A Nonhydrostatic Spectral-Element Atmospheric Dynamical-Core in CAM-SE

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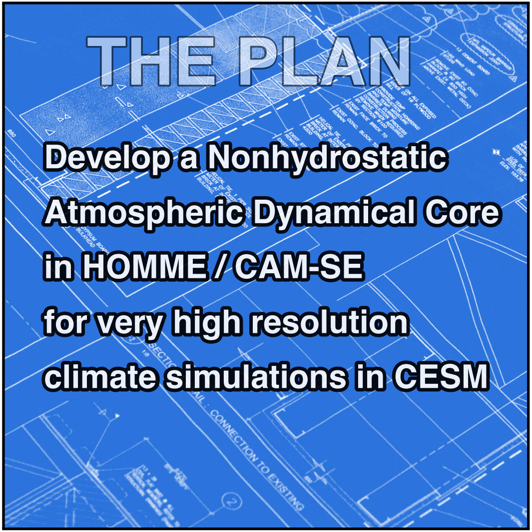
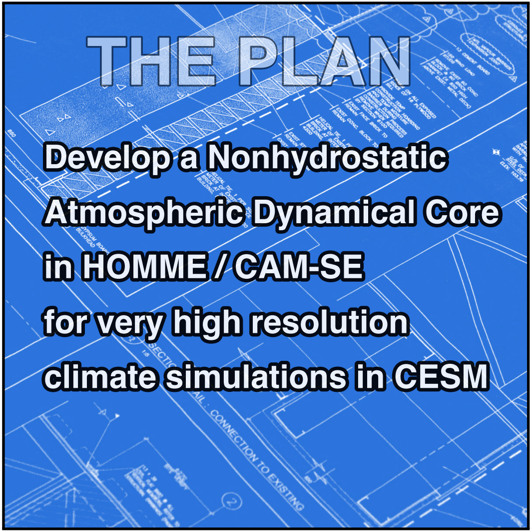

THE PLAN
Develop a Nonhydrostatic
Atmospheric Dynamical Core
in HOMME / CAM-SE
for very high resolution
climate simulations in CESM



- **Motivation:**
  Why do we need a nonhydrostatic model in CESM?
- Our two paths to nonhydrostatis:
  SE & DG nonhydrostatic models
- **SE governing equations**
- **Tests and Results**
- **Next Steps**

Why model the climate?

- To **predict** and **quantify** changes cause by anthropogenic influences

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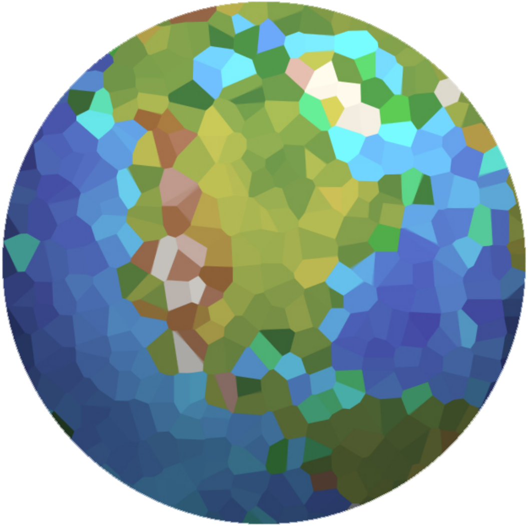
- **To inform** policy makers and the public, so they can make the best possible choices
- **To mitigate** their impacts by enabling policy makers to allocate resources appropriately

What are the advantages of high resolution?



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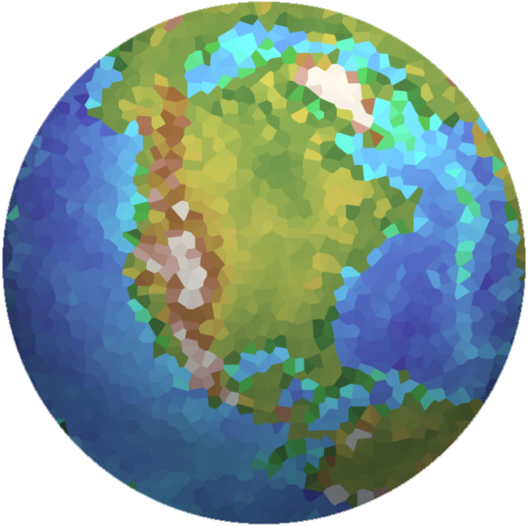

