NATIONAL CENTER FOR ATMOSPHERIC RESEARCH

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New Finite Volume based Tracer Transport Schemes for CAM-SE

Outline

1. Motivation
2. CSLAM and SPELT - two semi-Lagrangian schemes
3. Performance on Yellowstone
4. Performance/Comparison with Spectral Elements

thanks to:

P. Lauritzen[1], R. Nair[1], M. Taylor[2], H. Tufo[3]

[1]NCAR, Boulder, CO [2]SNL, Albuquerque, NM [3]CU Boulder, CO

$$$:**DOE BER DE-SC0001658 and DE-SC0006959**

Transport Scheme

Continuity equations in CAM 5

- Default configuration 26
- In chemistry version much more, > 100

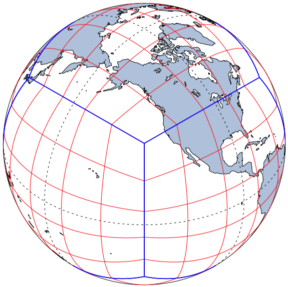
Multi tracers

The transport of a growing number of tracers in todays atmospheric modeling applications makes a dominated factor of computational costs.
Efficient algorithms are of highest interest.

AND: Semi-Lagrangian schemes allow longer time steps!

High-Order Method Modeling Environment

- High-order element-based conservative dynamical core
- Integrated into the Community Atmosphere Model (CAM) framework: CAM-SE (Spectral Elements)
- Cubed-sphere grids resulting from equi-angular gnomonic projection
- Domain decomposition (horizontal), scalable up to 170000 cores (Jaguar Cray XT)
- Parallel strategy over elements
- Originally for Galerkin schemes

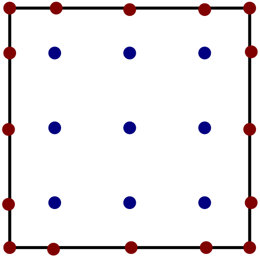


Cubed-sphere

Grid/Points in HOMME

Consider ONE element in HOMME:

GLL Points



$NP = 5$

data $= 25$

communication $= 16$

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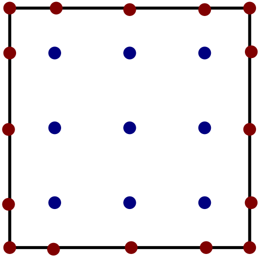

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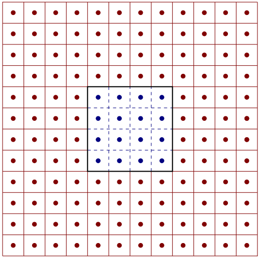
CSLAM



$NC = 4$
data $= 144$
communication $= 128$

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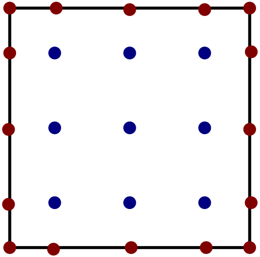

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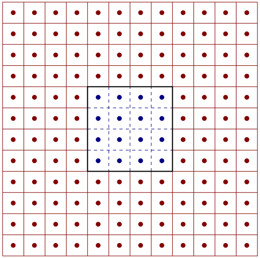

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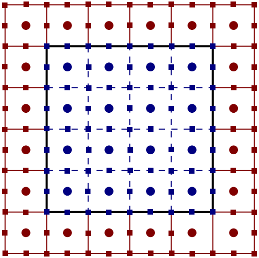
SPELT



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data $= 169$

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Grid/Points in HOMME

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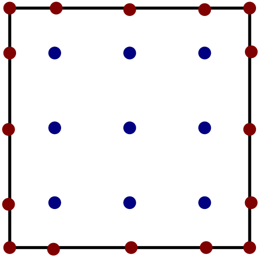

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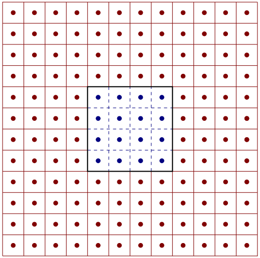

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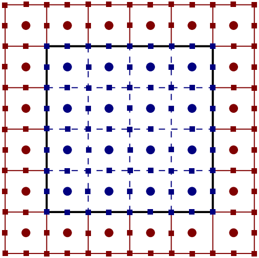

