High-Resolution Coupled Climate Simulations on Titan

Mark Taylor
Sandia National Labs
mataylo@sandia.gov

Valentine Anantharaj (ORNL), Dave Bader (LLNL), William Collins (LBNL), Kate Evans (ORNL), Robert Jacob (ANL), Philip Jones (LANL), Matthew Norman (ORNL), Philip Rasch (PNNL)

2014 OLCF Users Meeting
Oak Ridge, July 23 2014

U.S. Department of Energy — Office of Science
SciDAC Scientific Discovery through Advanced Computing
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Outline

- Overview of the CESM and ACME
  - Simulated climate vs. observations
- High Resolution Modeling on Titan
  - Performance and initial results from ACME v0
- Future computational requirements:
  - removing the uncertainty from parameterizing deep convection

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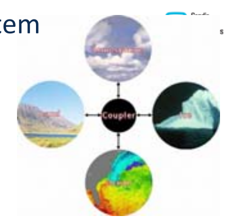
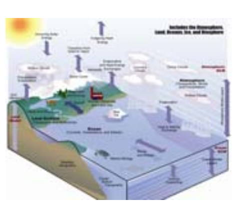
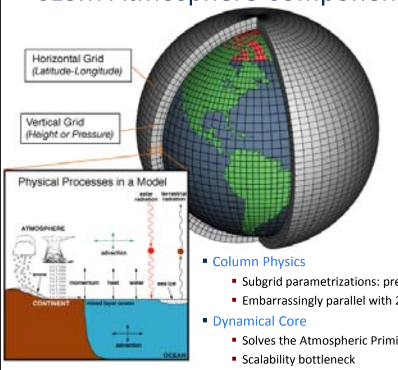
The Community Earth System Model (CESM)



- IPCC-class model developed by NCAR, U.S. National Labs and Universities
- Atmosphere, Land, Ocean and Sea ice component models
- CAM is the atmosphere component model
- Science & policy applications:
  - Seasonal and interannual variability in the climate
  - Explore the history of Earth's climate
  - Estimate future of environment for policy formulation
  - Contribute to assessments



CESM Atmosphere Component (CAM)

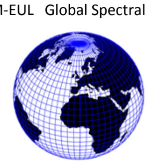


- Column Physics
  - Subgrid parametrizations: precipitation, radiative forcing, etc.
  - Embarrassingly parallel with 2D domain decomposition
- Dynamical Core
  - Solves the Atmospheric Primitive Equations
  - Scalability bottleneck

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

CAM-SE in the CESM

- CAM-SE: CAM with the Spectral Element (SE) dynamical core from HOMME
- CESM1.2 Release: June 2013
  - Switch to CAM-SE on a cubed-sphere grid
  - Motivation: parallel scalability for performance at high-resolution
- Previous CAM Dynamical Cores:
  - CAM-FV Lin-Rood FV lat/lon
  - CAM-EUL Global Spectral



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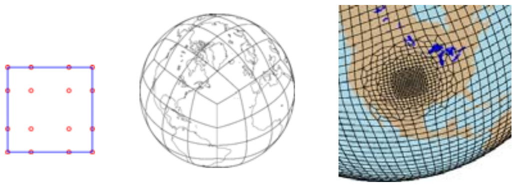
CAM-SE

- Hydrostatic equations
- Vertical Discretization
  - hybrid pressure/terrain following coordinate (Simmons & Burridge, 1981)
  - Vertically Lagrangian (S.J. Lin 2004) with monotone remap
- Horizontal Discretization:
  - Conservative spectral elements (Taylor & Fournier, JCP 2010)
  - SE monotone limiter for tracers (Guba et al., JCP, under review)
  - Hyperviscosity used for KE dissipation (both physical and numerical, Dennis et al., IJHPCA 20120)
- Runge-Kutta time-stepping
  - Tracers: 3 stage 2nd order SSP
  - Dynamics: 5 stage 3rd order high-CFL

