, \quad \text{CSLAM}$$

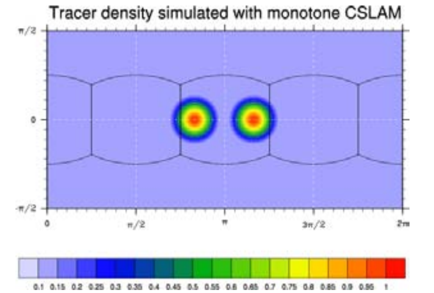
- If phi=1 then tracer equation should reduce to air density equation
- Similarly for specified dynamics: offline data wind-mass balance does not equal the dynamical core wind-mass balance
  (M. Prather, P. Cameron-Smith)
- A “safe” solution for SE-CSLAM coupling: move to Flux-Form version of CSLAM (FF-CSLAM; Harris et al., 2011) and use well-known and well-tested finite-volume “flux-tricks”

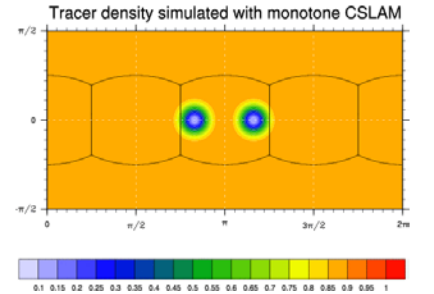
Accuracy of transport



Idealized passive transport test case suite designed to assess:

- numerical order of convergence
- `minimal' resolution
- ability to transport 'rough' distributions
- ability to preserve pre-existing functional relations between species,
- ability to preserve filaments





under challenging flow conditions
(Lauritzen, Skamarock, Prather and Taylor, 2012)
(Nair and Lauritzen, 2010)

Accuracy of transport: workshop

scheme acronym	full scheme name	primary reference	implementation grid	formal order
CAM-FV	Community Atmosphere Model -	Lin and Rood (1996)	Regular latitude-longitude	2
CAM-SE	Community Atmosphere Model - Spectral Elements	Dennis et al. (2012) Neale et al. (2010)	Gnomonic Cubed-sphere	4
CLAW	Wave propagation algorithm on mapped grids	LeVeque (2002)	two-patch sphere grid	2
CSLAM	Conservative Semi-LAgrangian Multi-tracer scheme	Lauritzen et al. (2010)	Gnomonic cubed-sphere	3
FARSIGHT	Departure-point interpolation scheme with a global mass fixer	White and Dongarra (2011)	Gnomonic cubed-sphere	2
HEL	Hybrid Eulerian Lagrangian	Kaas et al. (2012)	Gnomonic cubed-sphere	3?
HEL-ND	HEL - Non-Diffusive	Kaas et al. (2012)	Gnomonic cubed-sphere	3?
HOMME	High-Order Methods Modeling Environment	Dennis et al. (2012)	Gnomonic cubed-sphere (quadrature grid)	4
ICON-FFSL	ICOsahedral Non-hydrostatic model - Flux-Form semi-Lagrangian scheme	Miura (2007)	Icosahedral-triangular	2
LPM	Lagrangian Particle Method	Bosler (2013, in prep)	Icosahedral-triangular	?
MPAS	Model for Prediction Across Scales	Skamarock and Gassmann (2011)	Icosahedral-hexagonal	3
SBC	Spectral Bicubic interpolation scheme	Enomoto (2008)	Gaussian latitude-longitude	?
SFF-CSLAM	Simplified Flux-Form CSLAM scheme	Ullrich et al. (2012)	Gnomonic cubed-sphere	3&4
SLFV-SL	Semi-Lagrangian type Slope Limited	Miura (2007)	Icosahedral hexagonal	2
SLFV-ML	Slope Limited Finite Volume scheme with method of lines	Dubey et al. (2012)	Icosahedral hexagonal grid	2
TTS	Trajectory–Tracking Scheme	Dong and Wang (2012b)	Spherical Centroidal Voronoi Tessellation	?
UCISOM	UC Irvine Second-Order Moments scheme	Prather (1986)	Regular latitude-longitude	2
UCISOM-CS	UC Irvine Second-Order Moments scheme	-	Gnomonic cubed-sphere	2

