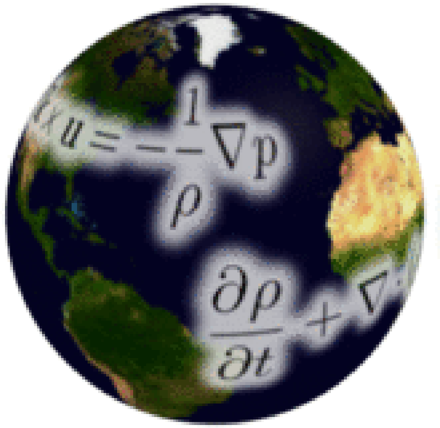
Dynamical Cores and Singletrack

Facilitators: Peter Hjort Lauritzen & Bill Skamarock
-> input from a lot more people

Cross-Working Group Session on
Unified Atmospheric Modeling / Single Track (June 20)



23rd Annual CESM Workshop
18 – 20, June 2018

Really fast but very fuel inefficient and can only drive fast on a smooth road

Very fast but can not go off-road and uses disruptive technology

Which car should I buy?
Should I buy more than one car?
Should I buy one or more cars and develop them further?
Should I make my own car?

Extremely robust but not particularly fast on a smooth road

Very fuel efficient but not particularly fast and can not go off-road

Singletrack vision document:

Singletrack Application Examples and Configurations

Frontier	*Example Application*	*Configuration*
Weather	Tropical Cyclones	3km refined mesh, coupled ocean, forecasts
Climate	Hydrologic Extremes	3km and 10km refined mesh, forecast and climate simulations
Polar	Arctic Prediction	10km refined mesh, coupled ocean, land, sea ice, land ice. Forecast and climate simulations
Geospace	Space Weather Prediction	25km global atmosphere to the ionosphere, forecast.
Chemistry	Urban/Regional Air Quality Prediction	Urban: <1km regional forecast. Regional: 4km refined global mesh, climate and forecast

Singletrack vision document:

Mesh refinement capability needed

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Singletrack vision document:

Non-hydrostatics needed

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Singletrack vision document:

Very efficient transport needed

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Singletrack vision document:

- **Shallow atmosphere approximation very questionable**
- **High top thermodynamics needed**

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		Climate	Weather	Geospace
(1)	Throughput: cost and scalability	Essential	Essential	Essential
(2)	Strong scaling	Essential	Desirable	Desirable
(3)	Efficient tracer transport	Essential	Essential	Essential
(4)	Conservation of mass (dry air, scalars)	Essential	Essential	Essential
(5)	Good tracer transport characteristics (shape-preservation, correlation, etc.)	Essential	Essential	Essential
(6)	Good conservation of total energy	Essential	Desirable	Essential
(7)	Conservation of angular momentum	Highly desirable		Essential
(8)	Dycore characteristics with topography	TBD	TBD	TBD
(9)	Non-hydrostatics	Desirable	Essential	Highly desirable
(10)	Global mesh-refinement capability	Desirable	Essential	Essential
(11)	Regional capability		Essential	
(12)	Cartesian geometry	Desirable	Essential	
(13)	Data assimilation capability. Has to play well with data assimilation	Desirable	Essential	Essential
(14)	Support simplified setups on the sphere	Essential	Essential	Essential
(15)	Support by developers	Essential	Essential	Essential

Essential: Judged necessary for some application(s)

Desirable: Would be nice to have for some application(s)

Highly Desirable: Would be really nice to have for some application(s)

Blank: Don’t care, or none of the above

Specific for geospace modeling

		Climate	Weather	Geospace
(16)	Stable over 30 scale heights (~700km)/O(13) in pressure			Essential
(17)	Efficient 2 way 3D inline grid coupling			Essential
(18)	Species dependent mean molecular mass and specific heats			Essential
(19)	Deep atmosphere: variation of gravity, Coriolis force and geometry			Highly desirable
(20)	High top thermodynamics (prefer solving thermodynamic eqn. with T rather than theta, which is not well defined above homopause)			Essential

Global dynamical cores at NCAR: Status & plans

- **CAM-FV (finite-volume):** "workhorse" dynamical core in CESM2 for 1 degree (horizontal resolution) applications
- **CAM-EUL (Eulerian spectral transform):** only used for simpler models applications
- **CAM-SLD (Semi-Lagrangian spectral transform):** decommissioned

- **CAM-SE (spectral-elements):** "workhorse" dynamical core in CESM2 for high resolution and mesh-refinement applications
- **CAM-FV3 (cubed-sphere version of FV):** being integrated into CESM (funded by NOAA)
- **WRF-MPAS (Model for Prediction Across Scales): used for weather applications with WRF physics**

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Global dynamical cores at NCAR: Status & plans

WRF-MPAS (Model for Prediction Across Scales):

- **Shallow-atmosphere non-hydrostatic.**
- **Local refinement capabilities.**
- **Tested for weather applications with WRF physics.**
- **Neither WRF nor MPAS are available to the community in CESM, although MPAS V4 is being run in CAM.**
- **Plans and schedule for supportable/sustainable MPAS port to CESM.**
- **MPAS extensions for geospace applications are being examined.**

Global dynamical cores at NCAR: Status & plans

CAM-SE (spectral-elements):

- Shallow-atmosphere hydrostatic
- Recently switched to dry-mass vertical coordinates with comprehensive treatment of condensates and energy; separate physics grid options and multi-tracer transport option (CSLAM)
- “Workhorse” dynamical core in CESM2 for high resolution (1/4 degree) and mesh-refinement applications
- Mainly used for climate applications with CAM physics.
- Available to the community in CESM.
- Is being configured for geospace applications (high top thermodynamics and ionosphere/thermosphere coupling), however, no non-hydrostatic deep atmosphere extension is planned at this point in time.

