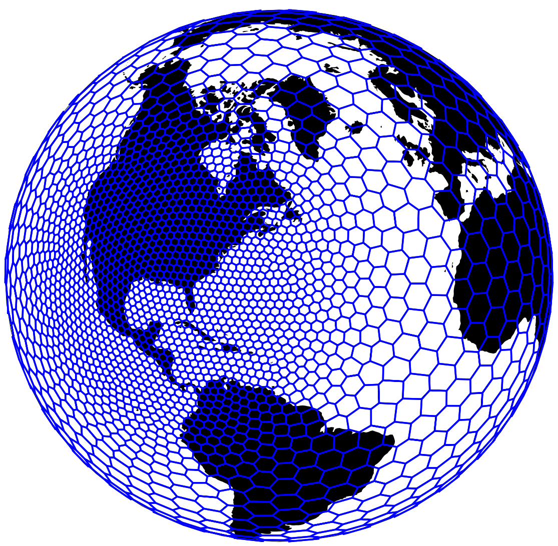
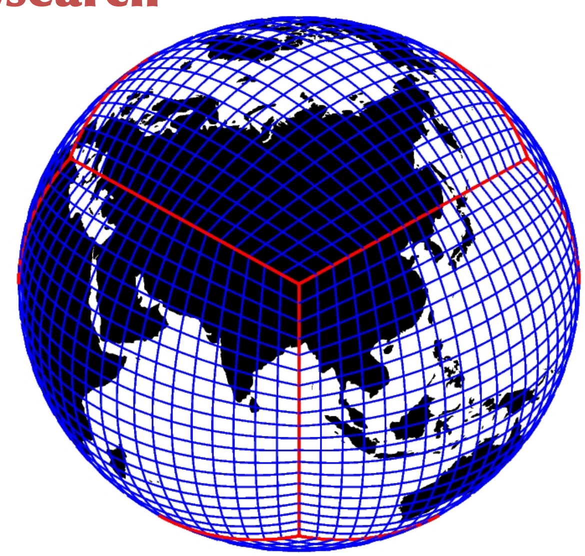
Dynamics update:
GMTD2010 topography, CAM-SE/MPAS

Peter Hjort Lauritzen
National Center for Atmospheric Research
Boulder, Colorado, USA





Collaborators:
S. Goldhaber (NCAR),
J. Bacmeister (NCAR), M.A. Taylor (SNL),
S.-H. Park (NCAR), P.A. Ullrich (UC Davis), R. Kelly (NCAR),R. Nair (NCAR), …

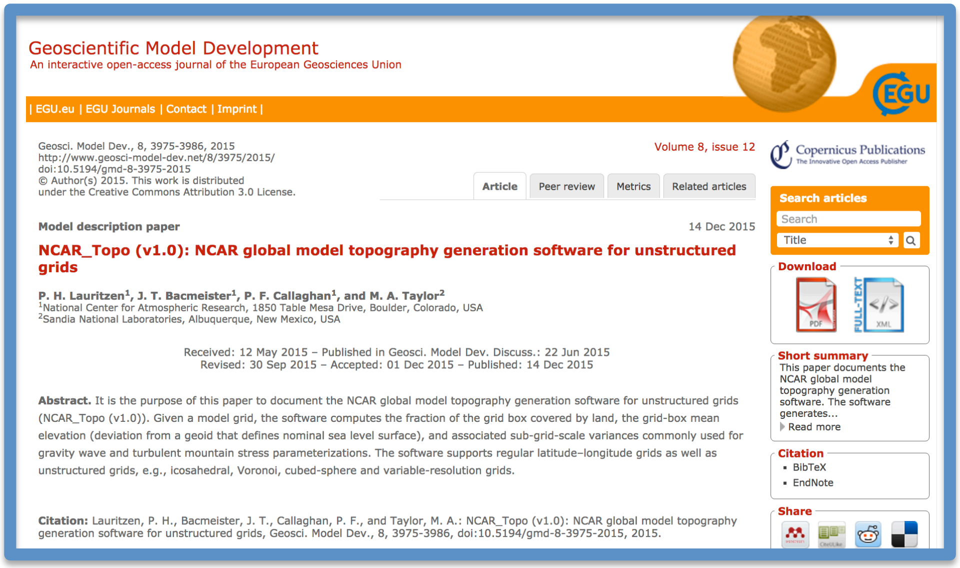
CESM joint Session of Atmosphere Model, Chemistry-Climate and Whole Atmosphere Working Groups
8 – 10 February, 2016
Boulder, Colorado, USA