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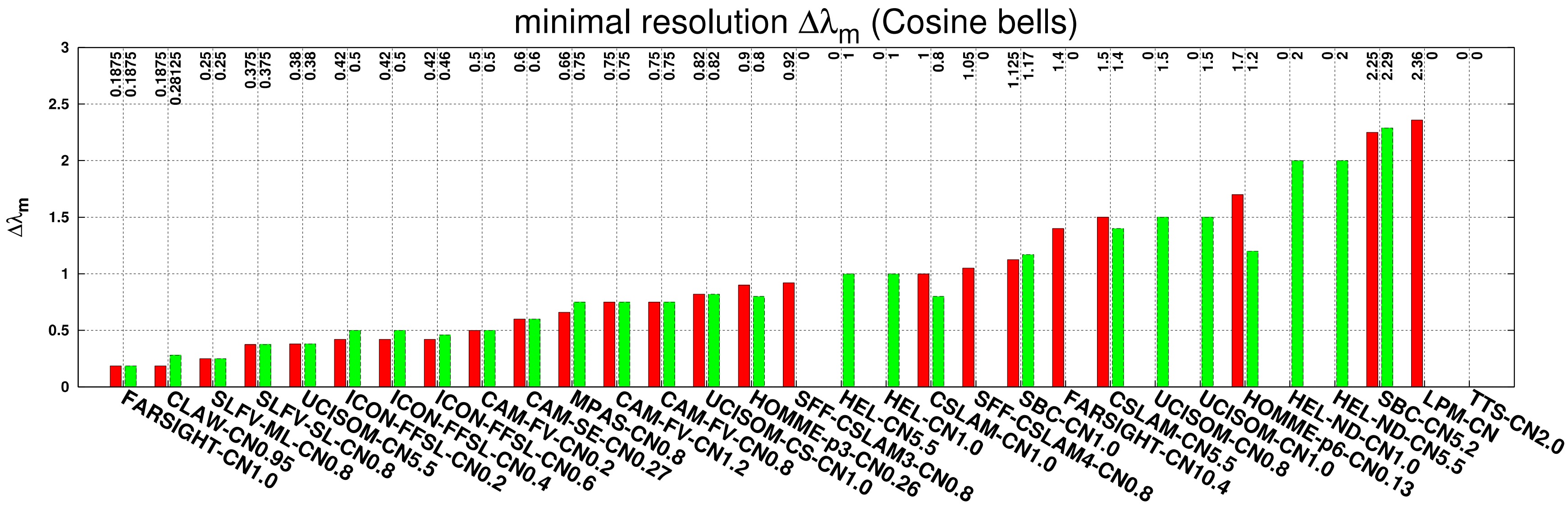
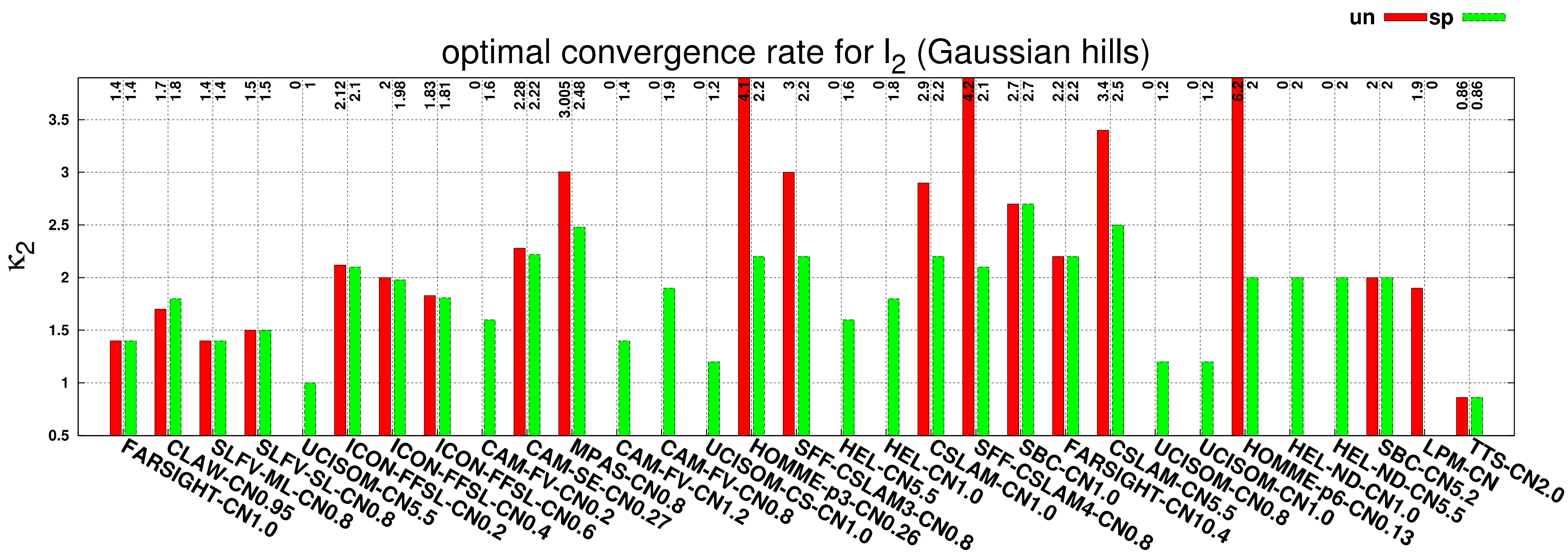