Global dynamical cores at NCAR: Status & plans

CAM-FV3 (cubed-sphere version of FV):

- Non-hydrostatic shallow-atmosphere
- Mesh-refinement capability
- Chosen by NOAA/NCEP to be their next generation global weather forecast model
- Being integrated into CESM (funded by NOAA); being setup/tested in Aqua-planet setup. Plans to setup AMIP-like simulations after that.
- Deep atmosphere version under development

None of the dycores currently meet all climate, weather and geospace requirements!

- How do we proceed?
- What is the process for selecting dynamical cores? (in CESM the process involves the community)
- Should we target one dynamical core for everything even though it may be less accurate and/or slower than other dynamical cores for certain applications? Should we proceed with several and maintain diversity (which CESM has historically done)?
- ???

Proposal:

Step 1: Integrate all candidate dycores into one framework

- **CAM-SE (spectral-elements):** "workhorse" dynamical core in CESM2 for high resolution and mesh-refinement applications
- **(ongoing) CAM-FV3 (cubed-sphere version of FV):** being integrated into CESM (funded by NOAA)
- **(starting) CAM-MPAS (Model for Prediction Across Scales):** being integrated into CESM (internal effort)

Note: The CESM simpler models functionality in CESM has been key in scientifically verifying ports to CESM

Step 2: Evaluate dycores in "climate setup"

Can they replace CAM-FV for climate applications? Throughput, conservation, accuracy, ...

- **CAM-SE** (spectral-el
  resolution and m
- **CAM-FV3** (cubed-s
- **CAM-MPAS** (Mode

Proposal:

		Climate	Weather	Geospa
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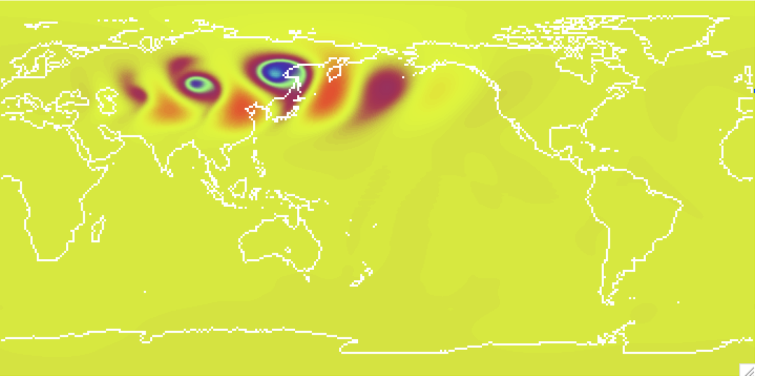
Proposal for preliminary benchmarks to assess degree to which requirements are met

Initial focus is on 1^0 horizontal resolution and run in CESM using simpler models capability

Idealized baroclinic wave
(short time-scales)



Some variant of Held-Suarez forcing
with and without topography
(long time-scales)

$$\frac{\partial v}{\partial t} = \cdots - k_v(\sigma) v$$

$$\frac{\partial T}{\partial t} = \cdots - k_T(\phi,\sigma)\left[T - T_{eq}(\phi,p)\right]$$

$$T_{eq} = \max\left\{200\mathrm{K}, \left[315\mathrm{K} - (\Delta T)_y \sin^2\phi - (\Delta\theta)_z \log\left(\frac{p}{p_0}\right)\cos^2\phi\right]\left(\frac{p}{p_0}\right)^{\kappa}\right\}$$

$$k_T = k_a + (k_s - k_a)\max\left(0, \frac{\sigma - \sigma_b}{1 - \sigma_b}\right)\cos^4\phi$$

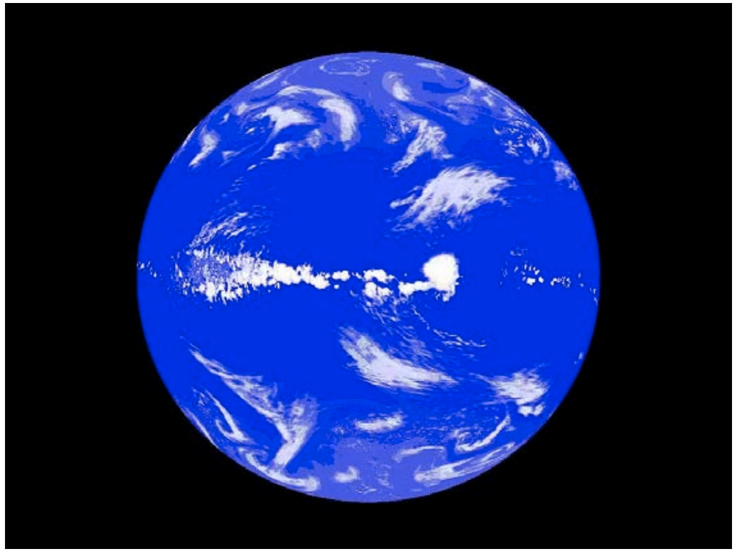
$$k_v = k_f \max\left(0, \frac{\sigma - \sigma_b}{1 - \sigma_b}\right)$$

$\sigma_b = 0.7$	$k_f = 1\ \mathrm{day}^{-1}$,
$k_a = {}^1/_{40}\ \mathrm{day}^{-1}$	$k_s = {}^1/_4\ \mathrm{day}^{-1}$
$(\Delta T)_y = 60\mathrm{K}$	$(\Delta\theta)_z = 10\mathrm{K}$

$p_0 = 1000$ mb $\quad \kappa = \frac{R}{c_p} = \frac{2}{7} \quad c_p = 1004\ \mathrm{J\ kg^{-1}\ K^{-1}}$

$\Omega = 7.292 \times 10^{-5}\ \mathrm{s}^{-1} \quad g = 9.8\ \mathrm{m\ s^{-2}} \quad a_e = 6.371 \times 10^6$ m.

