Some NCAR activities on next generation global dynamical cores

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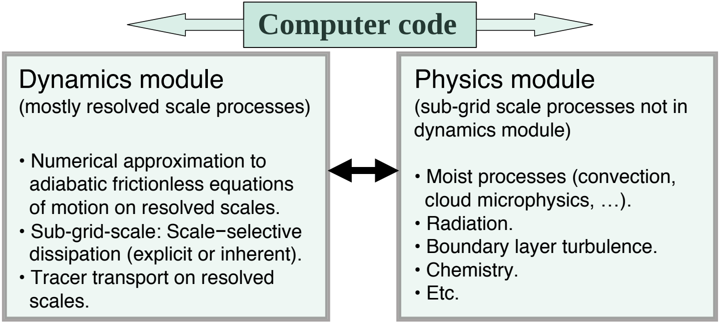
National Center for Atmospheric Research (NCAR)

NCAR ESSL's Climate & Global Dynamics

‘Definition’ of an atmospheric dynamical core

‘Roughly speaking, the **dynamical core** solves the governing fluid and thermodynamic equations on resolved scales, while the parameterizations represent sub-grid-scale processes and other processes not included in the dynamical core such as radiative transfer.’ - Thuburn (2008)



This talk is two-fold

- a new test case for global dynamical cores and results from the 2008 NCAR colloquium on dynamical cores (Lauritzen et al., 2009a)
- a new multi-tracer transport scheme on the cubed-sphere based on a semi-Lagrangian formulation (Lauritzen et al., 2009b)

Major challenges

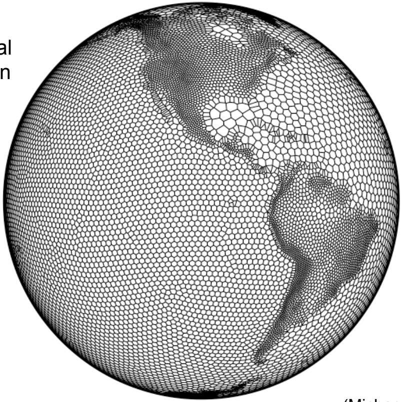
Preparing our coupled climate system models for massively, distributed memory computers as well as meeting the 'needs'/expectations of the user community.

Some expectations (for global dynamical cores):

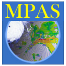
- Scalable (order $10^4 - 10^5$ processors)
- Conservation properties (at least mass; maybe total energy, ...)
- Capable of producing accurate solutions for small-scale (meso-scale) and large scale flows (synoptic ad global scales)
- Tracers: Accurate (consistent), efficient for $\mathcal{O}(100+)$ tracers
- Capability for regional climate (high regional resolution):
  - Through variable resolution grid (e.g., Voronoi)
  - Mesh-refinement
  - High global resolution
- Etc.

Selective Mesh Refinement Based on Terrain Height

spherical centroidal
voronoi tessellation



(Michael Duda, MMM)



Mesoscale & Microscale Meteorology Division / ESSL / NCAR

Slide from J. Klemp (NCAR)

Block refinement

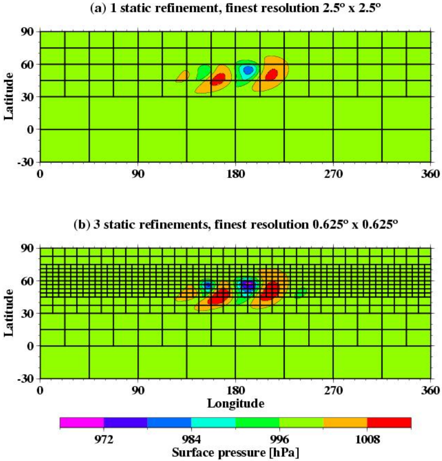
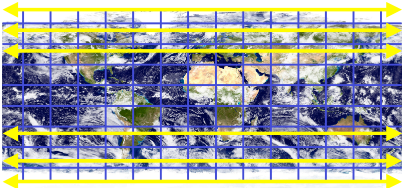


Figure courtesy of C. Jablonowski (University of Michigan)

Next generation global models

The dynamical core is the performance "bottleneck" in many coupled climate system models

Regular latitude-longitude grids need non-local (global) filters in the polar regions (e.g., NCAR CAM) or use non-local spectral transform methods (e.g., ECMWF IFS).



Rectangular computational space

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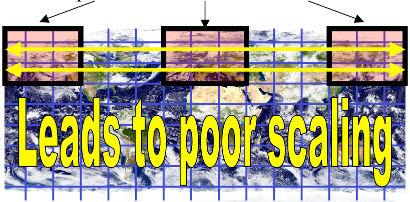
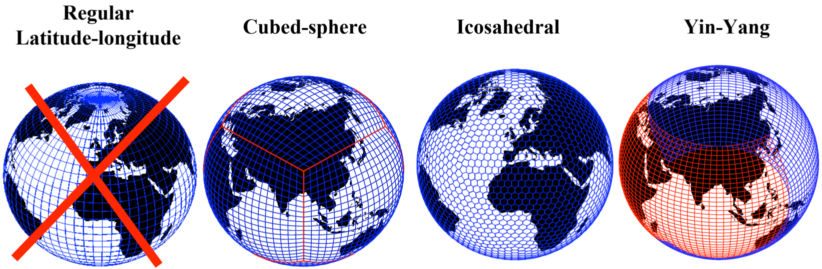
Grid patches that reside on different nodes