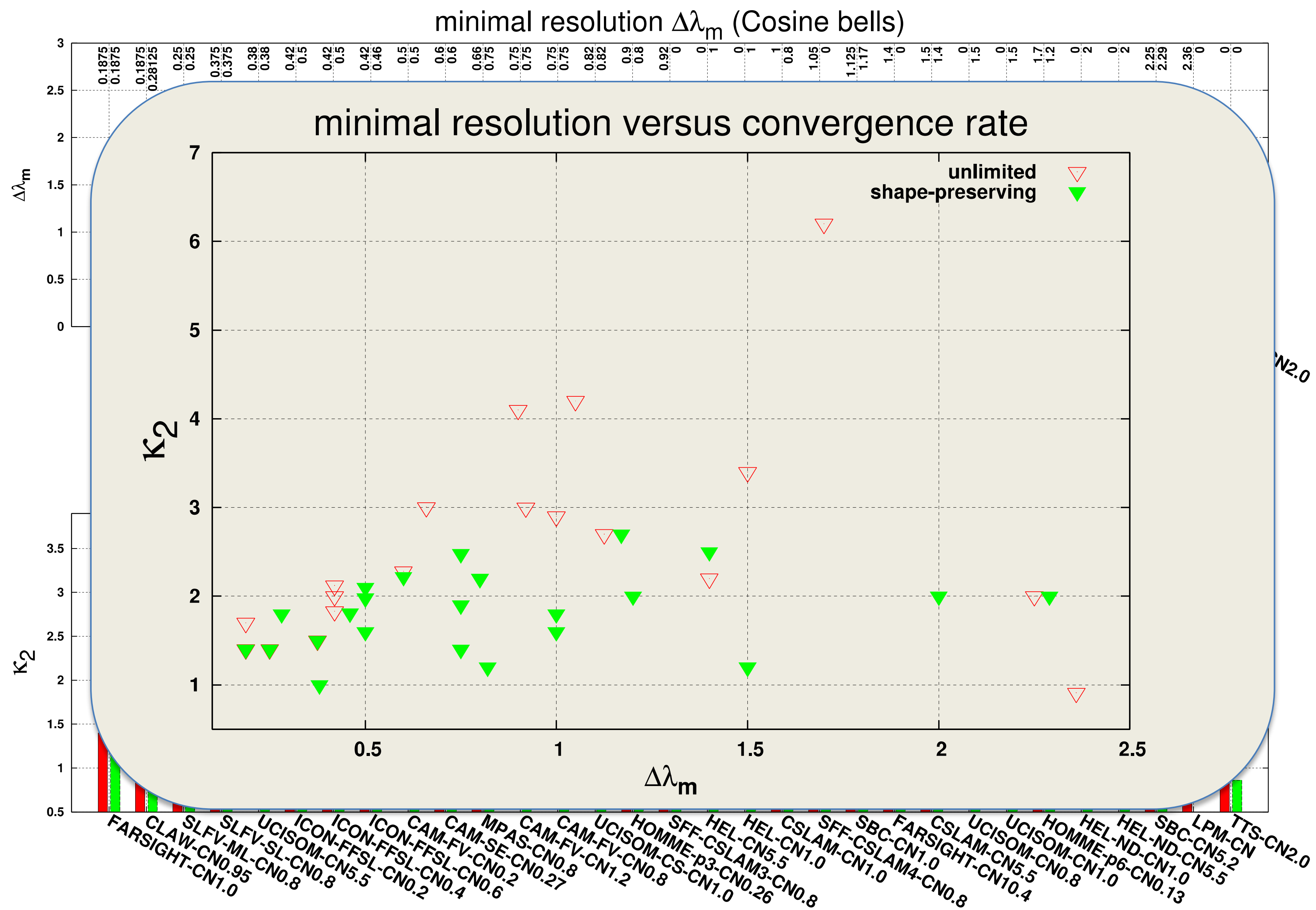
HOMME and CAM-SE codes are identical, however, different hyper-viscosity coefficients and polynomial order:

CAM-SE is running with default climate setup!





Lauritzen et al., 2013 (in prep)



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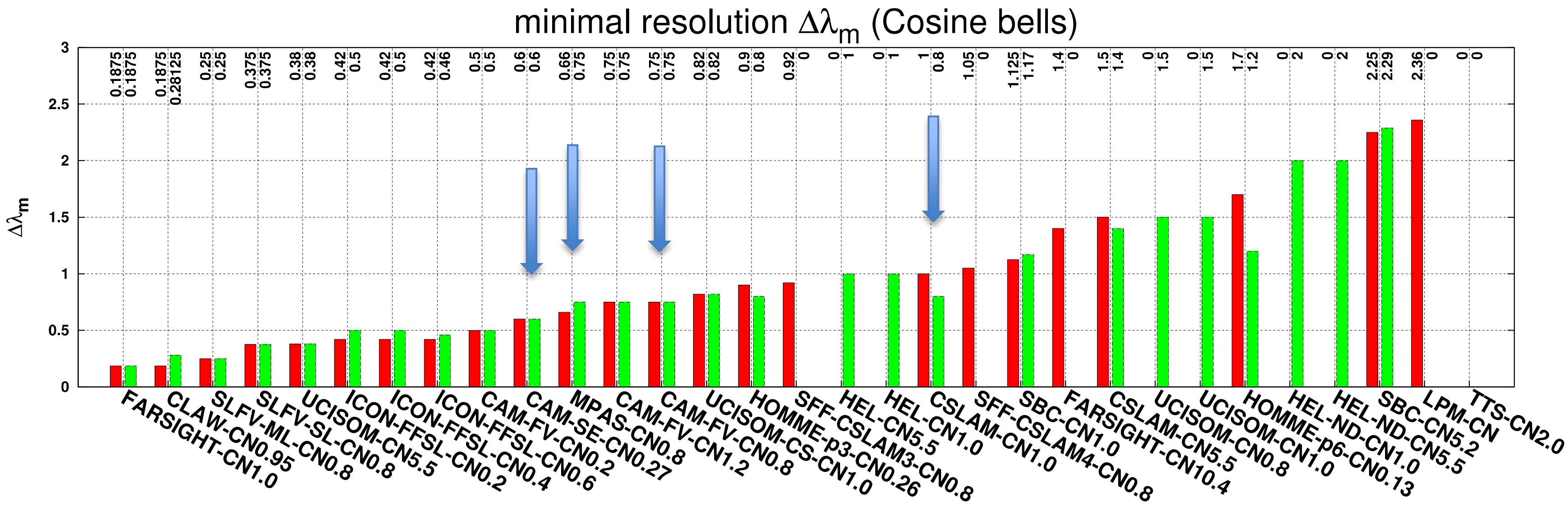