Aqua-planet
(long time-scales)



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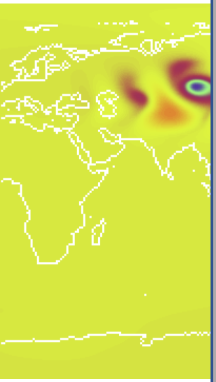
Idealize
(short ti



For more information on test case suite see talk from 2018 AMWG winter meeting:

http://www.cesm.ucar.edu/events/wg-meetings/2018/presentations/amwg/lauritzen.pdf

(slides also appended to this talk)

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Step 3: Based on step 2 decide how to proceed

A couple of observations:

- To meet requirements for geospace applications further development is needed for deep atmosphere extension
  (e.g., all dycores use shallow-atmosphere approximation, constant gravity, "2D" Coriolis, constant heat capacities and gas constants, etc.)

- CAM-SE is currently being coupled to ionosphere/thermosphere models (coupling is general so it can be re-used by MPAS and FV3) and high-top thermodynamic modifications are being implemented in SE dynamical core.

- Non-hydrostatics needed for resolutions finer than ~10km (CAM-SE is currently hydrostatic; FV3 and MPAS are non-hydrostatic)

As part of the Singletrack effort we have formed a Physics-Dynamics Coupling sub-group

- ensure the mass budget in the system as a whole is closed (by adding diagnostics to system)
- ensure some level of energetic consistency between the dynamical core and physical parameterizations or, at the very least, quantify the spurious energy leaks in the system as a whole:

  - do the continuous equations of motion conserve the same total energy as used by parameterizations (assuming the parameterizations have a closed energy budget)
  - what total energy formula should we use? (e.g., include condensates or not)
  - are the discrete total energies the same? Not trivial if, for example, different vertical coordinates are used in dynamical core and physics
  - …
- ensure that the way in which the physics tendencies are added to the dynamical core leads to a closed mass and, ideally, total energy budget (by adding diagnostics to the system)

These are challenging research tasks that involve all aspects of the model (dynamics, physics, coupling layers, …)

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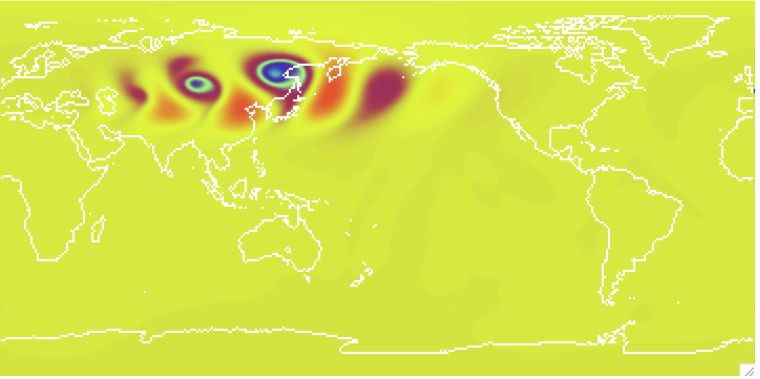

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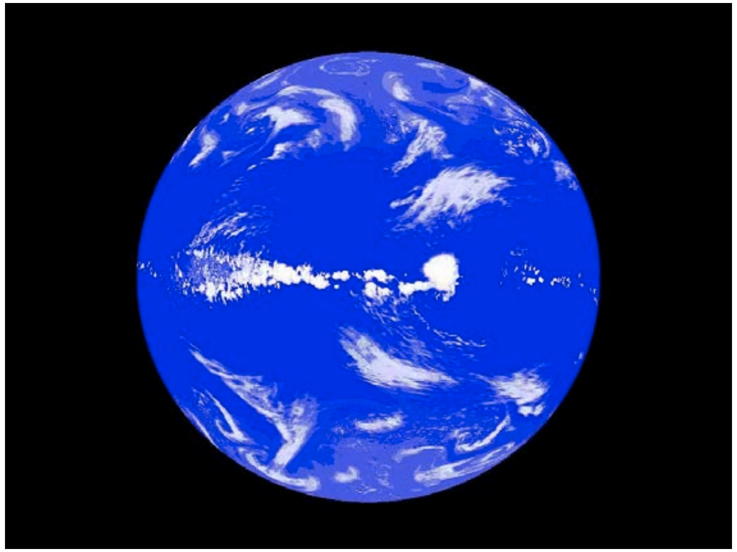
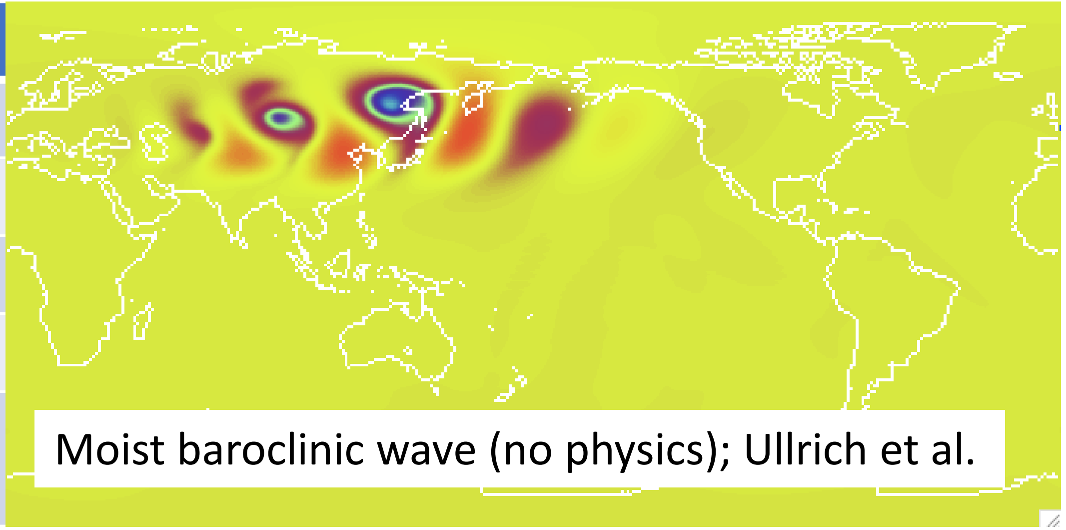
(long time-scales)