Spectral Element Method

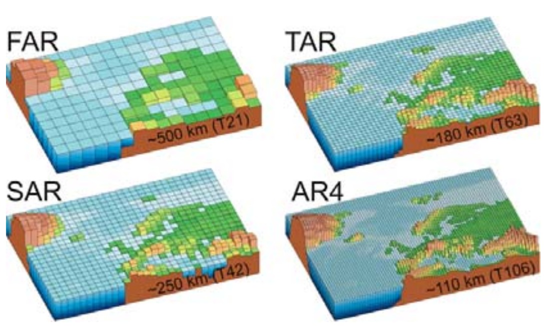


- Q^p-Q^p continuous Galerkin finite element (typically p=3)
- Maps well to modern computers: Arithmetically dense computations, high data locality, structured data access even on unstructured meshes.
- Unstructured, conforming quad meshes (cubed-sphere for uniform grids)
- Mimetic: discrete operators preserve adjoint and annihilator properties of div, grad and curl. Leads to local conservation of mass, tracer mass, energy, 2D PV and linear balance preservation (Taylor & Fournier, 2010)

CESM Simulated Climate

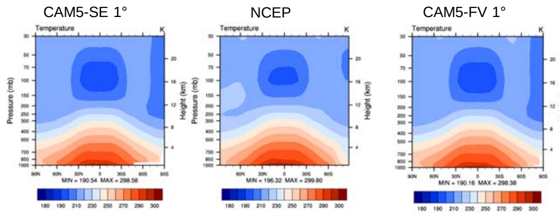
- Fully coupled: active atmosphere, ocean, land and sea ice components
- CAM5 physics with prognostic aerosols
- 1.0 degree (~110km) horizontal resolution

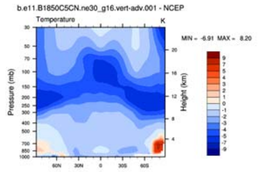
Horizontal Grid Resolution



Source: IPCC 4th Assessment Report, 2007

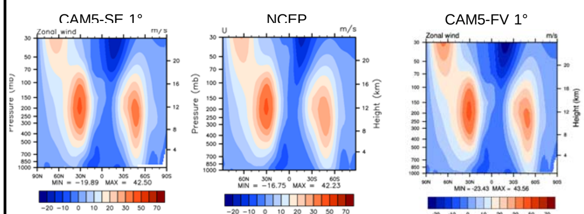
Zonal Mean Temperature (ANN)

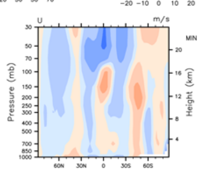




CAM has a long standing 200mb cold bias at the poles (both SE and FV)

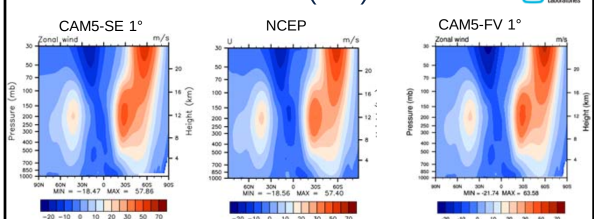
Zonal Mean Zonal Wind (DJF)

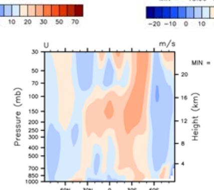




Polar jet is usually too strong in CAM5-FV (improved in CAM5-SE)

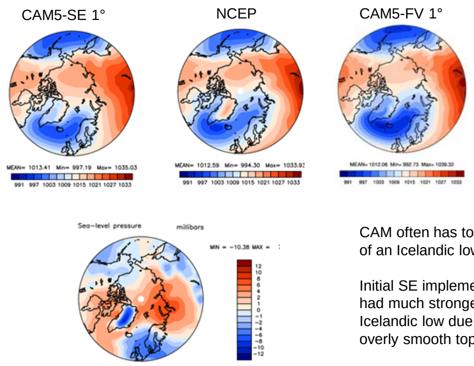
Zonal Mean Zonal Wind (JJA)