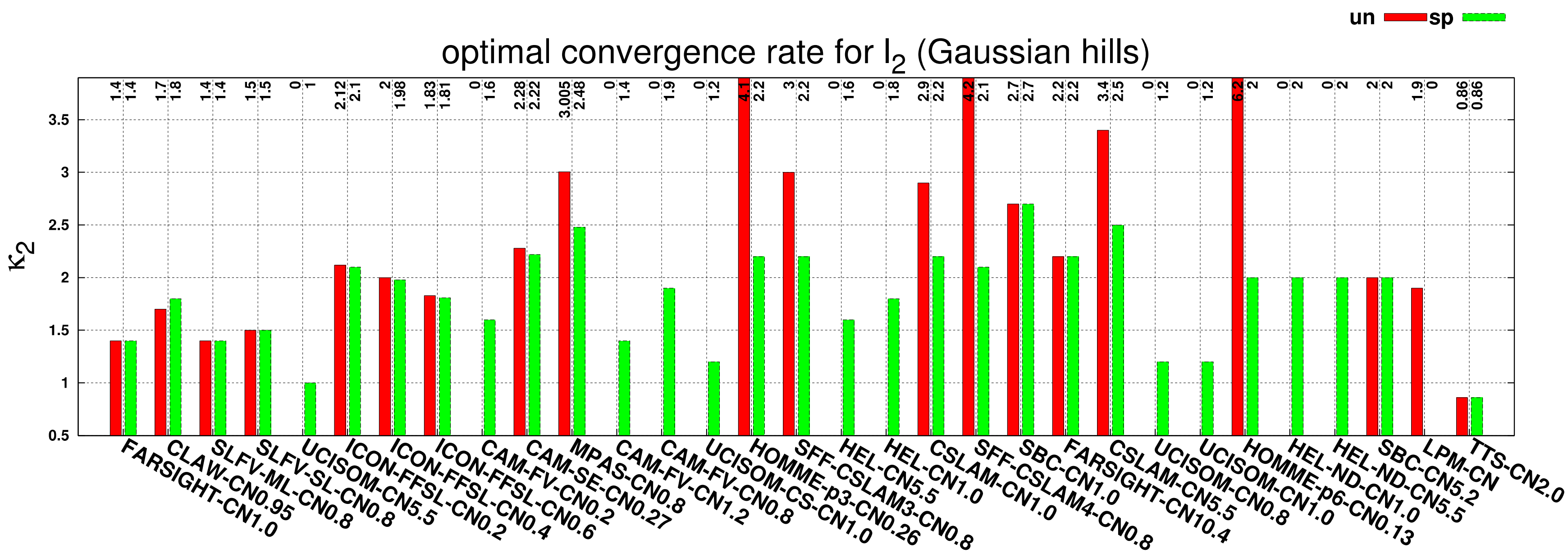

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THE TERMINATOR TEST

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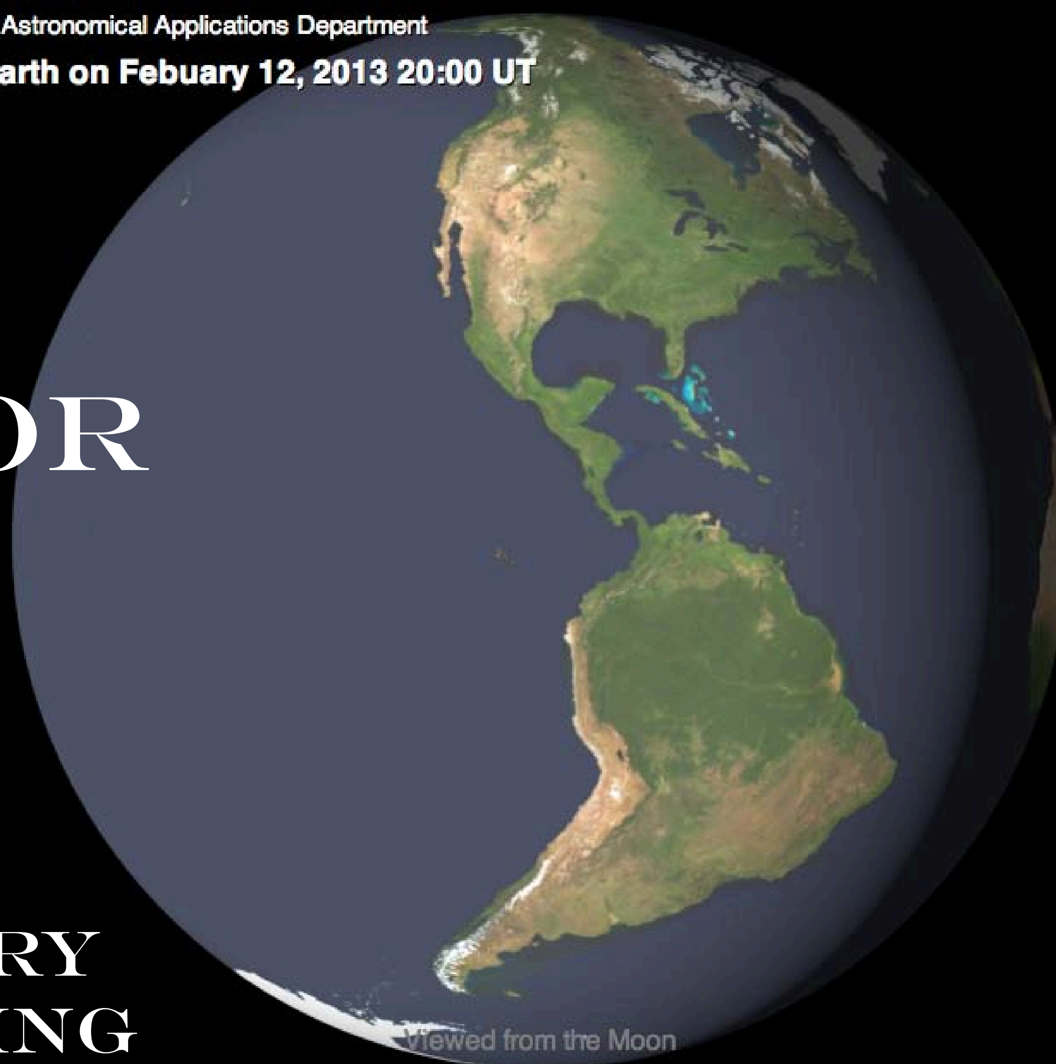
THE TERMINATOR TEST



VERY PRELIMINARY DESIGN AND TESTING

Example: Br

Goal:

1. Formulate an idealized test case with non-linear chemistry (relevant for photolysis driven chemistry).
2. Use 1. for investigating high-order transport/chemistry coupling

Beyond passive idealized transport testing: "Toy" chemistry

Two Chlorine species (Cl and Cl2) that react non-linearly: k1>>k2 - terminator
Total amount of Chlorine (Cly=2*Cl+Cl2) is conserved.

$$Cl_2 \rightarrow Cl + Cl : k_1$$
$$Cl + Cl \rightarrow Cl_2 : k_2$$

Figure shows k1 (k2 is constant)