Rectangular computational space

A solution

Use a more isotropic grid (avoid pole problem, can use full 2D domain decomposition in horizontal directions, if equations are solved explicitly there is only nearest neighbor communication):



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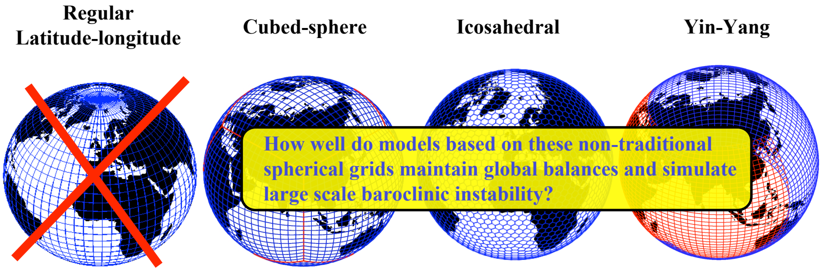

NCAR

NASA

U.S. Department of Energy
Office of Science

NCAR Summer Colloquium on Dynamical Cores

June 2-13, 2008; Organizers: **Lauritzen** (NCAR), Jablonowski (University of Michigan), Taylor (Sandia National Laboratories), Nair (NCAR)

"Idea": Gather global dynamical core community, have them port their models to NCAR supercomputers and have them oversee the students run idealized test cases defined by the colloquium organizers.

- 12 models: **NCAR** (CAM), **NASA** (GISS, GEOS FV), **CSU** (CSU GCM), **NCAR/Sandia** (HOMME), **Duke University** (OLAM), **NCEP** (GEF), **MIT** (MITgcm), **MPI** (ICON), **DWD** (GME).
- ~ 40 graduate students (North America, Europe, India, Brazil, South Korea, ...); collectively produced 1.1 TB of data.
- 12 keynote lecturers (see upcoming **Springer book in Lecture Notes in Computational Science and Engineering series**).

Springer
the language of science

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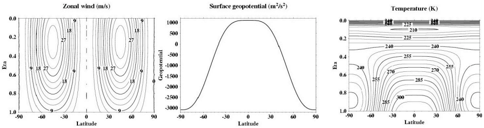
NCAR Summer Colloquium on Dynamical Cores

Idealized rotated steady-state test case (Lauritzen et al., 2009)

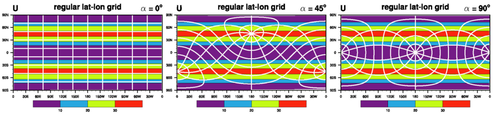
- Run model in adiabatic mode (no physics).
- Initialize the dynamical core with analytic initial conditions (balanced & steady state).

(Jablonowski and Williamson, 2006)



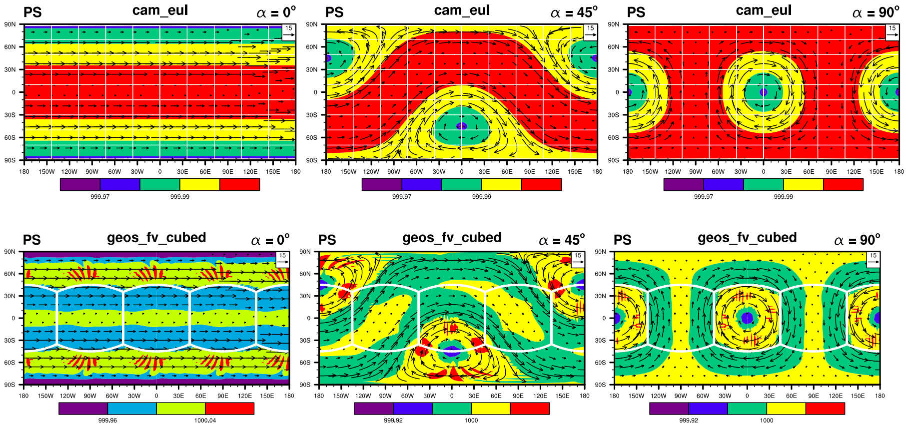
Surface pressure:
PS = 1000 hPa

- Rotate computational grid with respect to the physical flow.



- Run model: Does it maintain a steady state (flow is baroclinically unstable so perturbations will grow!)? Dependence on rotation angle?

Surface pressure day 1 plotted in model coordinates (not geographical coordinates)



- P_s at rotation angles $\alpha = 0^\circ$ (left column), $\alpha = 45^\circ$ (middle column) and $\alpha = 0^\circ$ (right column).
- White solid lines: Some of the grid lines for the computational grid (white solid lines)
- Arrows: Vector wind field at model level 3 near 14 hPa for the initial condition. The wind vectors are only shown to indicate the location of the jets with respect to the model grid.