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Overall memory for resolution 0.25^o, 100 tracers, 26 levels:

GLL Points	CSLAM	SPELT
$24\,101$ MB	$138\,823$ MB	$162\,924$ MB

CSLAM in HOMME - a remapping scheme

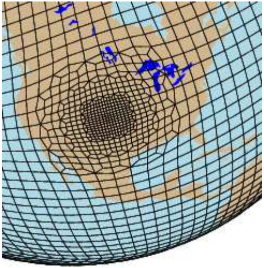
Discretization from the Lagrange form of the transport equation

- Multi-tracer efficient, third order scheme, monotonic option
- Now also mass-conservation for high-order high-resolution remapping schemes → eliminate some numerical instabilities
- only ONE nearest neighbor COMMUNICATION for each time step (array of multiple tracer values), with and without filter

(Erath et al., PCS 2012) and (Erath and Lauritzen, MWR 2013 sub.)

SPectral Element Lagrangian Transport

Motivation: SPELT for Variable Resolution C-S Mesh (extend the approach of Chen et al., 2010)



Why Variable resolution?

- Facilitate high-resolution regional modeling (less resources).
- Challenge: To develop a conservative FV semi-Lagrangian scheme which is efficient on arbitrary unstructured cubed-sphere mesh
- Regular FV semi-Lagrangian schemes relies on uniform grid and requires wider halo region
- SPELT is a local scheme and designed for arbitrary quadrilateral meshes

SPELT in HOMME

Discretization starts from the flux form of the transport equation:

$$\overline{\psi_k}^{n+1}|A_k| = \overline{\psi_k}^{n}|A_k| - \left(\oint_{\Gamma_k} \tilde{\mathbf{F}} \cdot \mathbf{n}\, d\Gamma\right) \qquad \text{with } \Gamma_k = \partial A_k$$

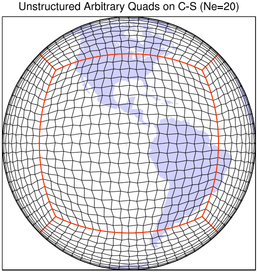
$\tilde{\mathbf{F}}$ time-integrated flux, $\overline{\psi}_k^n$ resp. $\overline{\psi}_k^{n+1}$ are the cell average at old resp. new time-level (prognostic variable).

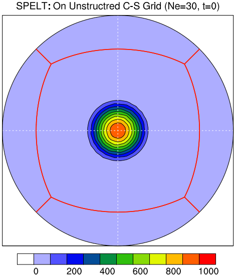
- Mass conservation no matter how you approximate fluxes
- No need for complex upstream area searching
- Multi tracer efficient, third order scheme
- only ONE nearest neighbor COMMUNICATION for each time step (array of multiple tracer values), without limiter; also with limiter possible $\rightarrow$ does this make sense?

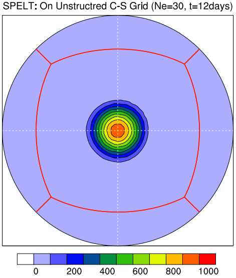
(Erath and Nair, 2013 in prep.)

First Results on arbitrary Grids

- Solid-Body rotation test (Williamson et al. 1992): Advection of a cosine-bell along the NE direction. Initial cosine-bell height (scalar) $\phi \in [0, 1000]$
- $30 \times 30 \times 6$ FV cells (approx. 3.0°), SPELT with positivity preservation
- After one revolution (12 days) with SPELT, height $\phi \in [0, 974]$