Polar jet is usually too strong in CAM5-FV (improved in CAM5-SE)

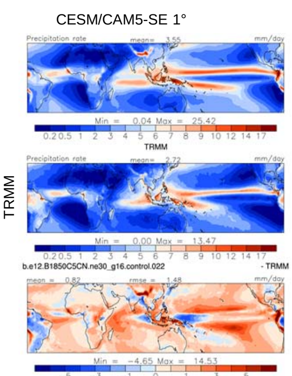
Sea Level Pressure (DJF)

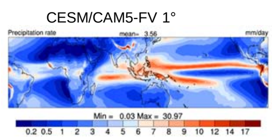


CAM often has too strong of an Icelandic low

Initial SE implementation had much stronger Icelandic low due to using overly smooth topography

Tropical Precip (ANN)

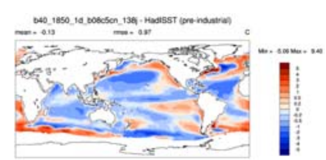




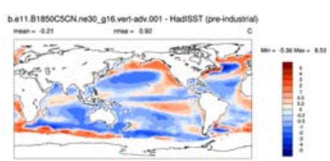
Precip is very similar. Double ITZ in both SE and FV

Temperature biases (Model–HadISST)

CESM w/CAM5-FV
mean = -0.13 K
RMSE = 0.97 K



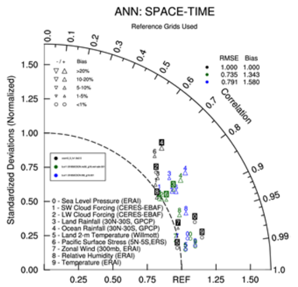
CESM w/CAM5-SE
mean = -0.21K
RMSE = 0.92 K



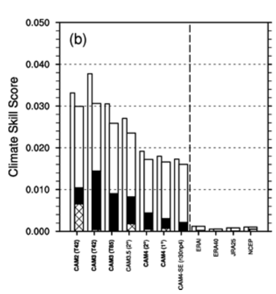
Taylor diagram

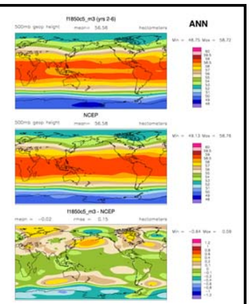
- CCSM3.5
- CESM1.1 (FV)
- CESM1.1 (SE)

	RMSE	Bias
CCSM3.5 (2008)	1.000	1.00
CCSM4 (2010)	0.883	0.78
CESM1.1 (FV) (2012)	0.791	1.58
CESM1.1 (SE) (2012)	0.735	1.34



Source: Cécile Hannay, AMWG Meeting, 2012





- CAM shows steady improvement as resolution is increased and physics improved
- 500mb geopotential height skill score (30-90N) DJF
- Mean square error from uncond. bias, cond. bias and phase error
- Source: Rich Neale (NCAR)

Accelerated Climate Modeling for Energy (ACME)

- Large (~45 FTE/year) DOE-BER Multi-lab project
- Developing ACME v1 (2017)
  - A branch of the CESM specialized for DOE science problems and high-resolution modeling on leadership computing facilities
- Science driven development
  - Water Cycle: How do the hydrological cycle and water resources interact with the climate system on local to global scales
  - Cryosphere Systems: How do rapid changes in cryospheric systems interact with the climate system?
  - Biogeochemistry: How do biogeochemical cycles interact with global climate change?

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Accelerated Climate Modeling for Energy (ACME)

- Short term science questions (guiding first two years of development):
  - Water Cycle: How will more realistic portrayals of features important to the water cycle (resolution, clouds, aerosols, snowpack, river routing, land use) affect river flow and associated freshwater supplies at the watershed scale?
  - Cryosphere Systems: Could a dynamical instability in the Antarctic Ice Sheet be triggered within the next 40 years?
  - Biogeochemistry: How do carbon, nitrogen, an phosphorus cycles regulate system feedbacks, and how sensitive are these feedback model structural uncertainty?