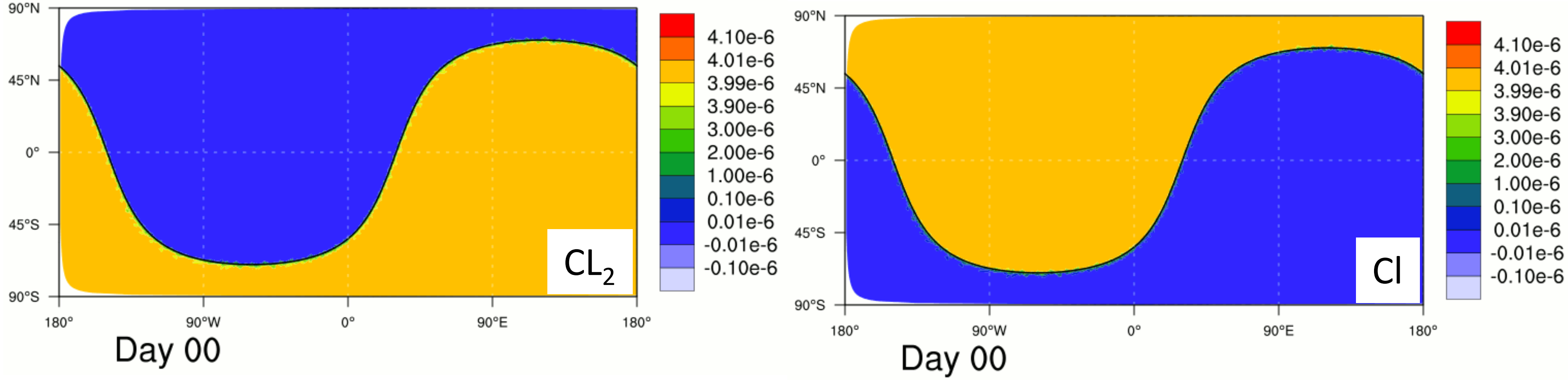
		Climate
(1)	Throughput: cost and scalability	Essential
(2)	Strong scaling	Essential
(3)	Efficient tracer transport	Essential
(4)	Conservation of mass (dry air, scalars)	Essential
(5)	Good tracer transport characteristics (shape-preservation, correlation, etc.)	Essential



(5a) **Linear correlation preservation**

Cl and Cl_2 that react with each other but always add up to a constant

(Lauritzen et al., 2015; 3D version in Lauritzen et al., 2017)



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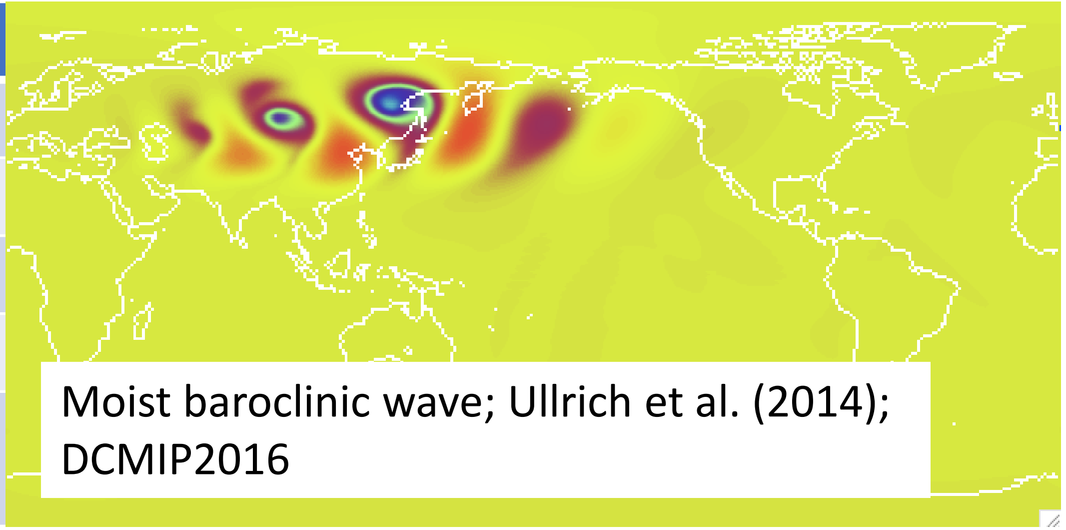


