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The Spectral Element Dynamical Core in the Community Climate System Model

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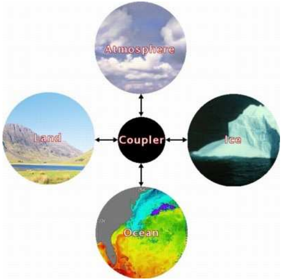
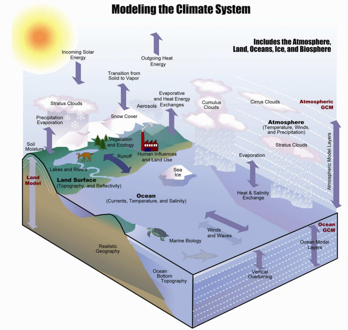
Sandia National Laboratories

Outline

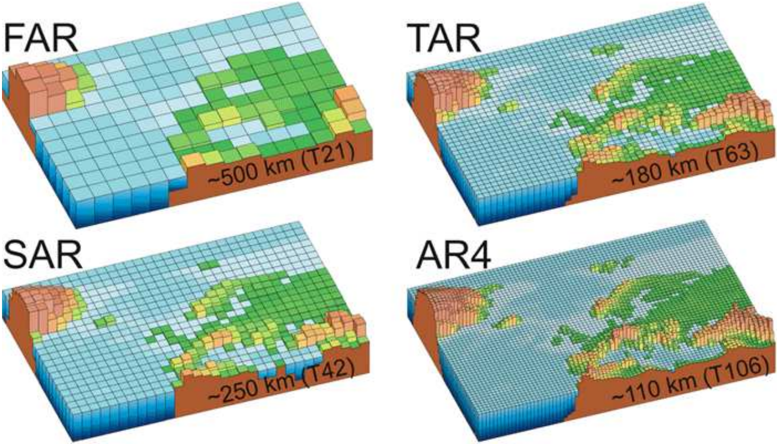
The Community System Climate Model (CCSM)

- IPCC-class model
  - Seasonal and interannual variability in the climate
  - Explore the history of Earth's climate
  - Estimate future of environment for policy formulation
  - Contribute to assessments
- Developed by NCAR, National Labs (DOE $\sim$ 40%), and Universities
- Fully documented, supported, and freely distributed
- Runs on multiple platforms and resolutions
- CCSM4 (Apr 2010) and CESM1 (June 2010): Higher resolution and increasing complexity





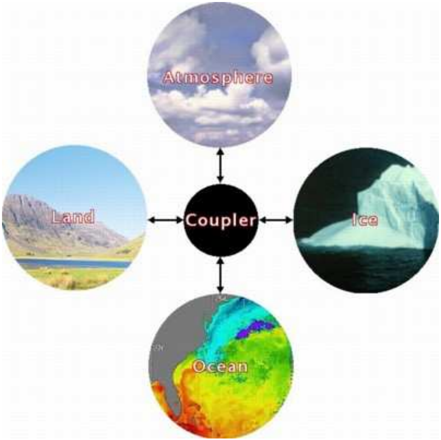
Horizontal Grid Resolution



Source: IPCC 4^{th} Assessment Report

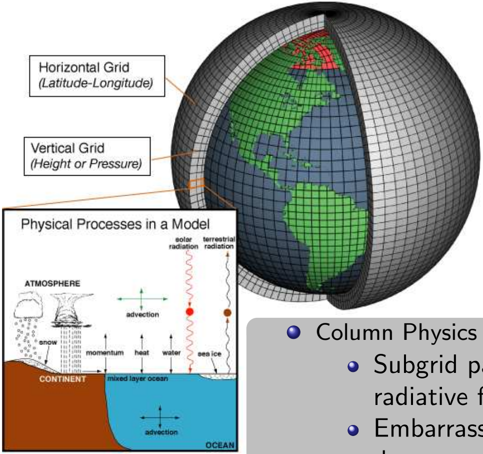
Community Climate System Model (CCSM)

Model Components



- Land and ice models are petascale-ready
- Ocean component is also petascale-ready (20 simulated years per day at 10km)
- **Atmosphere is the bottleneck!**