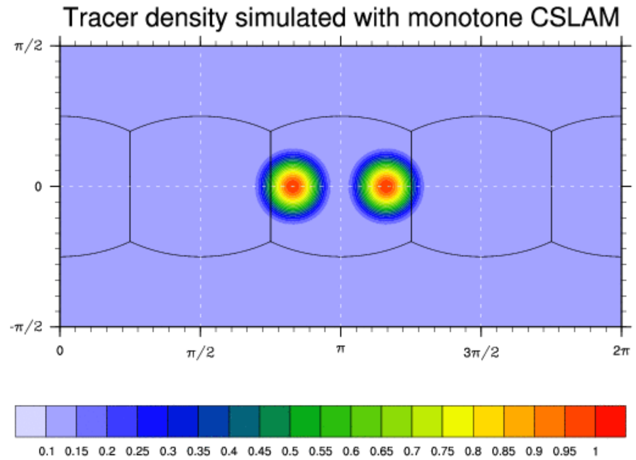
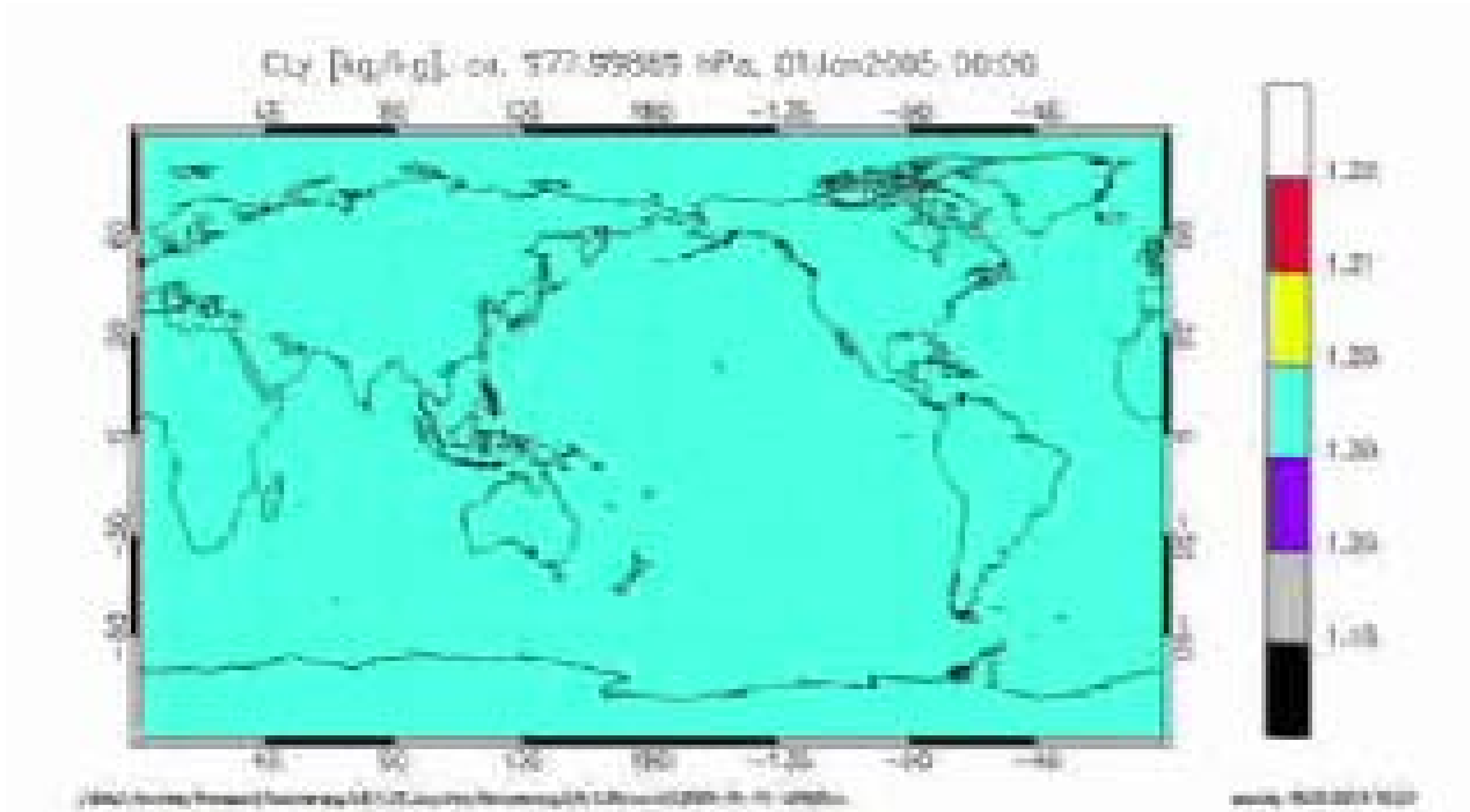