Moist baroclinic wave; Ullrich et al. (2014); DCMIP2016

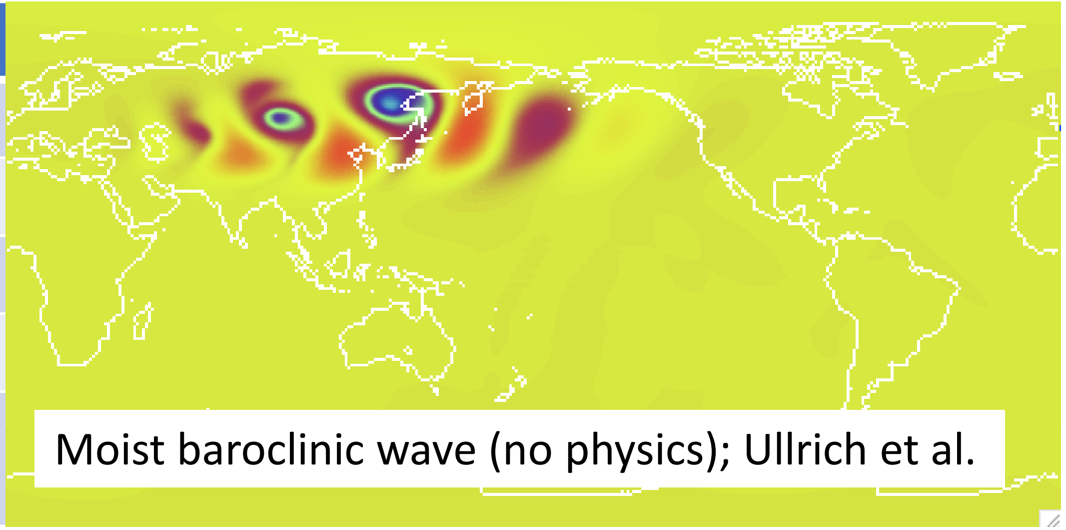
(1-3) At approximately 1^0 resolution evaluate throughput as a function of:

- number of tracers (from O(10) to O(300))
- vertical levels (from O(30) to O(200))
- number of processors (O(200) processor to O(5000) – few degrees of freedom, in the horizontal, per processor)

(4) Check for dry air mass conservation and scalar mass conservation

```
./create_newcase -compset FKESSLER (or variant thereof)
```

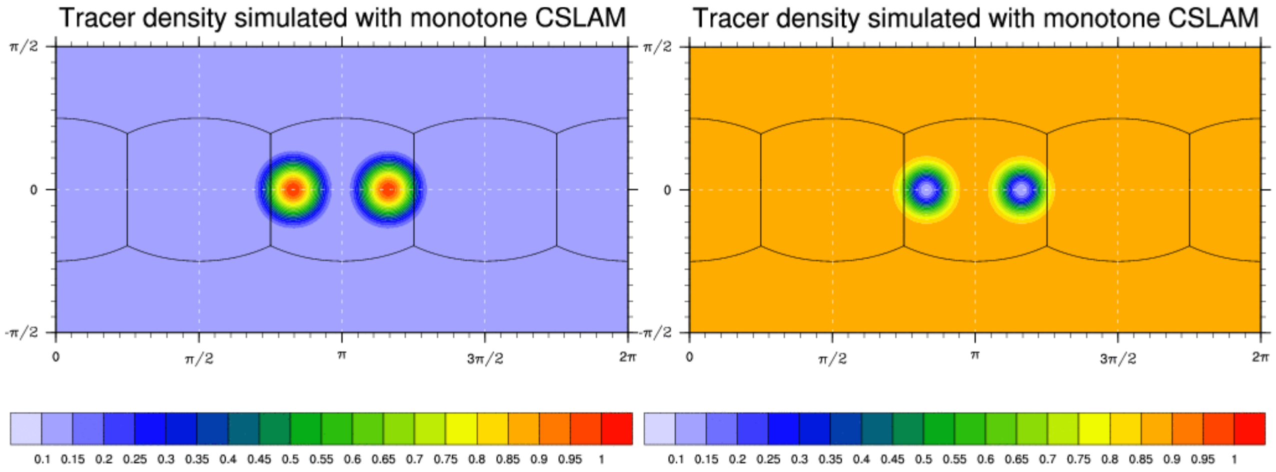
		Climate
(1)	Throughput: cost and scalability	Essential
(2)	Strong scaling	Essential
(3)	Efficient tracer transport	Essential
(4)	Conservation of mass (dry air, scalars)	Essential
(5)	Good tracer transport characteristics (shape-preservation, correlation, etc.)	Essential

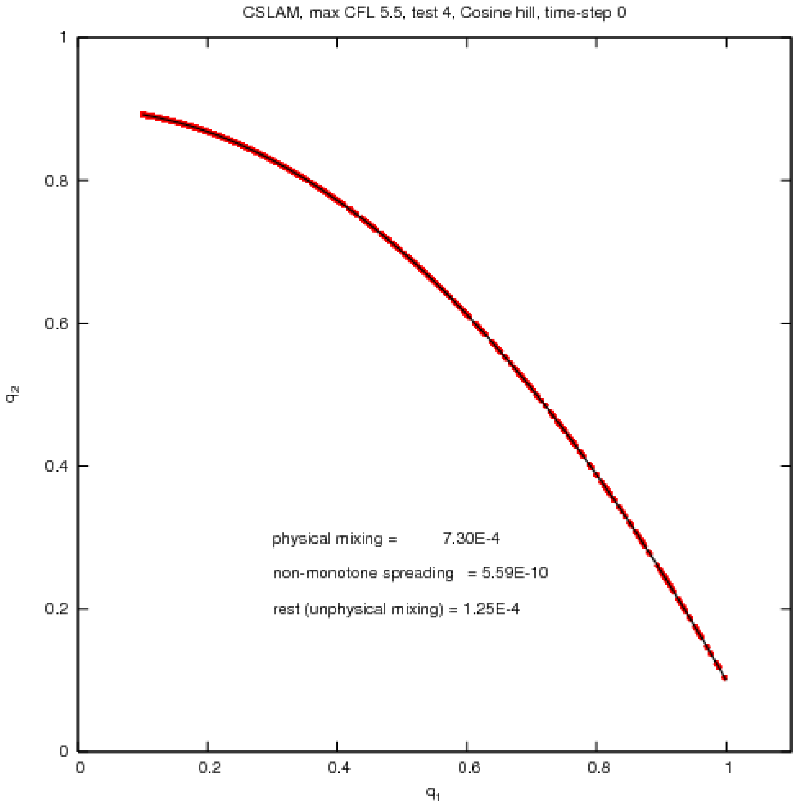

Moist baroclinic wave (no physics); Ullrich et al.