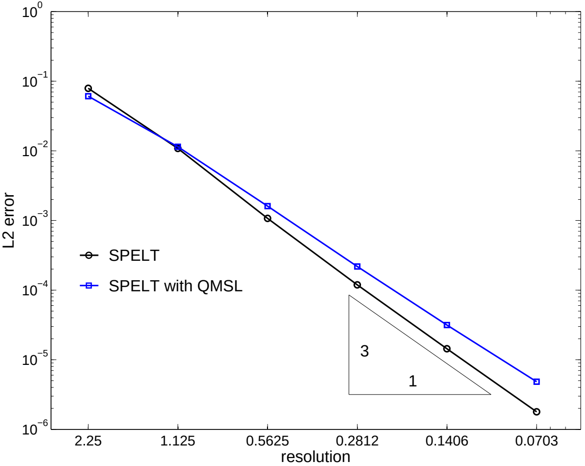






Convergence of both schemes in HOMME

Uniform grids: boomerang test case, two Gaussian Hills



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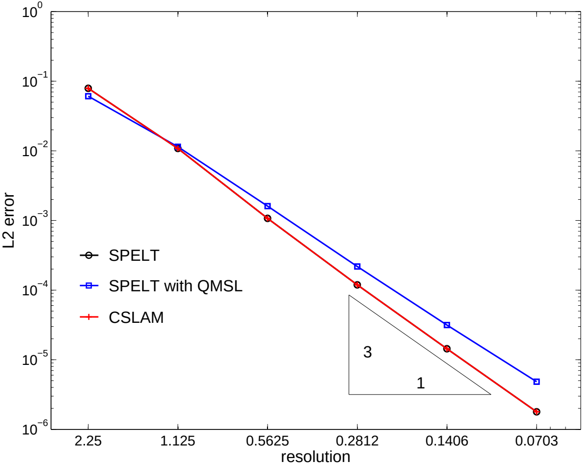

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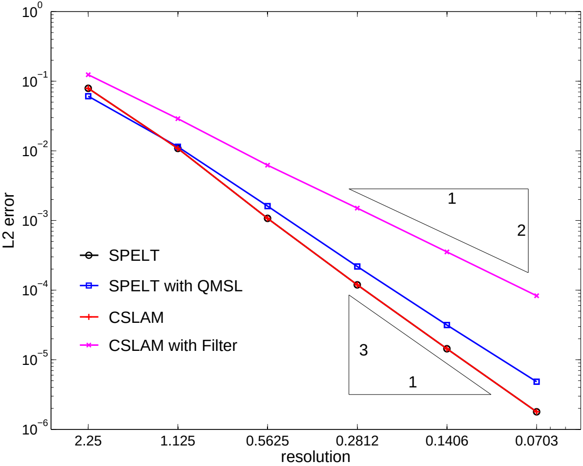
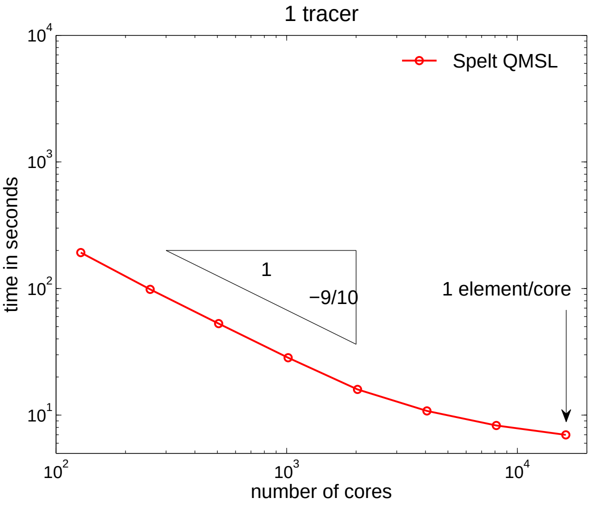


Yellowstone Scalability (strong)



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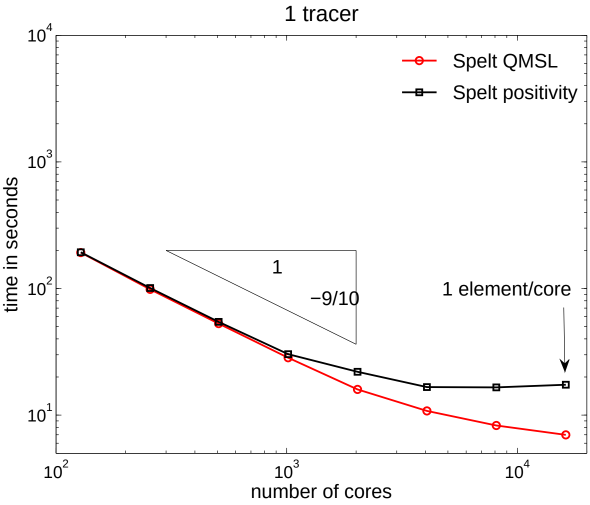

Spelt positivity has two communications!