Figure illustrating Flow field

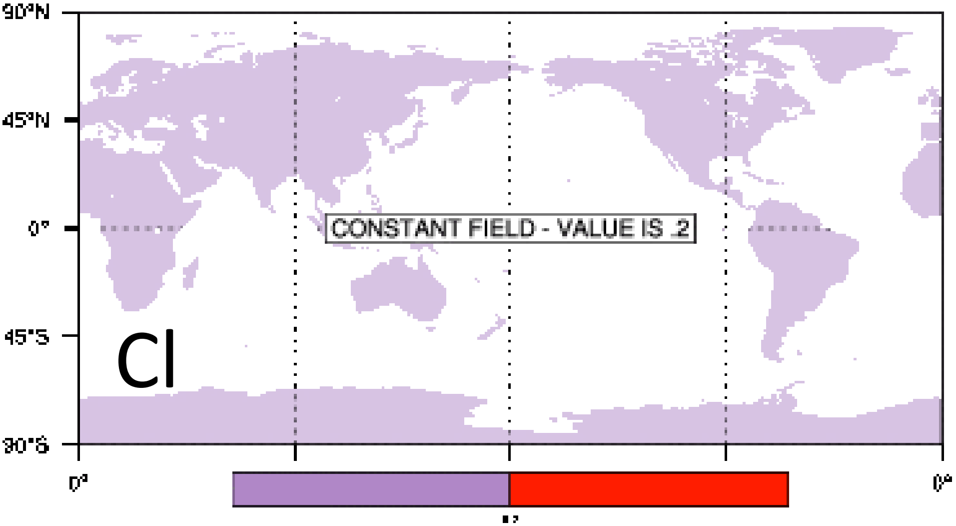
Beyond passive transport idealized testing: “Toy” chemistry

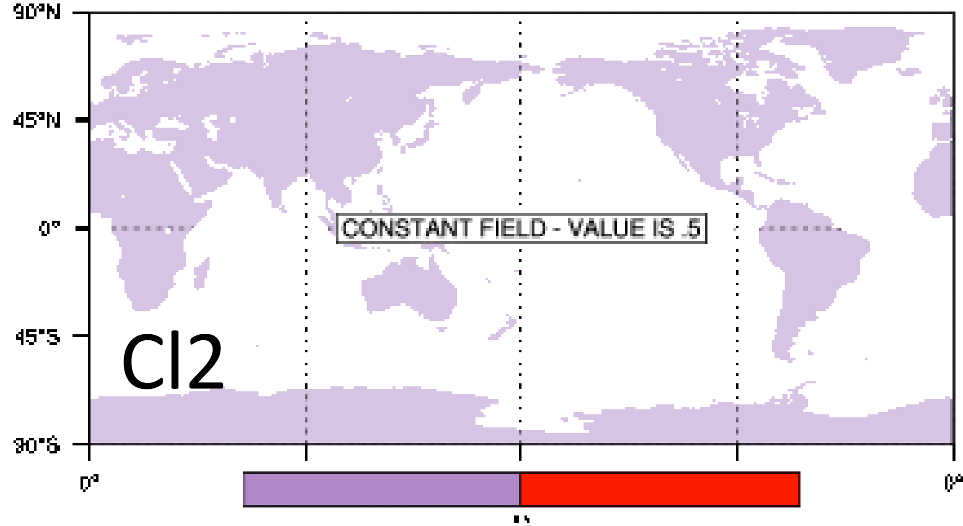


Results for CAM-FV

Properties of CSLAM important for chemistry

(preserves linear relations even when using shape-preserving limiter)





Non-linear "terminator-toy" chemistry:

$$Cl_2 \rightarrow Cl + Cl : k_1$$

$$Cl + Cl \rightarrow Cl_2 : k_2$$