CCSM Atmosphere Component (CAM)



http://celebrating200years.noaa.gov/breakthroughs/climate_model/welcome.html

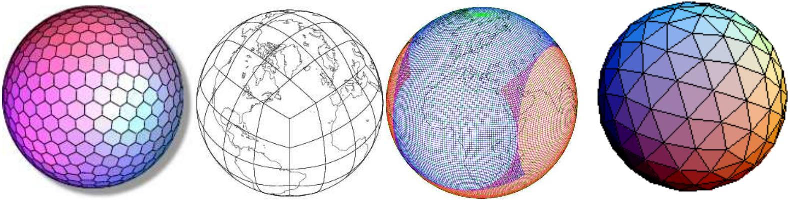
- Column Physics
  - Subgrid parameterizations: precipitation, radiative forcing, etc
  - Embarrassingly parallel with 2D domain decomposition
- Dynamical Core (Dycore)
  - Solves Atmospheric primitive equations
  - **Scalability Bottleneck!**

The Dynamical Core Scalability Bottleneck

Latitude-Longitude Grids

- Used by most dycores in operational models
- Well proven, many good solutions to "pole problem": spherical harmonics, polar filtering, implicit methods
- These approaches are all global and degrade parallel scalability

The Dynamical Core Scalability Bottleneck

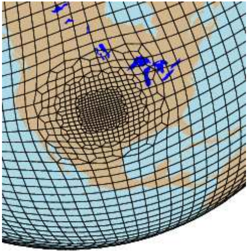


Petascale Dynamical Core

- Quasi-uniform grids avoid the pole problem
- Can use full 2D domain decompositions in horizontal directions
- Each column in the vertical / radial direction kept on processor
- Equations can be solved explicitly with nearest-neighbor communication

Spectral Element Method

- Continuous Galerkin Finite Element Method
  - Quadrilateral Elements
  - Nodal basis formulation
  - Gauss-Lobatto-Legendre quadrature / inner-product
- Unstructured Meshes: Any quadrilateral tiling of the sphere
  - Cubed-sphere for uniform resolution
  - Variable resolution grids coming soon to CAM-HOMME
- Efficient calibration of high-res global model
  - Evaluation of 0.125° parameterizations with ARM data



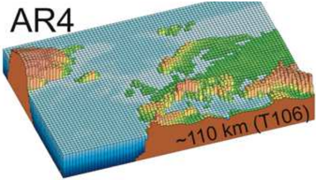
HOMME spectral element dynamical core option in CCSM4 / CESM1

- HOMME: NCAR's High-Order Method Modeling Environment
  - Based on SEAM (Taylor, Iskandarani, and Tribbia, 1997), a modification of SEOM (Iskandarani and Haidvogal, 1995)
- Excellent Numerical Conservation
  - Locally conserves mass, tracer mass, moist total energy, PV
- Dynamics: Modeled After CAM Global Spectral Core
  - Galerkin formulation with polynomial basis functions, collocated grid, high-order / low-dissipation numerics, KE dissipation through hyperviscosity
  - Vertical coordinate: Simmons and Burridge, 1981
- Advection
  - Monotone and sign-preserving options
  - Vertical Lagrangian (Lin, 2004) with monotone remap (Zerroukat et al., 2005)
  - Explicit RK-SSP time-stepping preserves monotonicity

Two *Time-Slice* Configurations in CCSM4 / CESM1

1°: ∼ 110 km

- Atmosphere: uniform cubed sphere, equatorial grid spacing 1°
- Land: 2° lat-lon
- Prescribed ocean and ice extent: `gx1v6`
- Physics / tracer / dynamics timesteps: 1800s / 360s / 90s

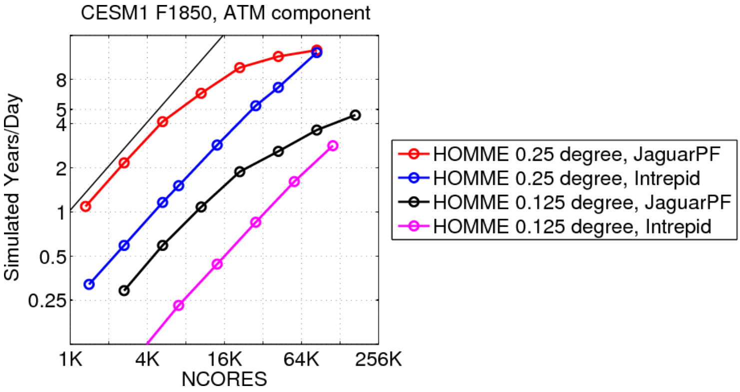


0.125°: ∼ 13 km

- Atmosphere: uniform cubed sphere, equatorial grid spacing 0.125°
- Land: 0.25° lat-lon
- Prescribed ocean and ice extent: `gx1v6`
- Physics / tracer / dynamics timesteps: 900s / 450s / 11.25s
- Scalability tested to $\mathcal{O}$(400k) cores