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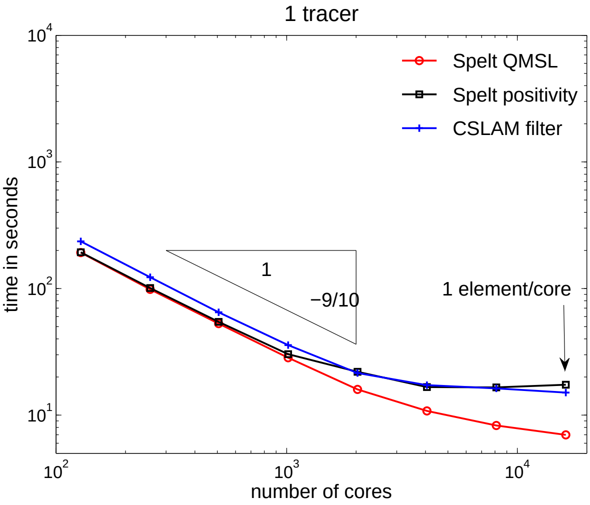

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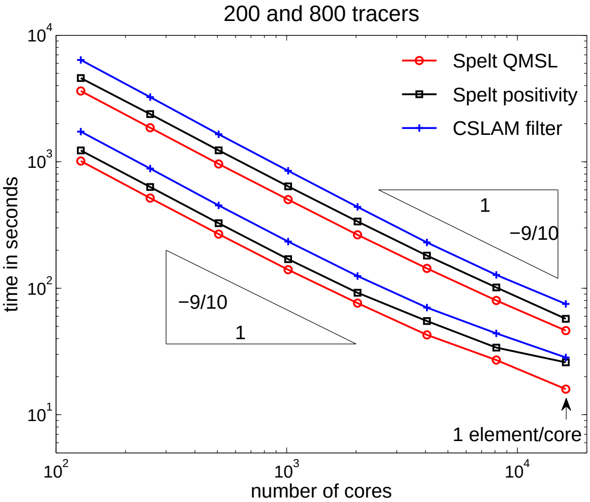
Yellowstone Scalability (strong)

200 and 800 Tracers



Comparison: Spectral Elements (SE) Advection Scheme versus SPELT and CSLAM

- Integrated in the atmospheric primitive equations SE,
- Resolution 0.75 degree on the equator, tstep$= 50$ s for the dynamics, running the baroclinic instability test case for 15 days
- CFL SE < 0.28 with shape preserving mode, CFL CSLAM< 1
  Tracer time steps: SE$= 250$ s, CSLAM$= 800$ s
- Looking only at the advection scheme times:

$$\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \mathbf{u}) = 0,$$
$$\frac{\partial (\rho\phi)}{\partial t} + \nabla \cdot (\rho\phi \mathbf{u}) = 0$$

ρ is the fluid density, $\mathbf{u}$ velocity, ϕ tracer concentration

(Erath and Taylor, 2013 in prep.)

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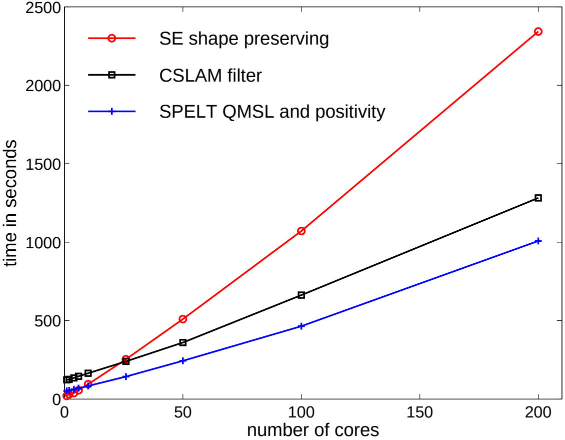
Compare Advection Schemes on Yellowstone