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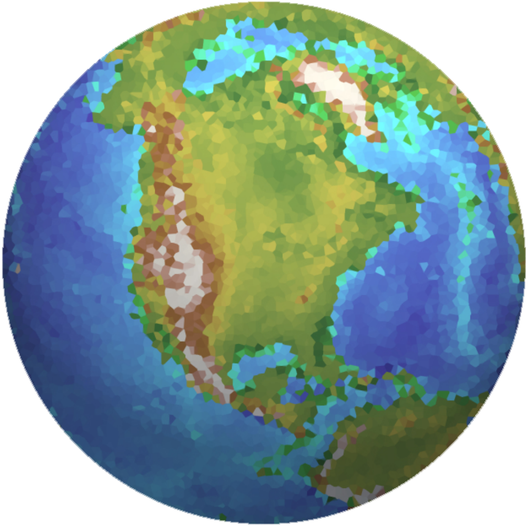

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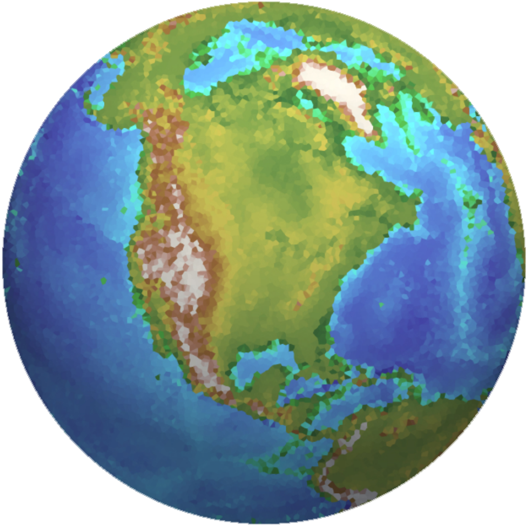
- Replace physical **parameterizations** with resolved dynamics



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- Greater **detail**
- Improved **accuracy**
- Replace physical **parameterizations** with resolved dynamics
- Capture **mesoscale phenomena**: tropical storms, orographic waves, tornados

What happens as we approach the hydrostatic limit? (10km per grid cell = $1/10°$)

Photo Credit: Greg Thow

What happens as we approach the hydrostatic limit? (10km per grid cell = $1/10°$)

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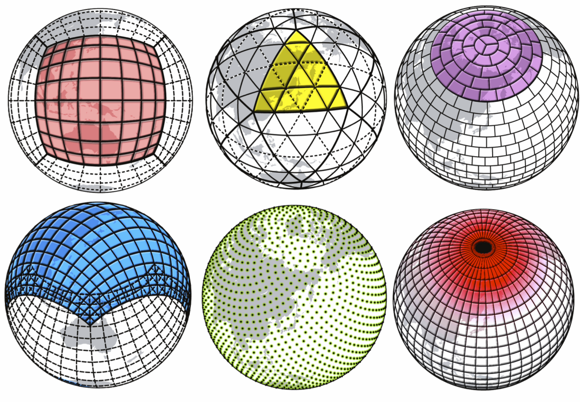
- **Hydrostatic balance** approximation breaks down
- **Vertical motion** becomes commensurate with horizontal
- **Pressure** is no longer monotonic in the vertical
- **Mesoscale phenomena** become significant
- **Nonhydrostatic equations** of motion must be employed
- **Simulation cost** rises rapidly with resolution

Many paths toward a nonhydrostatic model

- Independent Variables
- Coordinate Systems
- Discretization: H & V
- Mesh: H & V
- Approximation of fast waves
- Regularization



choices for a global horizontal mesh

Our two paths: SE and DG

- **Conservative Path: SE**
  - As close as possible to PE model
  - Spectral-Element discretization

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- Experimental Path: **DG**
  - Discontinuous-Galerkin discretization
  - Terrain-following Z coordinate