(5b) Non-linear correlation preservation

Two inert and passive distributions

(Lauritzen and Thuburn, 2010 -> need to extend to 3D!)





		Climate
(1)	Throughput: cost and scalability	Essential
(2)	Strong scaling	Essential
(3)	Efficient tracer transport	Essential
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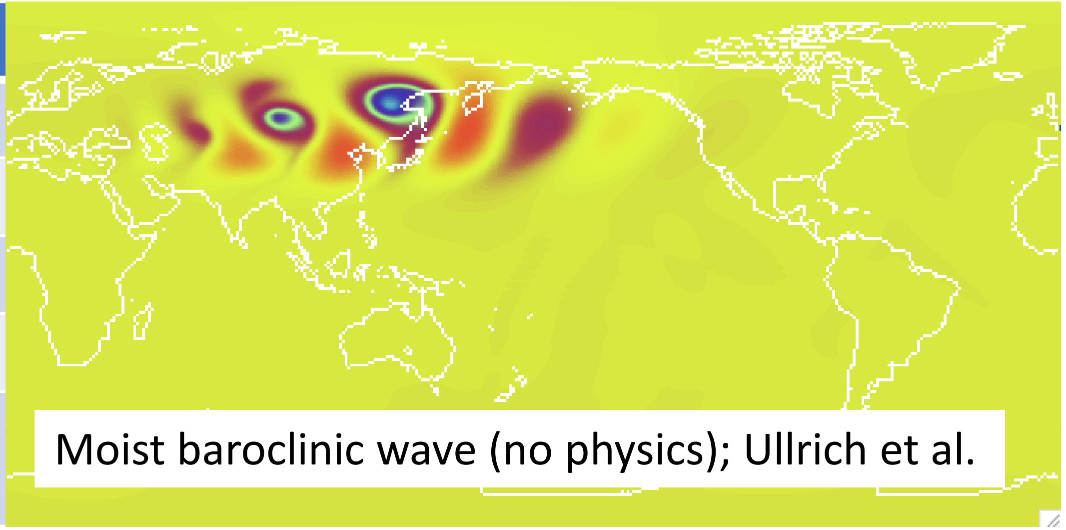
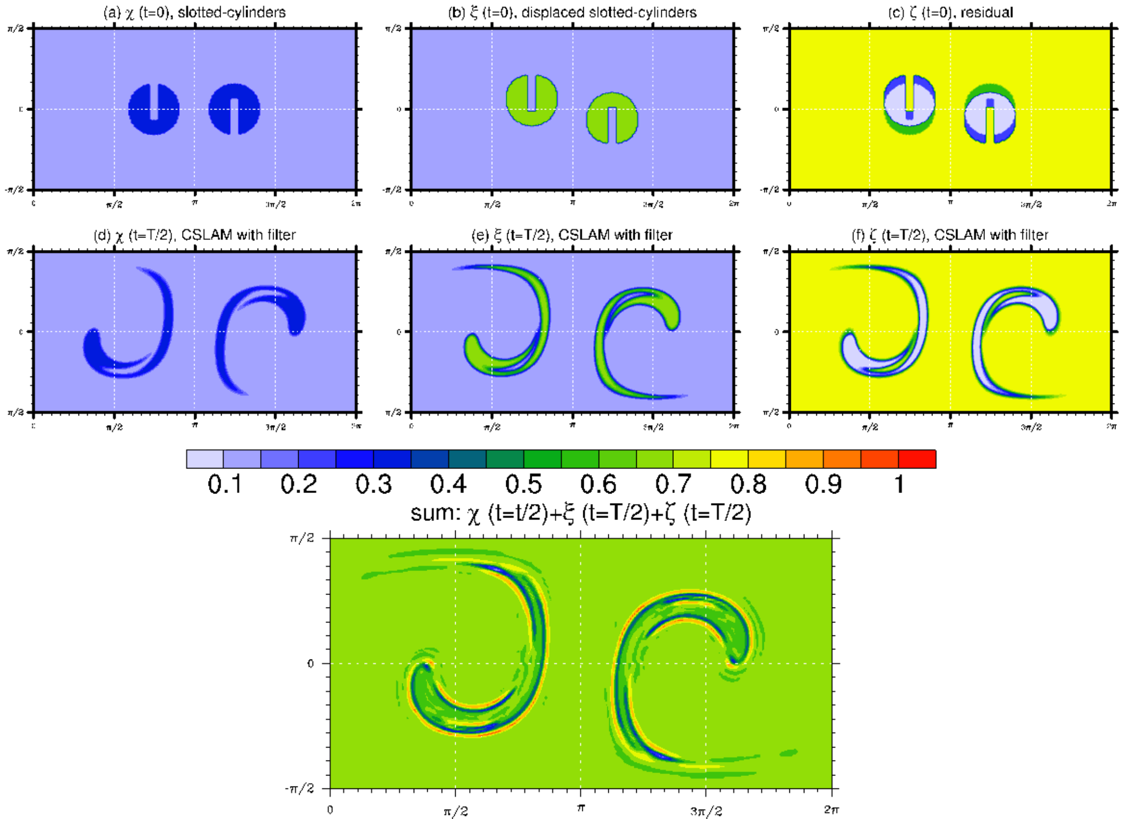
(5)	Good tracer transport characteristics (shape-preservation, correlation, etc.)	Essential



(5c) **Conserving family of species**

3 distributions that add up to a constant

(Lauritzen and Thuburn, 2010 -> need to extend to 3D!)