1024 cores; 5 elements/core



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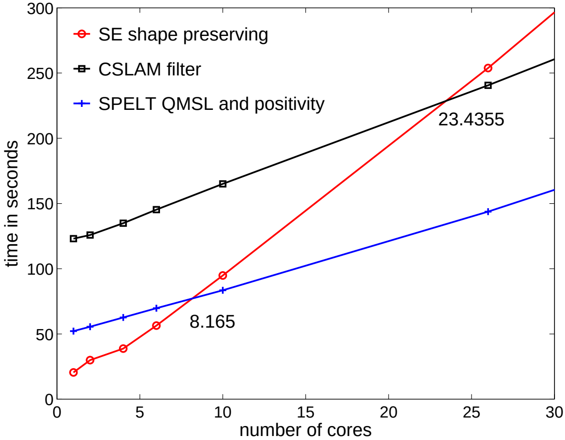
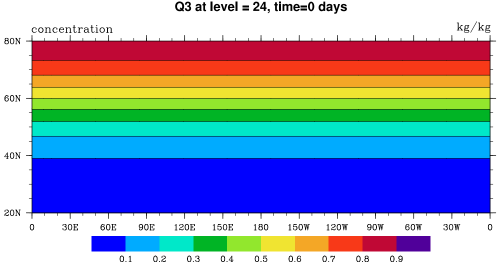
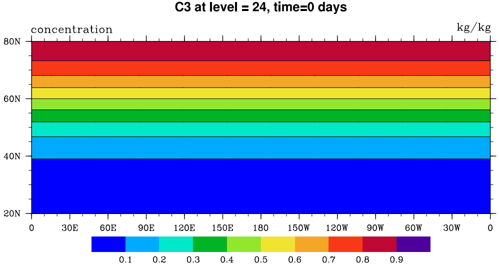


Results for one Tracer

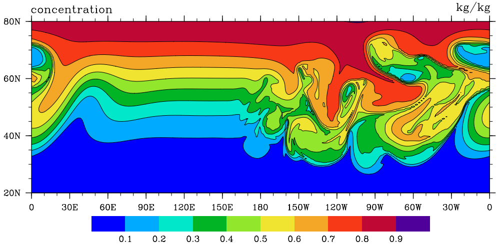




Results for one Tracer

Primitive equations baroclinic instability test: SE/CSLAM

Q3 at level = 24, time=13 days



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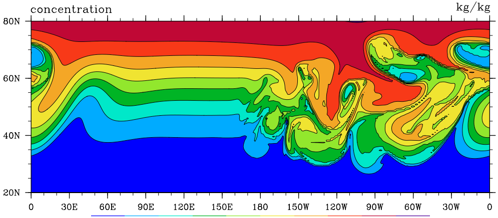

Results for one Tracer
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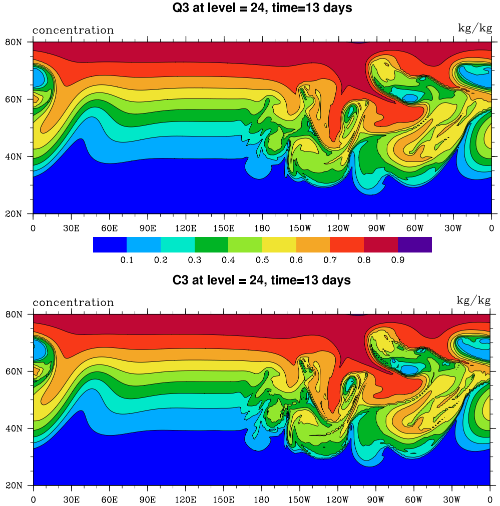


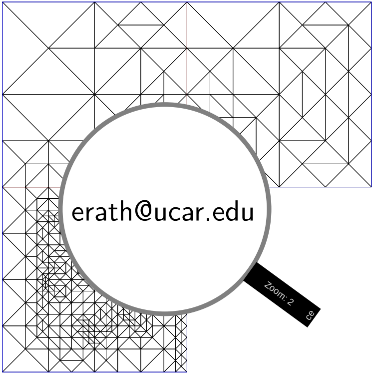
Conclusions

- Overwrite the Spectral Element air density every tracer time step IS NOT STABLE
- HOMME scales also for finite volume meshes
- Consistent coupling of Spectral Element air density with tracers for CSLAM does not work, unless one does a global optimization problem
- However, the excellent accuracy and performance of semi-Lagrangian schemes are the major advantages
- Both schemes are tested on 3 different machines
  $\rightarrow$ errors match up to machine precision

Future Work

- Filter/Limiter for the SPELT scheme (FCT based),
  it is also possible to avoid the communication
- Consistent coupling of Spectral Element air density with tracers for flux schemes is an ongoing research
  $\rightarrow$ it is easier to manipulate fluxes
- Integrating in CAM should be straight forward
- More evaluation of SPELT for future climate simulation

Thank you! – Further Questions?



http://www.csc.cs.colorado.edu/∼ce/