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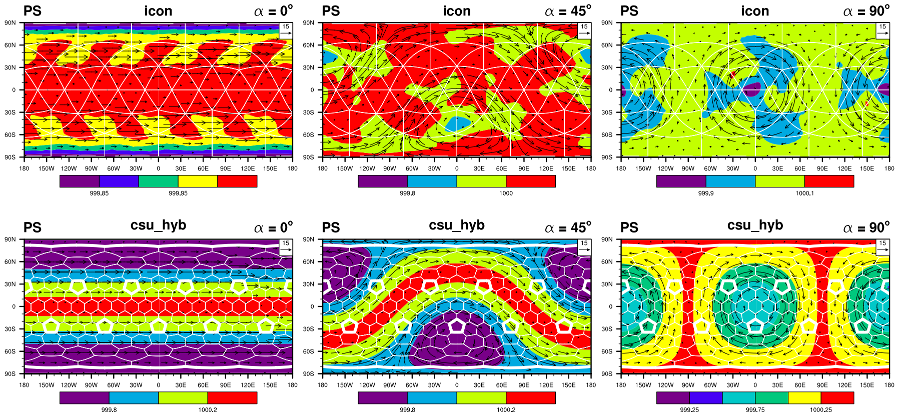

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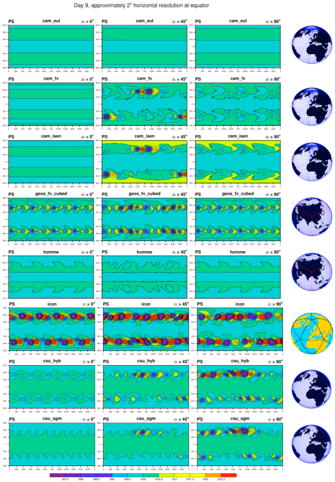

CAM_EUL (NCAR)	: Spectral transform
CAM_FV (NCAR)	: Finite-volume
CAM_ISEN (NCAR)	: CAM_FV with isentropic vertical coordinates
GEOS_FV_CUBED (NASA/GFDL)	: Finite-volume
HOMME (NCAR/Sandia)	: Spectral elements
ICON (MPI-M)	: Finite difference/volume
CSU_SGM (Colorado State University)	: Finite-difference
CSU_HYB	: CSU_SGM with isentropic vertical coordinate

- All models (except CAM_EUL) show “grid-imprinting”.
- Cubed-sphere models: Spurious wavenumber 4 and 2 waves.
- Icosahedral models: Spurious wavenumber 5 wave.
- Results “spuriously” vary with rotation angle.
- Amplitude of spurious waves vary significantly among models.

Test case can be used for debugging model code, assess isotropy of numerical methods, assess level of “grid-imprinting”.

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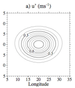
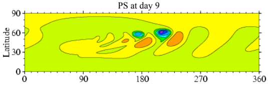
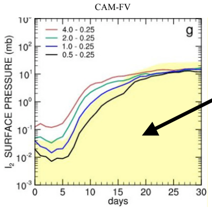
Idealized rotated ***baroclinic wave*** *test case (Lauritzen et al., 2009)*

- Add perturbation to steady-state initial conditions.
- Triggers the growth of a baroclinic wave over 10 days.





- Exact solution not known; an ensemble of high resolution reference solutions provide an estimate of the true solution and the uncertainty thereof.



Yellow region: Uncertainty of high resolution reference solutions.

- Run models at 2 and 1 degree resolutions at 0, 45, 90 degree rotation angles for 15 days.

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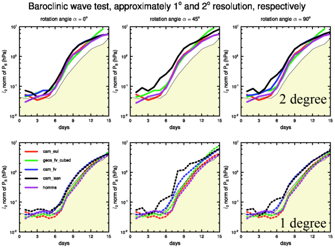

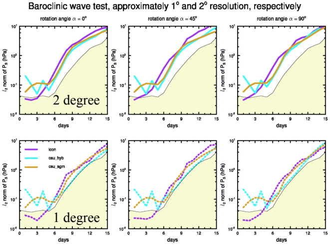

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- All cubed-sphere models have converged to the uncertainty of the reference solutions at 1 degree; the icosahedral models have not!

Test case can be used to assess:
- minimal resolution for resolving baroclinic waves.
- isotropy of numerical method.

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Final remarks on part I

- Dynamical cores on non-traditional global spherical grids still have to prove themselves in global climate modeling! (magnitude of spurious grid forcing versus ‘physical’ forcings)

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  - CAM-FV-cubed: Cubed-sphere version of GFDL/NASA dynamical core is being ported to CAM (University of Michigan).
  - A dynamical core based on an icosahedral grid is being implemented in CAM as well (Los Alamos National Laboratories and MMM at NCAR)

A Conservative Semi-Lagrangian Multi-Tracer Transport Scheme on the Cubed-Sphere (CSLaM)

Why new transport scheme?