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ACME v0 (CESM v1.2) simulation strategy

- (1) Atmosphere tuning at 25km (~25M core hours)
  - Run atmosphere component with prescribed SST and prescribed ice extent. Used for tuning uncertain parameters in many of the parameterizations
- (2) Pre-industrial fully coupled simulation (80M core hours)
  - Run in pre-industrial conditions where the Earth was in thermodynamic equilibrium
  - Ensure coupled model maintains realistic equilibrium state
  - Establish internal/natural variability of coupled model
- (3) 1970-2040 ensembles
  - 80M core hours per ensemble member

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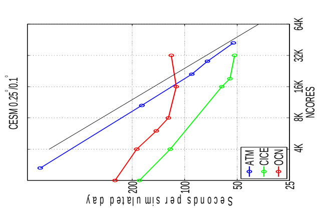
CESM Component Performance



- Strong scaling of ACME v0 components on Titan (when run in the coupled model)
- Atmosphere is the most expensive today w/26 tracers. Within the atmosphere, tracer advection is 50% of the total cost.
- Ocean is the second most expensive component
- With biogeochemistry (needing 100-1000 tracers), cost of both atmosphere and ocean components will be 5-40x more expensive

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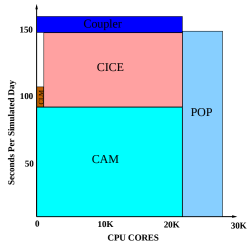
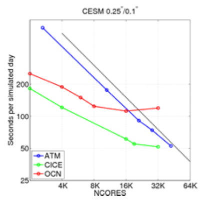
CESM High-Res Configuration Titan 25km atmosphere/land – 10km ocean/ice





CESM Processor layout and performance (drawn to scale) for an efficient fully coupled CESM configuration running on Titan (28K cores)

Latest configuration (not shown) runs on 68K cores at 1.6 SYPD (costing 1M core-hours per year)

CAM5 Tuning

- Tuned using F1850 compset (pre-industrial)
- ¼ degree (ne120)
- Adjusted dust_emis_fact and seasalt scale factor to tune global aerosol loading.
- “stock” settings have RESTOM ~ -5.0 W/m^2
  - Increasing low cloud relative humidity threshold (rhminl) to 0.91
  - Used ZM cloud fraction (dp1) to tune for RESTOM ~ 0 (instead of c0)
  - Kept the ZM autoconversion coefficient (c0_lnd,c0_ocn) low (0.0035)
- Ice autoconverson threshold (DCS) increased 50%. Improves LWCF with minimal impact on RESTOM
- ZM timescale (zmconv_tau) reduced slightly (to 3000s from 3600)

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Climate Uncertainty and Deep Convection

- The deep convection parameterization (and its unknown parameters) is the cause of much uncertainty in climate simulations
- Example: Tropical cyclones
- Tropical cyclones tracked using the Knutson et al. BAMS 2007 algorithm in the TECA code (Prabhat et al. ICCS 2012).

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Resolving Tropical Cyclones at High Resolution

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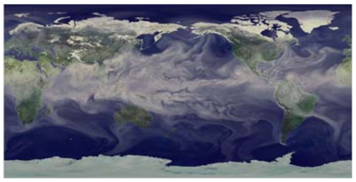
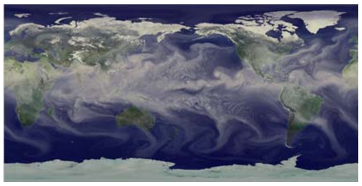
25km



13km



20 day loop, September conditions, showing vertically totaled atmosphere water content

High resolution is required in order for the model to simulated tropical cyclones

At 100km resolution, there is almost no cyclone activity

CESM at 25km does a reasonable job at capturing tropical cyclones, including category 5 storms

At 25km there is sufficient storm activity that the model can be *tuned* (with prescribed SST) to match observations (~80 TC per year, or ~50 category 1-5 per year)

At 13km, with the same tunings, the model is too energetic, producing 105 storms per year