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- Conservative Path: **SE**
  - As close as possible to PE model
  - Spectral-Element discretization
- Experimental Path: **DG**
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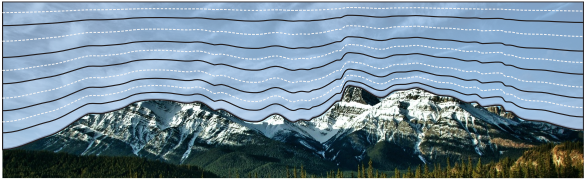
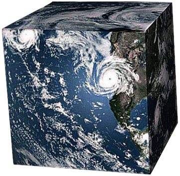
  - Terrain-following Z coordinate
- Best features of both models will be merged

The Nonhydrostatic SE Model

- **As similar as possible** to the CAM-SE primitive-equation model

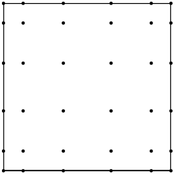


hydrostatic-pressure terrain-following coordinates



cubed-sphere

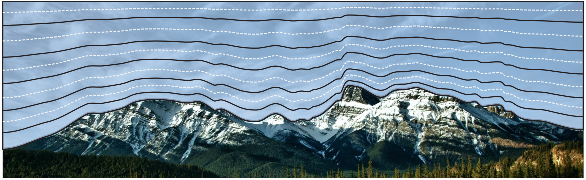
shallow-atmosphere



GLL spectral-elements

The Nonhydrostatic SE Model

- **As similar as possible** to the CAM-SE primitive-equation model
- Hybrid terrain-following **pressure coordinates**



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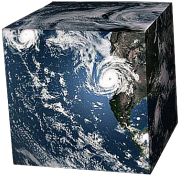

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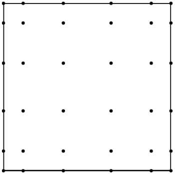

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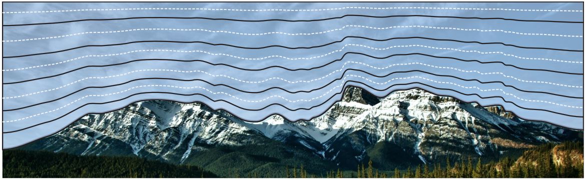

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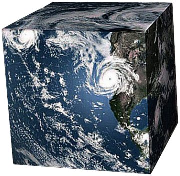

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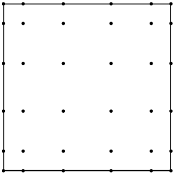

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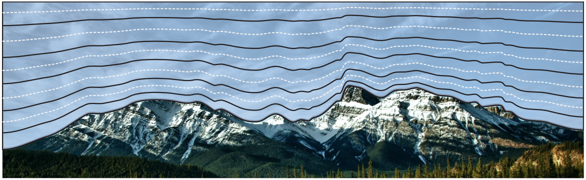

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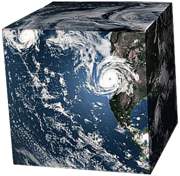

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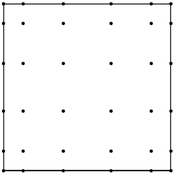

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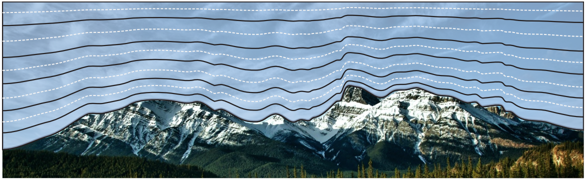

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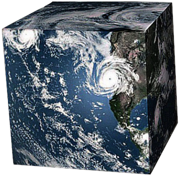

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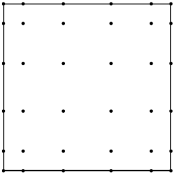

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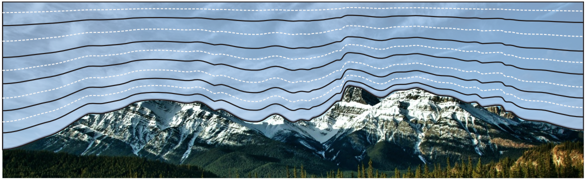

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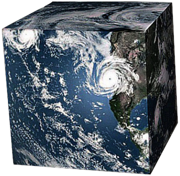

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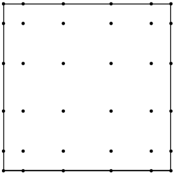