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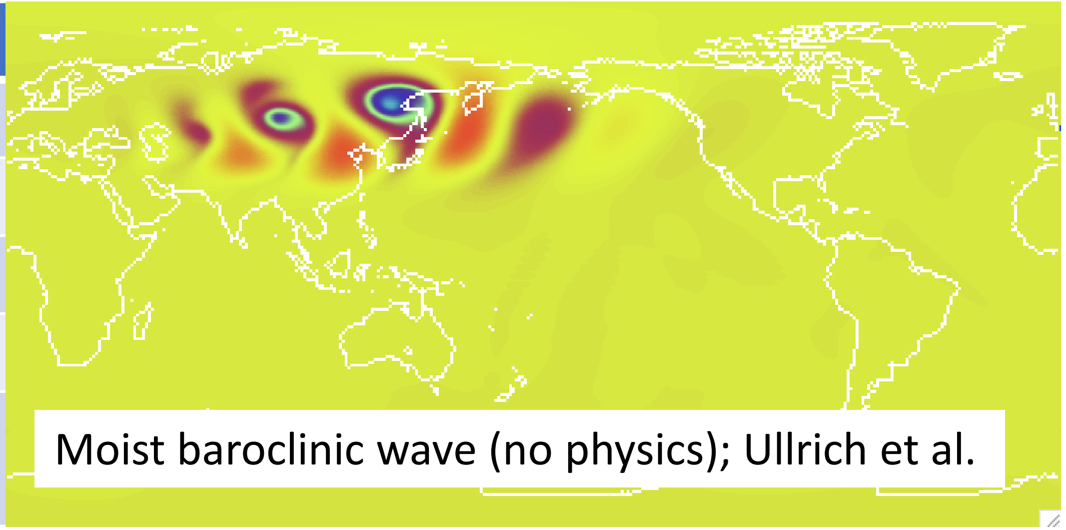
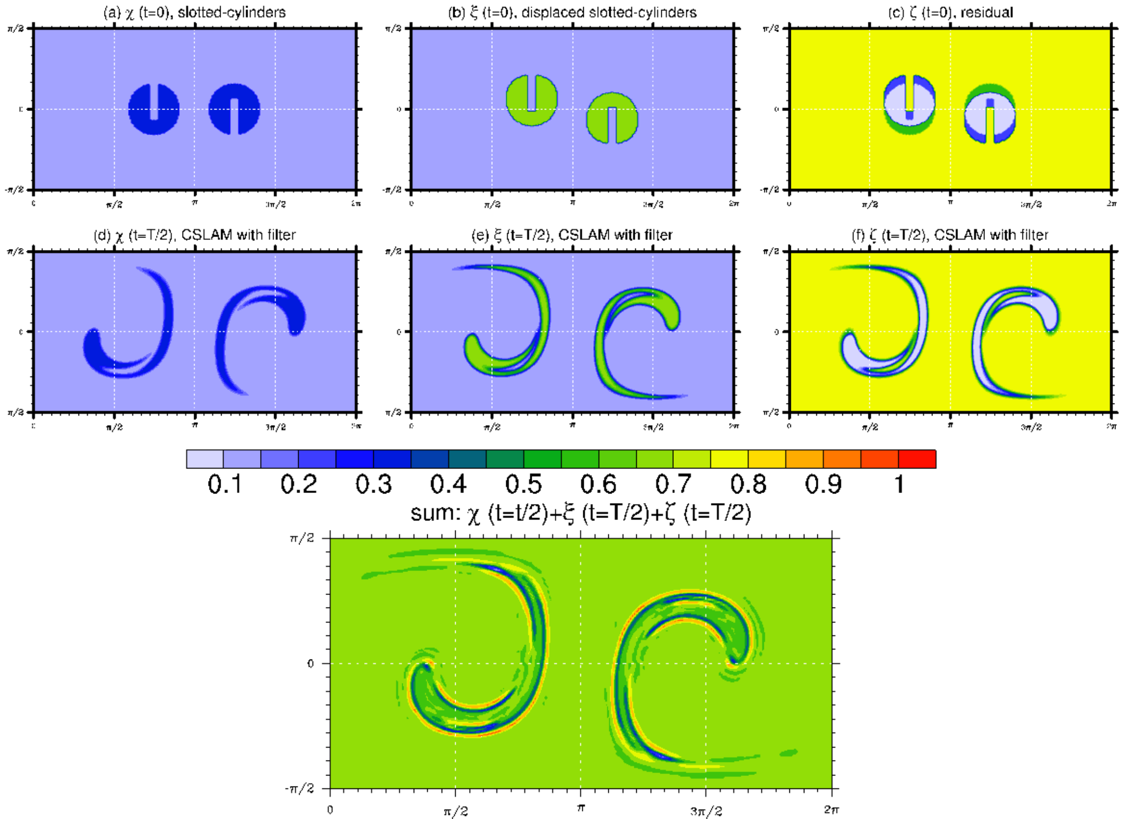

Moist baroclinic wave (no physics); Ullrich et al.