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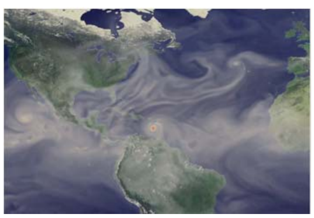
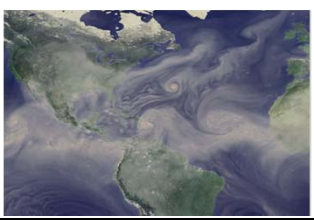
27km



13km



Closeup, showing Category 5 Gulf of Mexico hurricane example comparing 25km and 13km resolutions

13km resolution does have more realistic hurricane structure but is too expensive for climate simulations (80 year simulation ~500M core-hours). Currently being used for short TC forecasts

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TC tracks (over 5 years)

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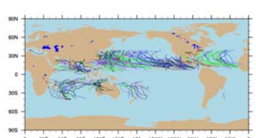
100km

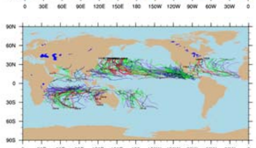
Only 9 TC per year
Only 1 TC in North Atlantic
No Cat 4 or 5 storms

25km



TC# per year: 88
Cat 0-5: 34/24/10/11/8/1

13km



TC# per year: 105
Cat 0-5: 30/26/10/14/18/7

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Climate Uncertainty and Deep Convection

- At 25km resolution, the number of tropical cyclones is very sensitive to several of the deep convection parameters.
- Example: zmconv_tau: ranging from 900s to 3600s gives TC counts from 37-150
- Little confidence on the models ability to predict absolute number of storms
- Some confidence in sensitivity: i.e. changes in storm statistics due to a warming ocean

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Future Computational Requirements

- Reduce uncertainty related to deep convection:
  - Improved convection parameterizations (extensive efforts in this at all modeling centers. E.g. UNICON and CLUBB)
  - Run at cloud resolving resolution (~1km) where deep convection is directly simulated (no need to parameterize)
- Could we run a cloud resolving (1km) Earth system model on an Exascale system?
- Compare cloud resolving (1km) on Exascale System to weather resolving (10km) on today's 10PF System

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Future computational requirements

- Cloud resolving (1km) vs Weather Resolving (10km)
  - 10^2 more grid points (ignoring the vertical)
  - 10x smaller timestep
  - Exascale system as 10^2 more computing power than Mira
- Assume perfect weak scaling:
  - Cloud resolving (1km) model will run 10x slower on an Exascale system then a 10km model will run on Today's 10PF systems
- Examine weather resolving CESM on Mira
  - 1/8 degree (13.5km resolution) Atmosphere/ Land
  - 1/10 degree (3km – 11km resolution) Ocean / Sea Ice

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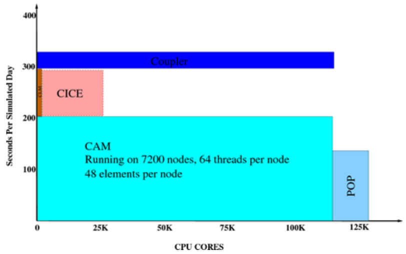
Weather Resolving (13km) CESM on Mira



CESM:
13km atm/land
10km ocean/ice
8K BG/Q nodes.
0.7 SYPD

- Processor layout and performance (drawn to scale).
- Atm,ocean and ice components running near the limit of there current scalability (20% of Mira)
- Performance rate is borderline for climate (goal: 5 SYPD)
- Atmosphere dominates the cost of the system.