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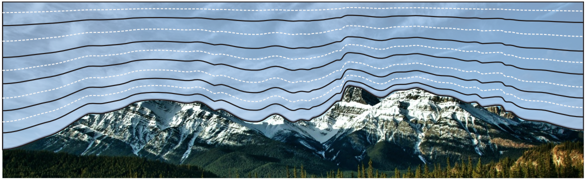
- Laprise **Compressible Euler** equations instead of PE



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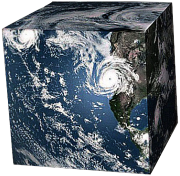

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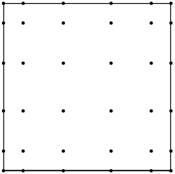

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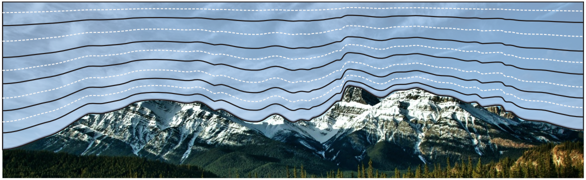
- **Hydrostatic pressure** vertical coordinate (instead of pressure)



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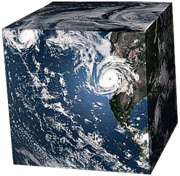

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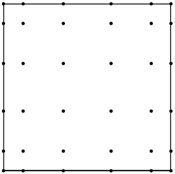

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The CAM-SE Primitive Equations

prognostic equations only (excluding tracers) in hybrid pressure coordinates η

horizontal velocity $\frac{d\mathbf{u}}{dt} = -f\hat{\mathbf{k}} \times \mathbf{u} - \frac{RT}{\pi} \nabla_\eta \pi - \nabla_\eta \Phi + \mathbf{F}_u$

temperature $\frac{dT}{dt} = \frac{RT}{c_p \pi} \dot{\pi} + \frac{Q}{c_p}$

surface pressure $\frac{\partial \pi_s}{\partial t} = \int_1^{\eta_{\text{top}}} \nabla_\eta \cdot \left(\mathbf{u} \frac{\partial \pi}{\partial \eta} \right) d\eta$

vertical velocity $\frac{dw}{dt} = 0$

note: $p = \pi$ due to hydrostatic balance approximation

hybrid coordinate	η	2d gradient, constant η	∇_η	material derivative	d/dt
horizontal velocity	$\mathbf{u} = [u, v]$	total pressure	p	surface pressure	π_s
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gas constant	R	vertical unit vector	$\hat{\mathbf{k}}$	heat capacity	c_p
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acceleration: coriolis force, pressure grad, grav grad, momentum sources

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temperature increases: compression, heat sources

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surface-pressure increases: flux of matter into the column

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The CAM-SE Primitive Equations

hydrostatic balance: vertical accelerations neglected

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Nonhydrostatic Laprise Equations in p and π

pressure gains a **nonhydrostatic component**: $p = \pi + p'$

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vertical velocity	$\frac{dw}{dt} = -g\left(1 - \frac{\partial p}{\partial \pi}\right)$
total pressure	$\frac{1}{p}\frac{dp}{dt} = -\frac{c_p}{c_v}(\nabla \cdot \mathbf{v}) + \frac{Q}{c_v T}$

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a **new prognostic** is needed for total pressure.

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nonhydrostatic pressure gradient: vertical acceleration, gravitational gradient

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hydrostatic pressure	π	pressure deviation	p'	3d gradient	∇
pressure velocity	$\omega = \dot{\pi}$				

Nonhydrostatic Laprise Equations in p and p'

track p' **instead of** p to reduce numerical approximation errors in $p - \pi$

horizontal velocity	$\frac{d\mathbf{u}}{dt} = -f\hat{\mathbf{k}} \times \mathbf{u} - \frac{RT}{p}\nabla_\eta p - \left(1 + \frac{\partial p'}{\partial \pi}\right)\nabla_\eta \Phi + \mathbf{F}_u$
temperature	$\frac{dT}{dt} = \frac{RT}{c_p p}\left(\dot{\pi} + \dot{p}'\right) + \frac{Q}{c_p}$
surface pressure	$\frac{\partial \pi_s}{\partial t} = \int_1^{\eta_{\text{top}}} \nabla_\eta \cdot \left(\mathbf{u}\frac{\partial \pi}{\partial \eta}\right) d\eta$
vertical velocity	$\frac{dw}{dt} = g\left(\frac{\partial p'}{\partial \pi}\right)$
total pressure	$\frac{1}{p}\frac{dp}{dt} = -\frac{c_p}{c_v}\left(\nabla \cdot \mathbf{v}\right) + \frac{Q}{c_v T}$