Overview

- New `raw' topography dataset in CAM
- CAM-SE development (CMIP6 ¼ degree model):
  - CAM-SE physgrid
  - CAM-SE-CSLAM
  - dry mass vertical coordinates & condensate loading
- CAM-MPAS (for more details see Sang-Hun Park's talk from yesterday)
  - typhoon forecasts with CAM5 physics versus WRF physics using variable resolution MPAS

Part I

New ~1km source elevations data



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Geosci. Model Dev., 8, 3975-3986, 2015
http://www.geosci-model-dev.net/8/3975/2015/
doi:10.5194/gmd-8-3975-2015
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Volume 8, issue 12

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Model description paper — 14 Dec 2015

NCAR_Topo (v1.0): NCAR global model topography generation software for unstructured grids

P. H. Lauritzen[1], J. T. Bacmeister[1], P. F. Callaghan[1], and M. A. Taylor[2]
[1]National Center for Atmospheric Research, 1850 Table Mesa Drive, Boulder, Colorado, USA
[2]Sandia National Laboratories, Albuquerque, New Mexico, USA

Received: 12 May 2015 – Published in Geosci. Model Dev. Discuss.: 22 Jun 2015
Revised: 30 Sep 2015 – Accepted: 01 Dec 2015 – Published: 14 Dec 2015

Abstract. It is the purpose of this paper to document the NCAR global model topography generation software for unstructured grids (NCAR_Topo (v1.0)). Given a model grid, the software computes the fraction of the grid box covered by land, the grid-box mean elevation (deviation from a geoid that defines nominal sea level surface), and associated sub-grid-scale variances commonly used for gravity wave and turbulent mountain stress parameterizations. The software supports regular latitude–longitude grids as well as unstructured grids, e.g., icosahedral, Voronoi, cubed-sphere and variable-resolution grids.

Citation: Lauritzen, P. H., Bacmeister, J. T., Callaghan, P. F., and Taylor, M. A.: NCAR_Topo (v1.0): NCAR global model topography generation software for unstructured grids, Geosci. Model Dev., 8, 3975-3986, doi:10.5194/gmd-8-3975-2015, 2015.