Future (and some current) climate models will have over 100 prognostic tracers.
=> Computational cost of running dynamics will be (is) dominated by tracers.
=> Multi-tracer efficiency is important (as well as conservation, monotonicity, …).
=> Scheme needs to be accurate on `fancy geometry'

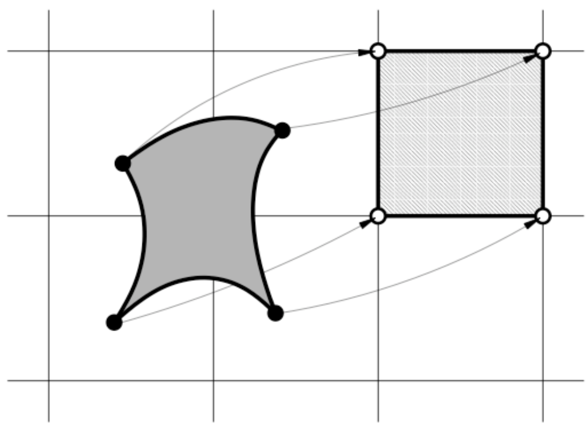
For simplicity I will derive CSLaM scheme in Cartesian geometry

A Conservative Semi-Lagrangian Multi-Tracer Transport Scheme on the Cubed-Sphere (CSLaM)

Consider two-dimensional transport equation for a passive tracer:

$$\frac{d}{dt}\int_{A(t)} \psi \, dA = 0$$

where ψ density and $A(t)$ arbitrary Lagrangian area (e.g., Machenhauer et al, 2008).



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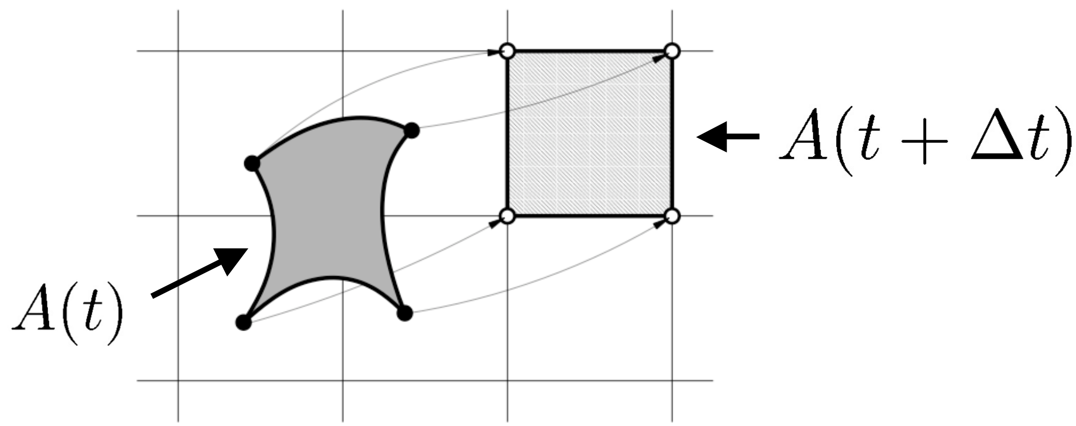

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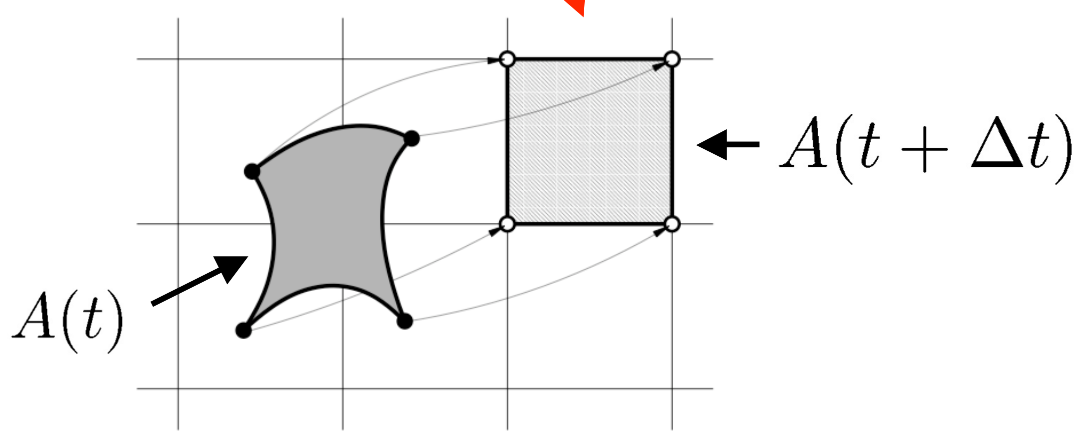

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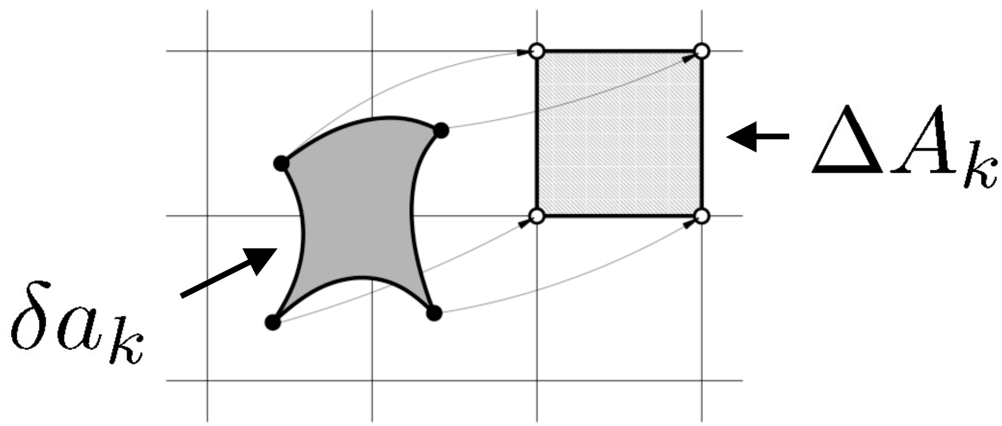