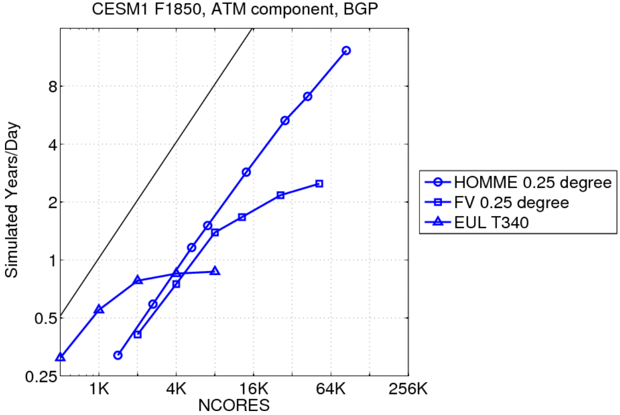
$\mathbf{8^3} \times$

CCSM / HOMME Scalability



- BGP (4 cores / node): Scalable to 1 element per proc (86400 proc at 0.25°)
- JaguarPF (12 cores / node): 3× faster per core, poorer scaling

CCSM $^1/_4{}^\circ$ Scalability

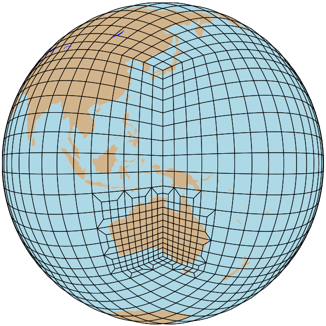


- Spectral model (EUL) faster with $\mathcal{O}(1k)$ cores, does not scale beyond
- FV (lat-lon) loses scalability due to polar filters
- HOMME scales to 1 element per core

Mesh Refinement in HOMME

Conforming Unstructured Static Refinement

- Conforming: Every edge is shared by exactly two elements
- Unsctructured: Domain is tiled arbitrarily
- Static: Mesh is refined prior to run (based on topography, regional interests, etc)



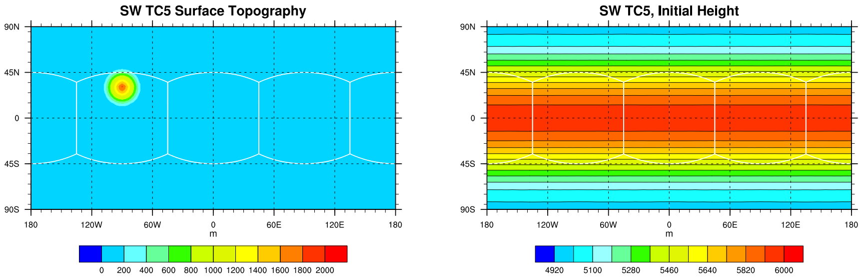
Currently testing in stand-alone HOMME, working on CAM / CCSM

More on Refinement Choice

Why Conforming Unstructured Static Refinement?

1. CAM-HOMME currently uses conservative SEM
    - Non-conforming refinement breaks conservation in SEM, would be better suited for DG (currently not part of CAM-HOMME)
    - Unstructured meshes allow more flexibility in refinement
2. Will be running CAM-HOMME with variable resolution by end of fiscal year
    - Dynamic refinement would take significantly longer to implement (and would restrict refinement options)

Shallow Water Test



Williamson et al. – Test 5

- Flow around an isolated mountain
- Good test for refinement: refine around the mountain

Experiment

Mountain has radius of 20°, refine area w/ radius 30°

Compare meshes based on coarsest elements

Notation

Grid: `N20_x4_s9`

- **N20** Begin with uniform grid based on 20×20 elements on each face of cubed sphere
- **x4** Refine such that edge length in coarse region is 4 times the length of that in fine
- **s9** Apply smoothing operator to grid 9 times