hybrid coordinate	η	2d gradient, constant η	∇_η	material derivative	d/dt
horizontal velocity	$\mathbf{u} = [u, v]$	total pressure	p	surface pressure	π_s
temperature	T	geopotential	Φ	Coriolis parameter	f
gas constant	R	vertical unit vector	$\hat{\mathbf{k}}$	heat capacity	c_p
velocity source (force)	$\mathbf{F}_u$	heat source term	Q	total velocity	$\mathbf{v} = [u, v, w]$
hydrostatic pressure	π	pressure deviation	p'	3d gradient	∇
pressure velocity	$\omega = \dot{\pi}$				

Nonhydrostatic Laprise Equations in p and p'

replace pressure prognostic with **pressure deviation prognostic**

horizontal velocity $$\frac{d\mathbf{u}}{dt} = -f\hat{\mathbf{k}} \times \mathbf{u} - \frac{RT}{p} \nabla_\eta p - \left(1 + \frac{\partial p'}{\partial \pi}\right) \nabla_\eta \Phi + \mathbf{F}_u$$

temperature $$\frac{dT}{dt} = \frac{RT}{c_p p} \left(\dot{\pi} + \dot{p}'\right) + \frac{Q}{c_p}$$

surface pressure $$\frac{\partial \pi_s}{\partial t} = \int_1^{\eta_{\text{top}}} \nabla_\eta \cdot \left(\mathbf{u} \frac{\partial \pi}{\partial \eta}\right) d\eta$$

vertical velocity $$\frac{dw}{dt} = g\left(\frac{\partial p'}{\partial \pi}\right)$$

pressure deviation $$\frac{dp'}{dt} = -\dot{\pi} - p\frac{c_p}{c_v}\left(\nabla \cdot \mathbf{v}\right) + p\frac{Q}{c_v T}$$

hybrid coordinate	η	2d gradient, constant η	∇_η	material derivative	d/dt
horizontal velocity	$\mathbf{u} = [u, v]$	total pressure	p	surface pressure	π_s
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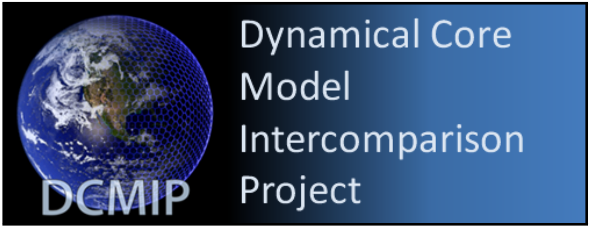
Test DCMIP 3.1: Nonhydrostatic Gravity Waves

- Dynamical-Core Model Intercomparison Test



Test DCMIP 3.1: Nonhydrostatic Gravity Waves

- Dynamical-Core Model Intercomparison Test
- Gavity waves produced by a sudden thermal perturbation

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- Dynamical-Core Model Intercomparison Test
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- Reduced planet, scale factor $X = 125$

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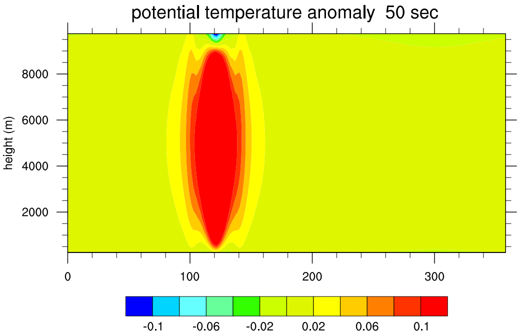

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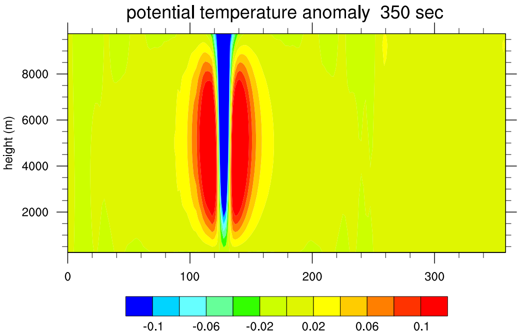