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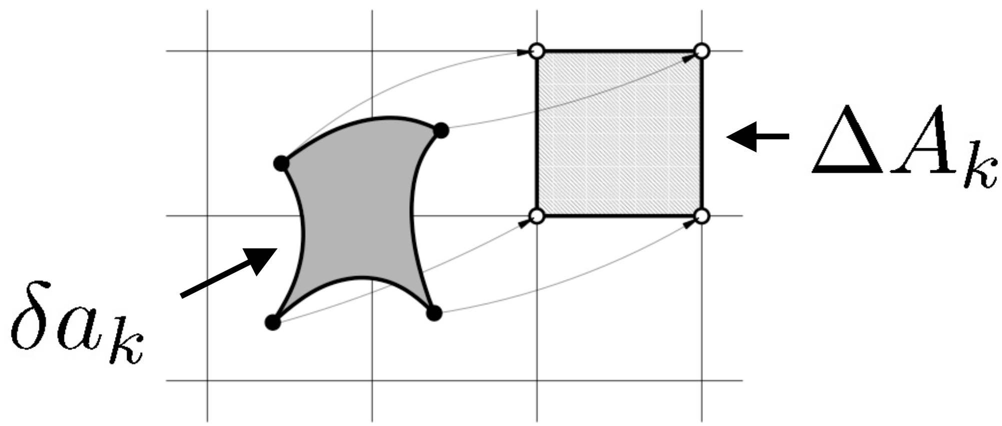

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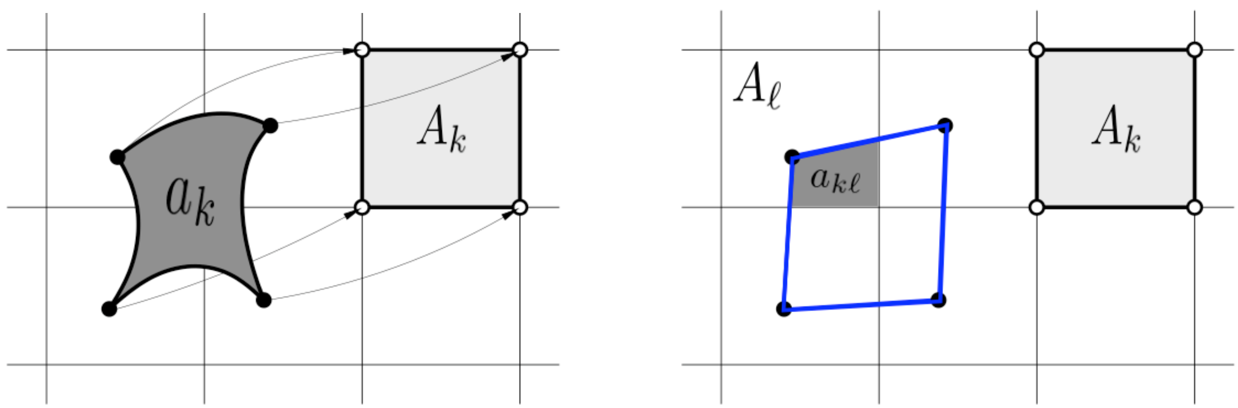
where overlap areas are

$$a_{k\ell} = a_k \cap A_\ell, \quad a_{k\ell} \neq \emptyset; \quad \ell = 1,\ldots,L_k$$



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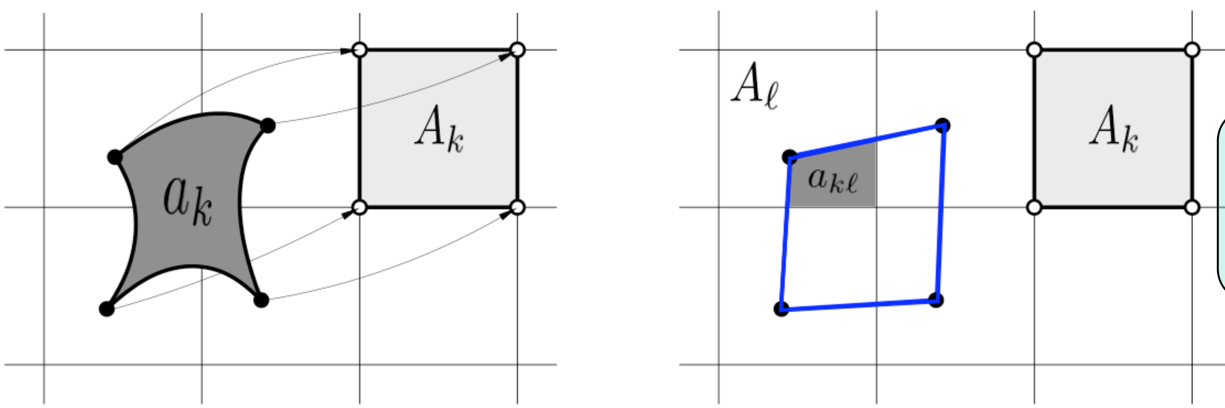

Use **Gauss-Green's** theorem to convert area integrals into line-integrals.