Future computational requirements

- Scaling up ACME to 1km resolution on an Exascale system: expect 0.07 SYPD
- Sufficient for short forecast simulations, but not for climate simulations
  - Need >10x improvement in performance
  - Could be obtained with improved scaling and/or better node performance (such as GPUs)
  - This will require large effort mostly in the atmosphere component

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Summary

- ACME v0 Earth System Model running well on titan at 25km resolution on 60K cores
- ACME v1 will be more complex and needs to run faster on Titan and Mira
  - 2-3x in on node performance
  - 2-3x in parallel scalability
- Cloud resolving climate modeling:
  - Need an Exascale machine
  - >10x improvements in scalability and/or performance

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Publications

- Taylor, Fournier, *A compatible and conservative spectral finite element method on unstructured grids*, J. Comput. Phys. 2010
- Taylor, *Conservation of mass and energy for the moist atmospheric primitive equations on unstructured grids*, Springer, Lecture Notes in Computational Science and Engineering, 2011
- Dennis, Edwards, Evans, Guba, Lauritzen, Mirin, St-Cyr, Taylor, Worley, *CAM-SE: A scalable spectral element dynamical core for the Community Atmosphere Model*, Int. J. High Perf. Comput. Appl., 2012
- Reed, Jablonowski, Taylor, *Tropical cyclones in the spectral element configuration of the Community Atmosphere Model*, Atmos. Sci. Let. 2012
- Levy, Overfelt, Taylor, *A Variable Resolution Spectral Element Dynamical Core in the Community Atmosphere Model*, SNL Tech note 2013-0697J, 2013.
- Zarzycki, Levy, Overfelt, Taylor, Jablonowski, *Using Variable Resolution Meshes to Model Tropical Cyclones in The Community Atmosphere Model,* MWR 2013
- Evans, Lauritzen, Mishra, Neale, Taylor, Tribbia, *AMIP Simulation with the CAM4 Spectral Element Dynamical Core*, J. Climate, 2013
- Lauritzen, Bacmeister, Dubos, Lebonnois, Taylor, *Held-Suarez simulations with the Community Atmosphere Model Spectral Element (CAM-SE) dynamical core: a detailed global axial angular momentum analysis using Eulerian and floating Lagrangian vertical coordinates*, J. Adv. Model. Earth Syst., 2014
- Guba, Taylor, St.Cyr, *Optimization based limiters for the spectral element method,* J. Comput. Phys.. 2014

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Extra Slides

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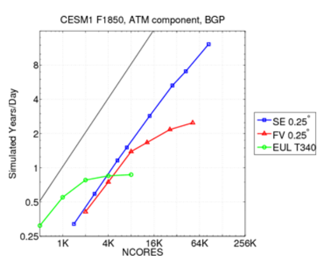
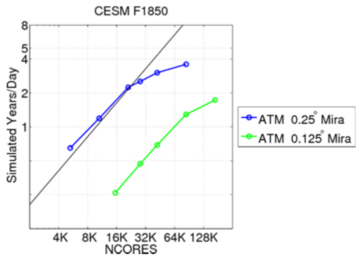
Atmosphere dynamical core scalability



- CAM (CESM Atmosphere component) running on IBM BG/P Intrepid
- CAM4 physics at 0.25° (27km) resolution
- Compare CAM with SE, FV and EUL (global spectral) dycores
- CAM-SE achieves near perfect scalability to 1 element per core (86,000 cores).

CAM5 27km & 13.5km on BG/Q



- BG/Q system with 16 cores per node, each with 4 FPU
- CESM running with 4 MPI tasks per node, each with 16 openMP threads
- Best performance: 0.25° 3.6 SYPD
- Best performance: 0.125° 1.7 SYPD

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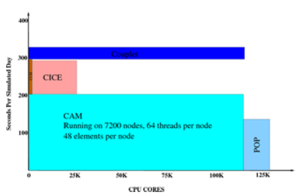
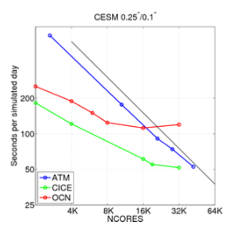
Weather Resolving (13km) CESM on Mira



POP and CICE ocean models: new dycore could dramatically improve scaling, making their cost negligible as compared to the atmosphere

Heroic efforts needed in atmosphere to improve performance on Mira



Strong scaling of CAM (27km), POP (10km) and CICE (10km) Within the CESM, running on Titan.