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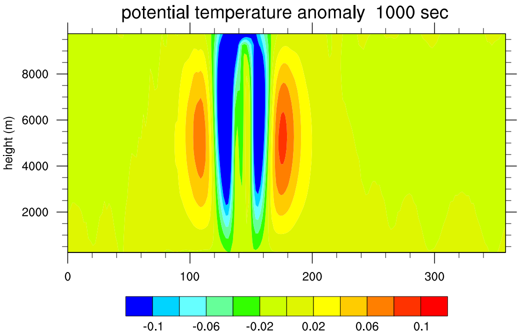

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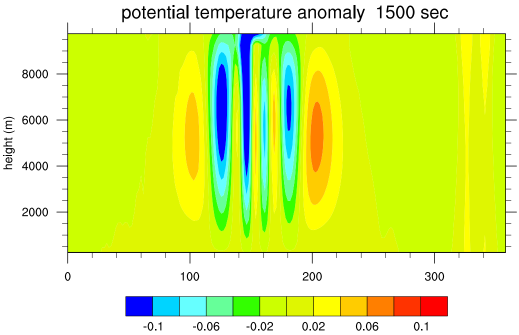

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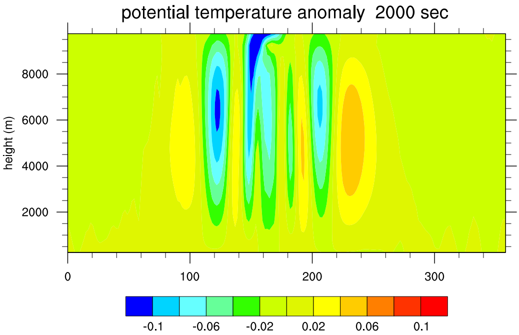

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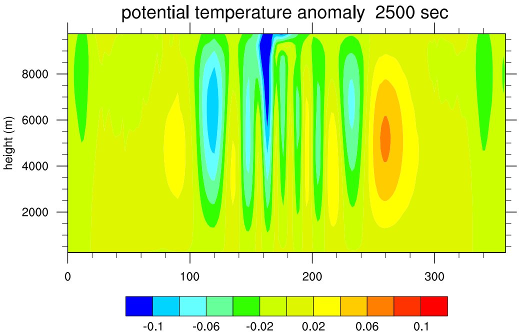

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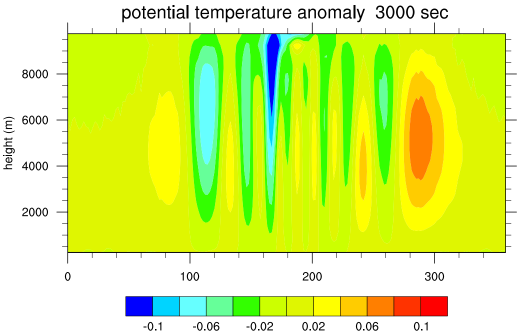
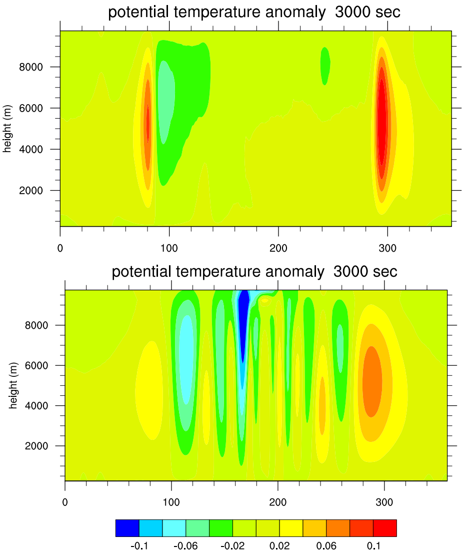


Test DCMIP 3.1: Nonhydrostatic Gravity Waves

- Dynamical-Core Model Intercomparison Test
- Gavity waves produced by a sudden thermal perturbation
- Reduced planet, scale factor $X = 125$
- CAM-SE NH vs PE