A Conservative Semi-Lagrangian Multi-Tracer Transport Scheme on the Cubed-Sphere (CSLaM)

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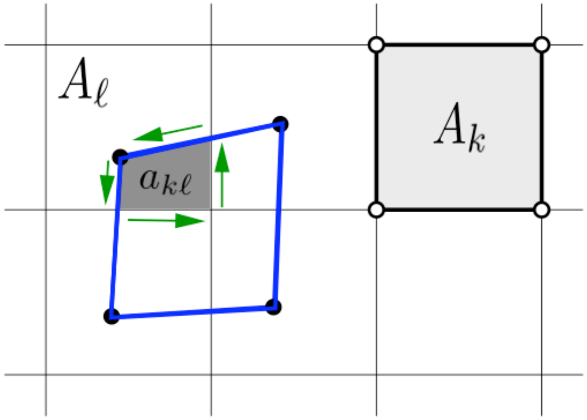
$$\overline{\psi}_k^{n+1} \Delta A_k = \overline{\psi_k^*}^{n} \delta a_k = \sum_{\ell=1}^{L_k} \oint_{\partial a_{k\ell}} [P\, dx + Q\, dy] \,,$$

where P, Q are potentials so that

$$-\frac{\partial P}{\partial y} + \frac{\partial Q}{\partial x} = f_\ell(x, y)$$



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where P, Q are potentials so that

$$-\frac{\partial P}{\partial y} + \frac{\partial Q}{\partial x} = f_\ell(x,y) = \sum_{i+j\le 2} c_\ell^{(i,j)} x^i y^j, \quad i,j \in \{0,1,2\}$$

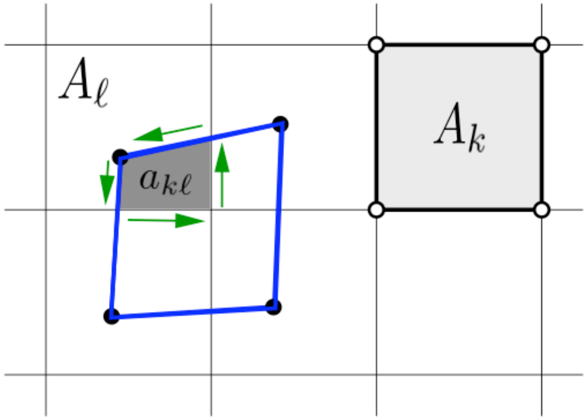
and $c_\ell^{(i,j)} = c_\ell^{(i,j)}(\ldots, \overline{\psi}_{k-1}^n, \overline{\psi}_k^n, \overline{\psi}_{k+1}^n, \ldots)$

A Conservative Semi-Lagrangian Multi-Tracer Transport Scheme on the Cubed-Sphere (CSLaM)

Final **CSLaM** forecast equation becomes:

$$\overline{\psi}_k^{n+1} \Delta A_k = \overline{\psi_k^*}^n \delta a_k = \sum_{\ell=1}^{L_k} \left[\sum_{i+j\leq 2} c_\ell^{(i,j)} w_{k\ell}^{(i,j)} \right],$$

where weights $w_{k\ell}^{(i,j)}$ are functions of the coordinates of the vertices of the overlap areas $a_{k\ell}$



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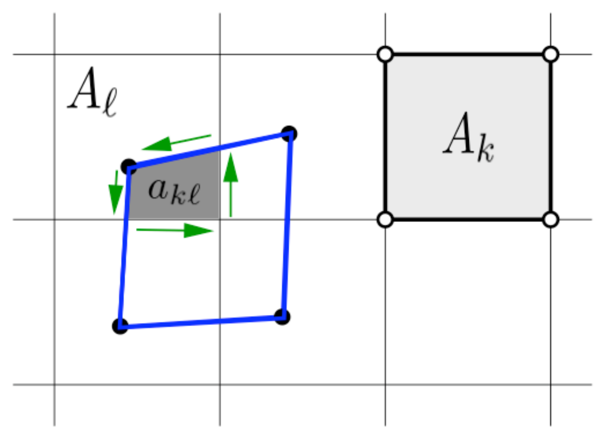
$w_{k\ell}^{(i,j)}$ can be reused for each additional tracer.