Source

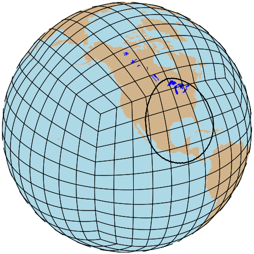
Exploring a Multi-Resolution Modeling Approach within the Shallow-Water Equations

T. D. Ringler, D. Jacobsen, M. Gunzburger, L. Ju, M. Duda, W. Skamarock

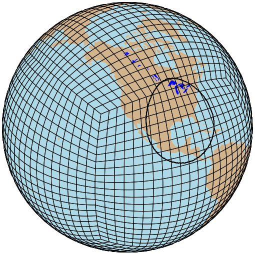
Submitted to Monthly Weather Review

Comparing three grids

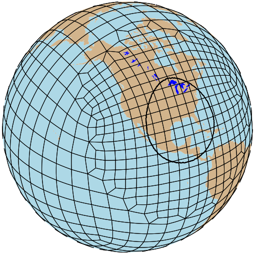
N10_x1.g



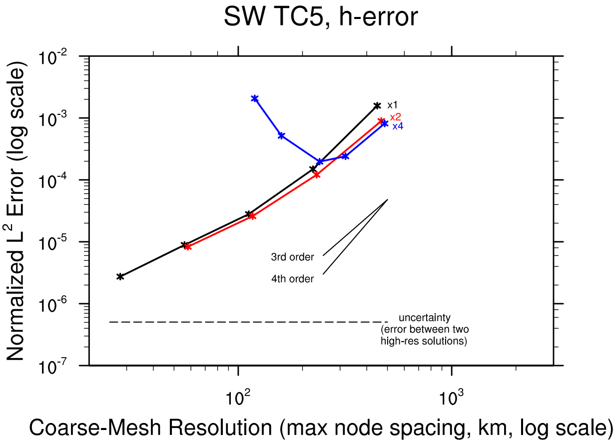
N20_x1.g



N10_x2_s6.g

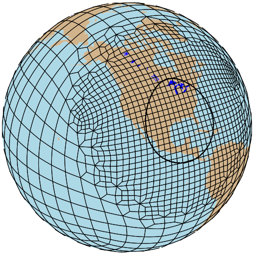


First wave of results

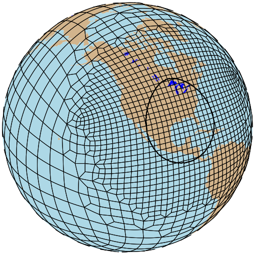


Problem in the *x4* Grids

N10_x4_s6_old.g



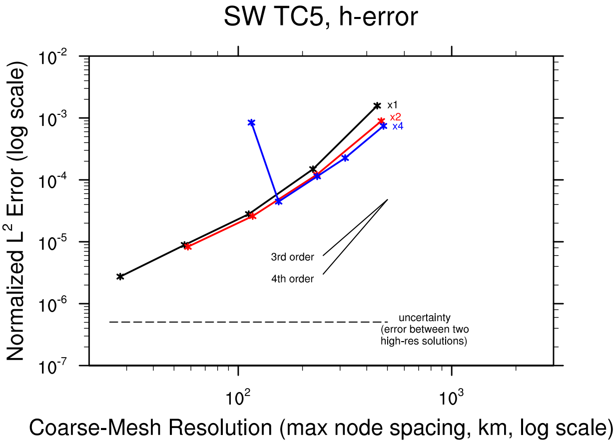
N10_x4_s6.g



Transition Region

We kept the size of the fine mesh the same, but enlarged the transition region. This fixed the low-res `x4` grids, but still had a problem around `N40`.

Second Wave of Results



Conclusions

- CCSM with HOMME dycore scales to $\mathcal{O}$(100k) proc on today's hardware
- CCSM dynamics capable of 0.125° simulations (near climate integration rates)
- DOE target: High-res configuration of CESM (0.125° atmosphere, 0.1° ocean) running 5 SYPD with tuned / calibrated physics by 2015

Acknowledgements

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