Test DCMIP 3.1: Nonhydrostatic Gravity Waves

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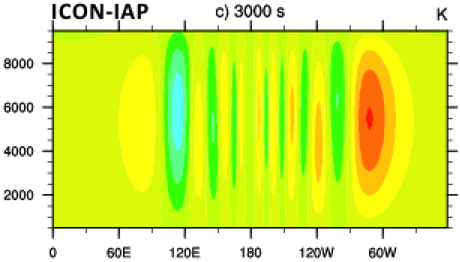
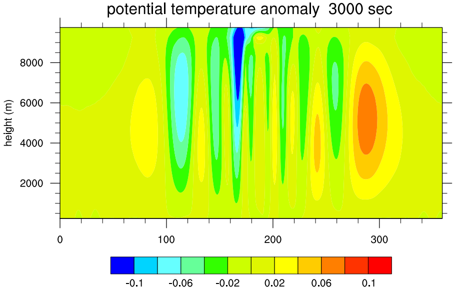
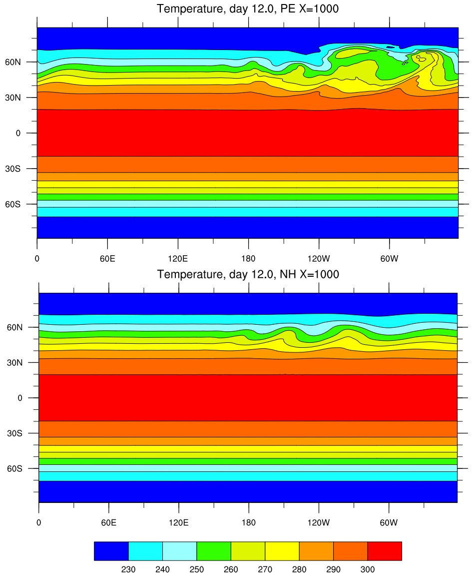
- Gavity waves produced by a sudden thermal perturbation
- Reduced planet, scale factor $X = 125$
- CAM-SE NH vs PE
- CAM-SE NH vs ICON-IAP





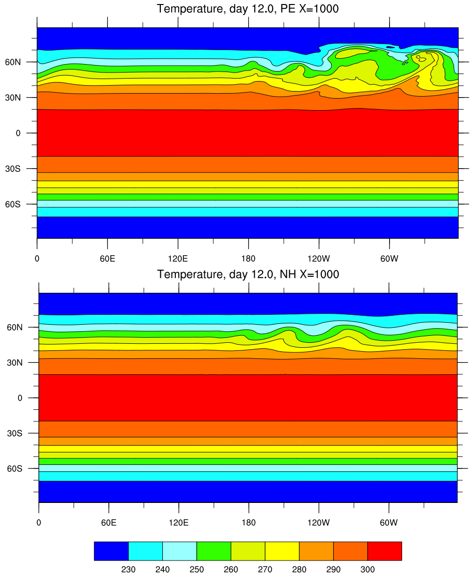
Test DCMIP 4.1.4: Baroclinic Instability

- Nonhydrostatic Baroclinic instability



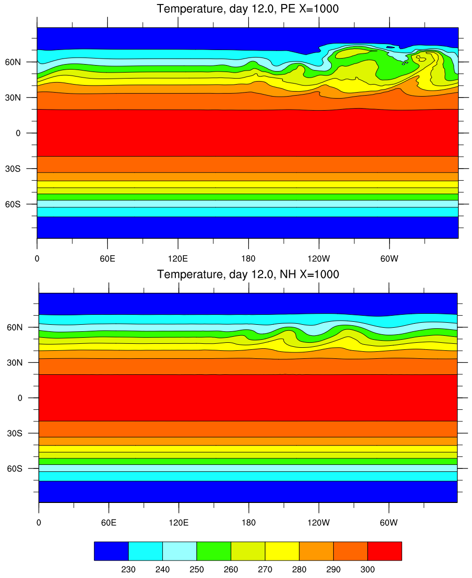
Test DCMIP 4.1.4: Baroclinic Instability

- Nonhydrostatic Baroclinic instability
- Reduced planet, scale factor $X = 1000$



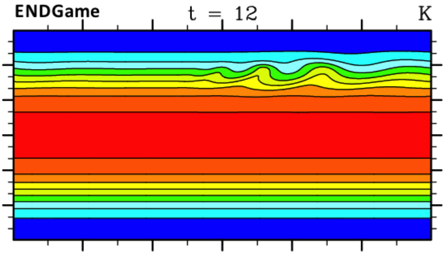
Test DCMIP 4.1.4: Baroclinic Instability