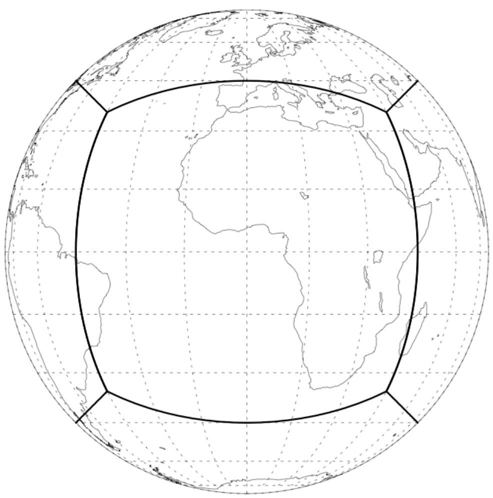


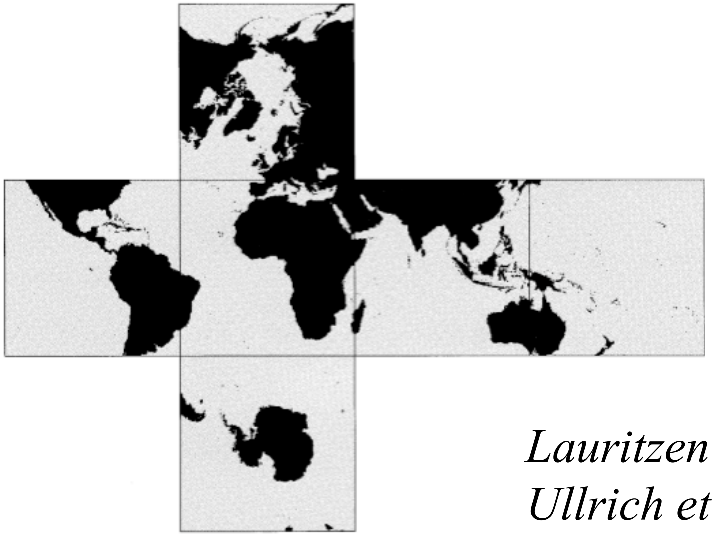
A Conservative Semi-Lagrangian Multi-Tracer Transport Scheme on the Cubed-Sphere (CSLaM)

Cubed-sphere faces are "Cartesian-like" so Cartesian algorithm can be reused to a large extent, except:

- Gauss-Green's theorem must be converted to gnomonic coordinates and associated potentials must be computed (doable but a lot of algebra!).

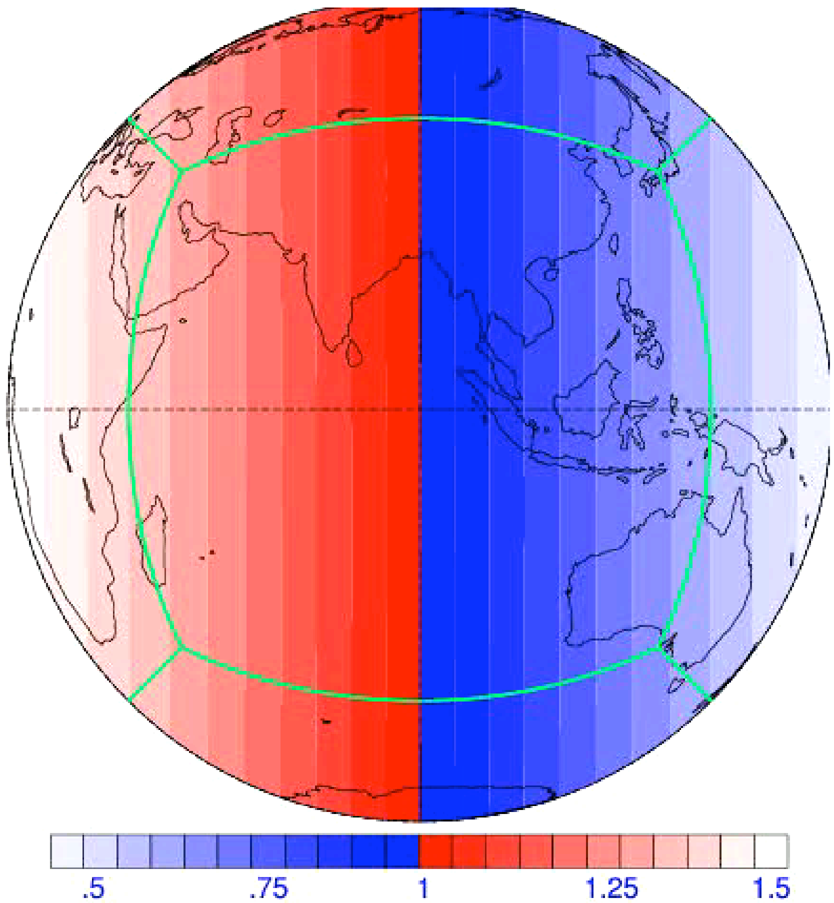
- Consistently couple the panel discretizations for the global domain (since algorithm is fully two-dimensional this is straightforward!).





Lauritzen et al. (2009b)
Ullrich et al. (2009)