(5d) **Gradient preservation & shape-preservation**

Filament diagnostic: A measure of how well a transport scheme preserves gradients

(Lauritzen et al., 2012)



		Climate	Weather	Geospace
(1)	Throughput: cost and scalability	Essential	Essential	Essential
(2)	Strong scaling	Essential	Desirable	Desirable
(3)	Efficient tracer transport	Essential	Essential	Essential
(4)	Conservation of mass (dry air, scalars)	Essential	Essential	Essential
(5)	Good tracer transport characteristics (shape-preservation, correlation, etc.)	Essential	Essential	Essential

(5e) **Age-of-air (longer time-scales)**

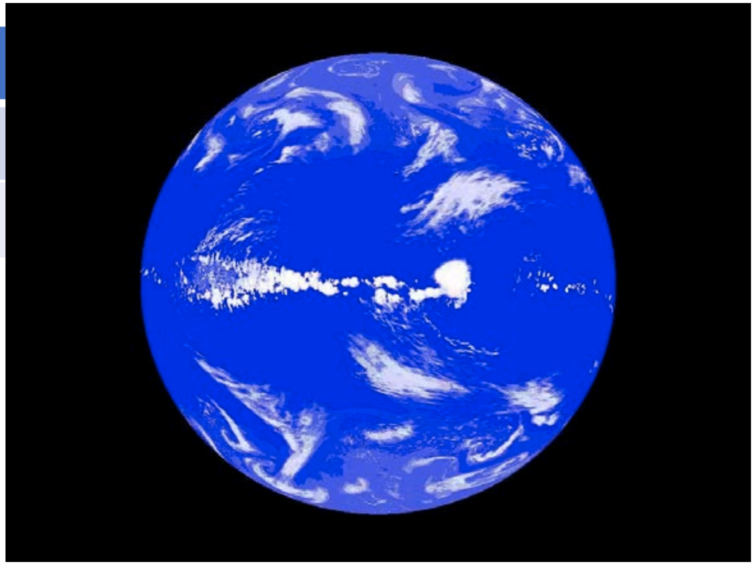
Polvani-Kushner (= variant of Held-Suarez with more realistic stratosphere) forcing with "clock tracer"

(Gerber and Gupta, NYU)

(4) Trends in mass-conservation over long time-scales

```
./create_newcase -compset FHS94 (modified)
```

		Climate	Weather
(6)	Good conservation of total energy	Essential	Desirable
(7)	Conservation of angular momentum	Highly desirable	



(4) Check for dry air mass conservation and scalar mass conservation

(6) **Derive what total energy the continuous equations of motion (on which dycore is based) conserve.**

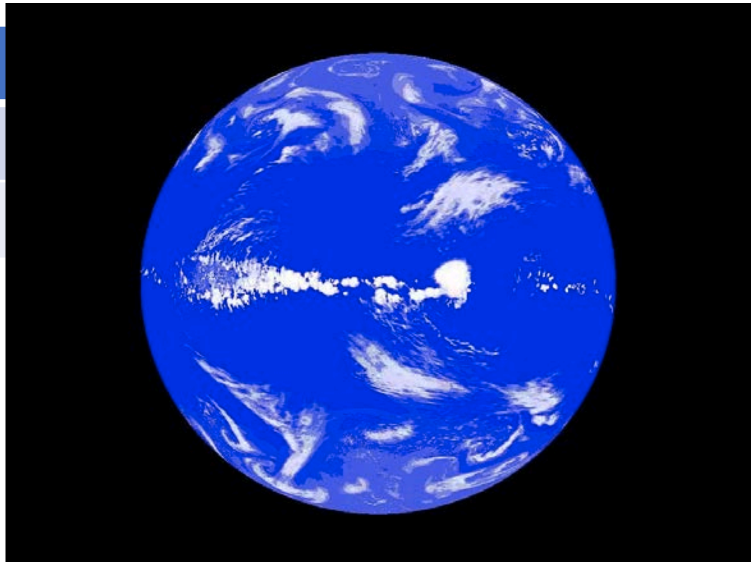
Total energy dissipation of the dynamical core should be assessed with moist physics (simplest setup is probably Aqua-planet) at (?) ~1^0 horizontal resolution

-> Diagnostics already exist in CAM physics layer

-> A detailed analysis of the energy conservation properties of different aspects of the dynamical core is of interest (currently diagnostics only in CAM-SE)

```
./create_newcase -compset QPC6 (or QPC4 or QPC5)
```

		Climate	Weather
(6)	Good conservation of total energy	Essential	Desirable
(7)	Conservation of angular momentum	Highly desirable	



(6) **Derive what axial angular momentum the continuous equations of motion (on which dycore is based) conserve (in the absence of mountain torque).**

Total axial angular momentum conservation can be tested with Aqua-planet or Held-Suarez (at (?) ~1^0 horizontal resolution).

Spurious torque from the dynamical core should << torque from parameterizations

-> Diagnostics already exist in CAM (in physics layer)

		Climate	Weather	Geospace
(8)	Dycore characteristics with topography			

(8) To my knowledge: **No “real-word” topography test in the literature!**

Topography smoothing and the dynamical core are closely related. It is, in general, desirable to have rougher topography. However, rough topography can trigger grid-scale noise from dynamical core.

Held-Suarez (or similar) forcing with real-world topography smoothed at different predefined scales (using the NCAR topography generation software; Lauritzen and Bacmeister):

-> all dycores “will see” the same topography and we can get an idea of the dynamical cores response to topographic forcing (e.g., magnitude and structure of vertical velocity)

-> add tracers to assess (“spurious”) vertical transports over orography

ANY OTHER IDEAS?