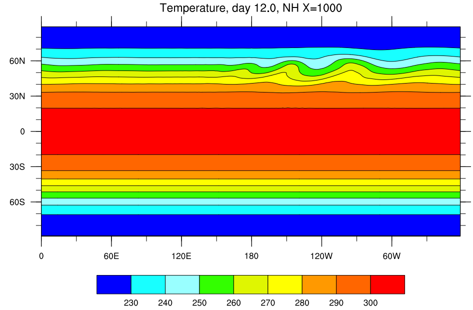
- Nonhydrostatic Baroclinic instability
- Reduced planet, scale factor $X = 1000$
- CAM-SE NH vs PE



Test DCMIP 4.1.4: Baroclinic Instability

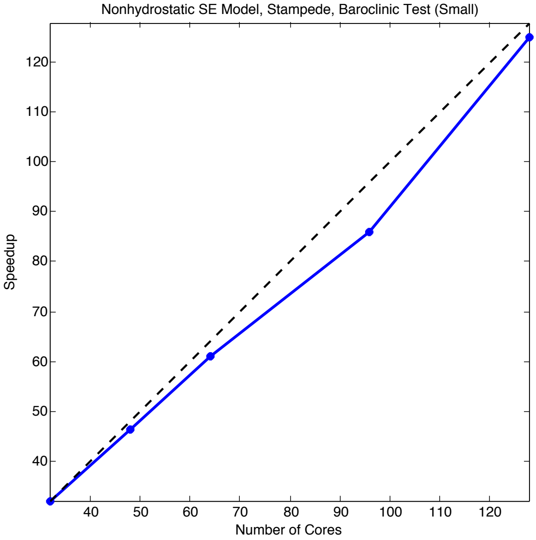
- Nonhydrostatic Baroclinic instability
- Reduced planet, scale factor $X = 1000$
- CAM-SE NH vs PE
- CAM-SE NH vs ENDGame NH





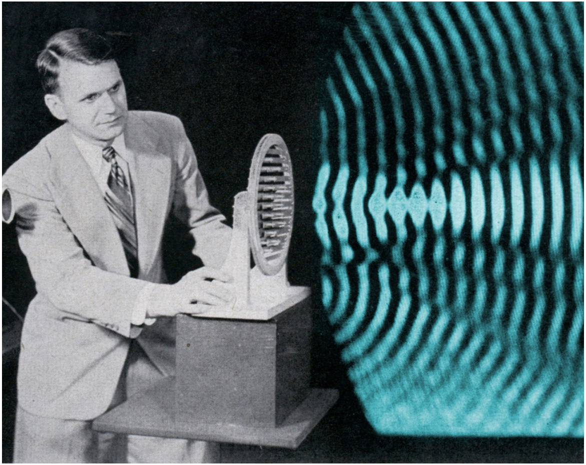
Strong Scaling

- Baroclinic instability test
- 1.4°, ne=9, polynomial order=7
- XSEDE Stampede supercomputer



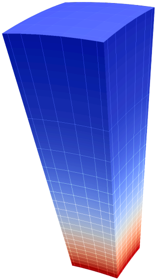
Dealing With Fast Acoustic Waves

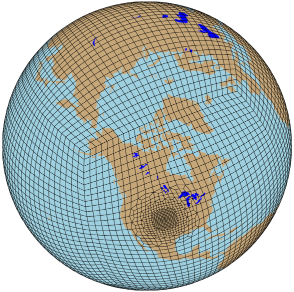
- Explicit CFL Number limited by fast acoustic waves
- HE-VI Solution
- Implicit Solver in the column
- DIRK: diagonally-implicit runge kutta



Next Steps

- Implicit vertical solver
- Coupled testing in CESM
- Integration with variable-resolution grids
- Improved vertical coordinates





Summary

- **CESM needs a nonhydrostatic model** to achieve resolutions beyond 10km
- The CAM-SE / HOMME team is taking **two approaches**: SE and DG
- An **explicit version** of the nonhydrostatic SE model is in the testing stage
- An **implicit solver** in the vertical is the next step
- Much remains to be done