Moving Vortices on the Sphere: A Test Case for Horizontal Advection Problems

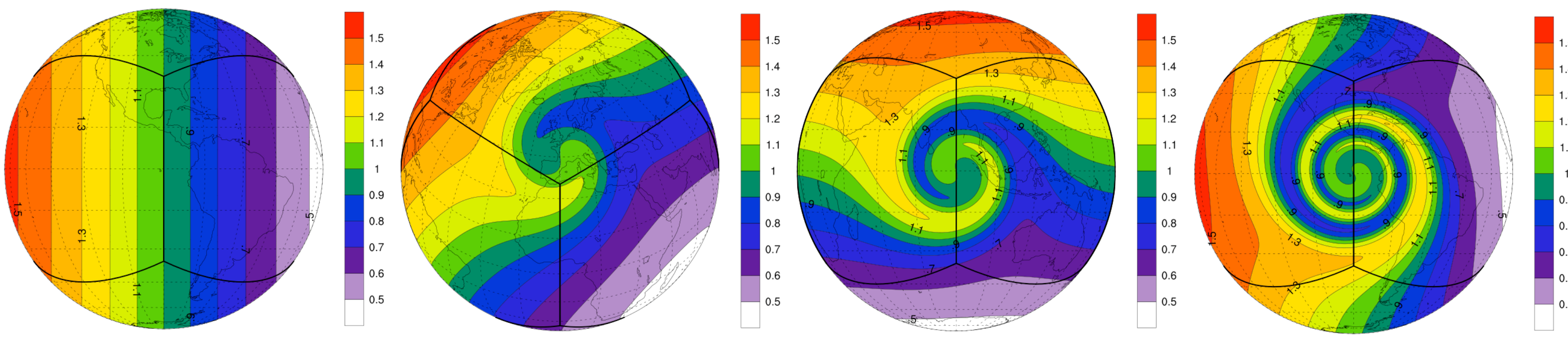


Courtesy of R.D. Nair

Nair and Jablonowski (2008)

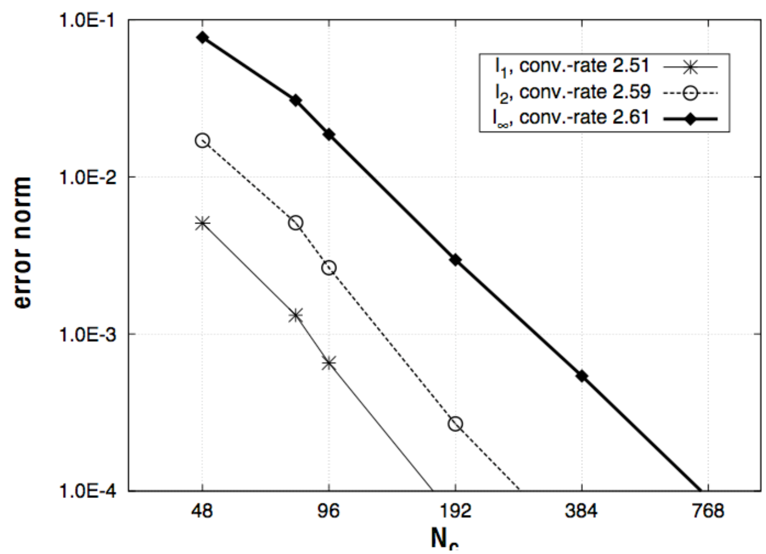
Moving Vortices on the Sphere: A Test Case for Horizontal Advection Problems

Exact solution: Initial condition, 1/4, 1/2, 1 revolution, respectively



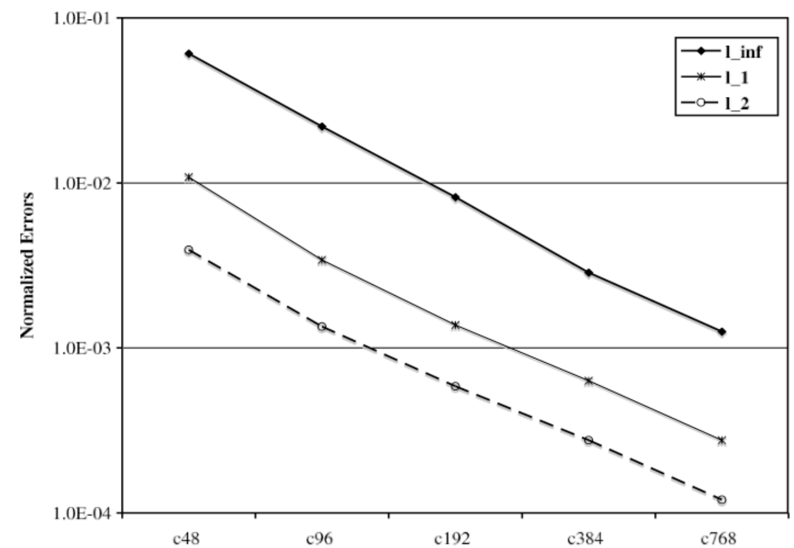
Standard error measures for moving vortices test case

CSLaM (Lauritzen et al. 2009b)



Putman and Lin (2008)

Cubed-sphere version of widely used Lin-Rood scheme used at GFDL, NASA, NCAR, MPI-M, …



Major improvement in accuracy compared to widely used state-of-the-art scheme!

- **CSLaM** to be implemented in HOMME (High-Order Methods Modeling Environment) as part of DOE proposal to design and implement non-hydrostatic dynamical core in HOMME.
- **CSLaM** is in theory extendable to other grids (e.g., icosahedral grids).

Final remarks on part II

• CSLaM properties:

- high-order accurate (+ Lagrangian accuracy)
- preserves linear tracer correlations
- has monotone options (ask me for details)
- multi-tracer efficiency
- general (applicable to any type of spherical grid defined in terms of great circle arcs; but high-order reconstructions must be provided!)
- Eulerian flux-form version of CSLAM was implemented and tested this summer (Lucas Harris, University of Washington):

Why?

- allows for FCT (flux-corrected transport) limiters for monotonicity
- allows for sub-cycling (large computational savings)