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Short summary
This paper documents the NCAR global model topography generation software. The software generates...
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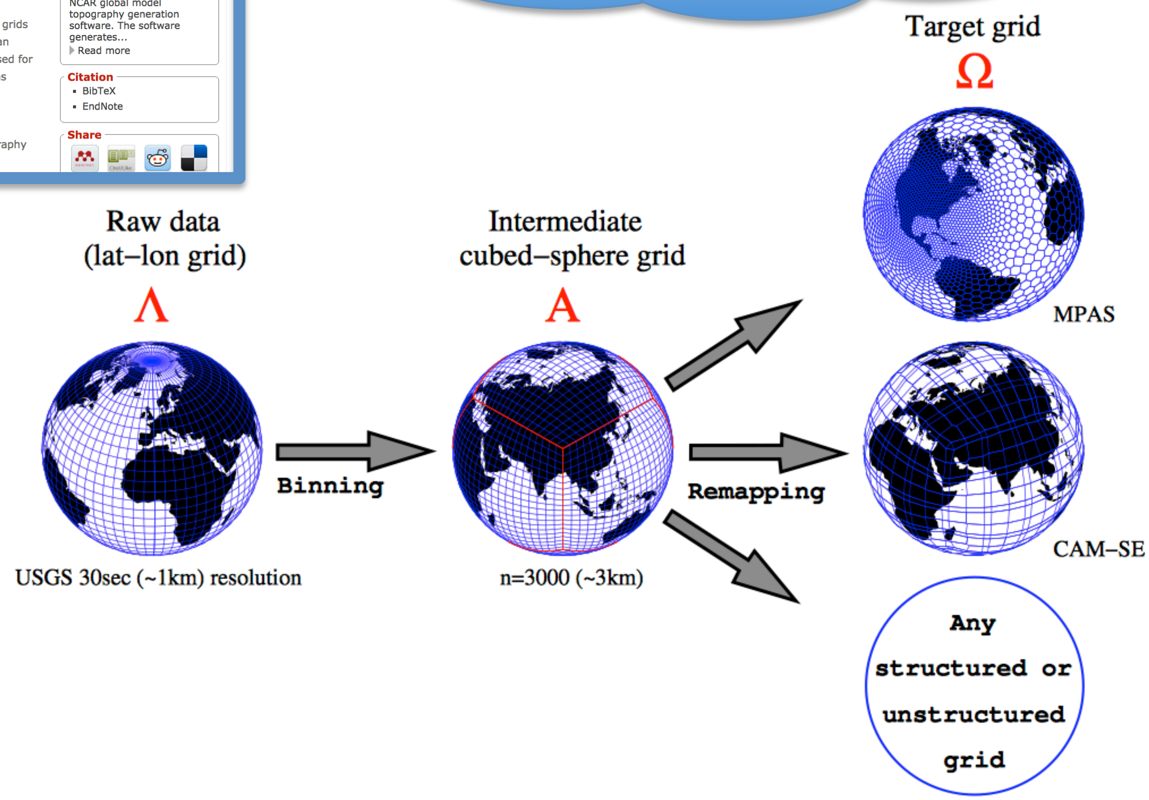
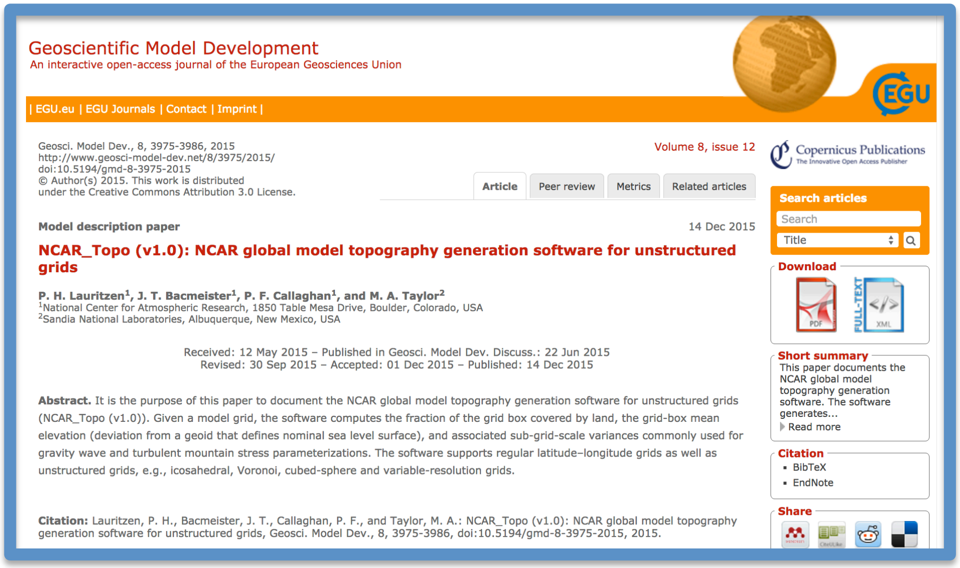
https://github.com/NCAR/Topo



variables:
```
h
(height in m)
LANDFRAC
(land fraction [0,1])
```

variables:
```
PHIS
(surface geopotential)
LANDFRAC
SGH30
(standard deviation
 of 30sec h)
```

variables:
```
PHIS
LANDFRAC
SGH30
SGH
(standard deviation of
~3km cubed-sphere h)
```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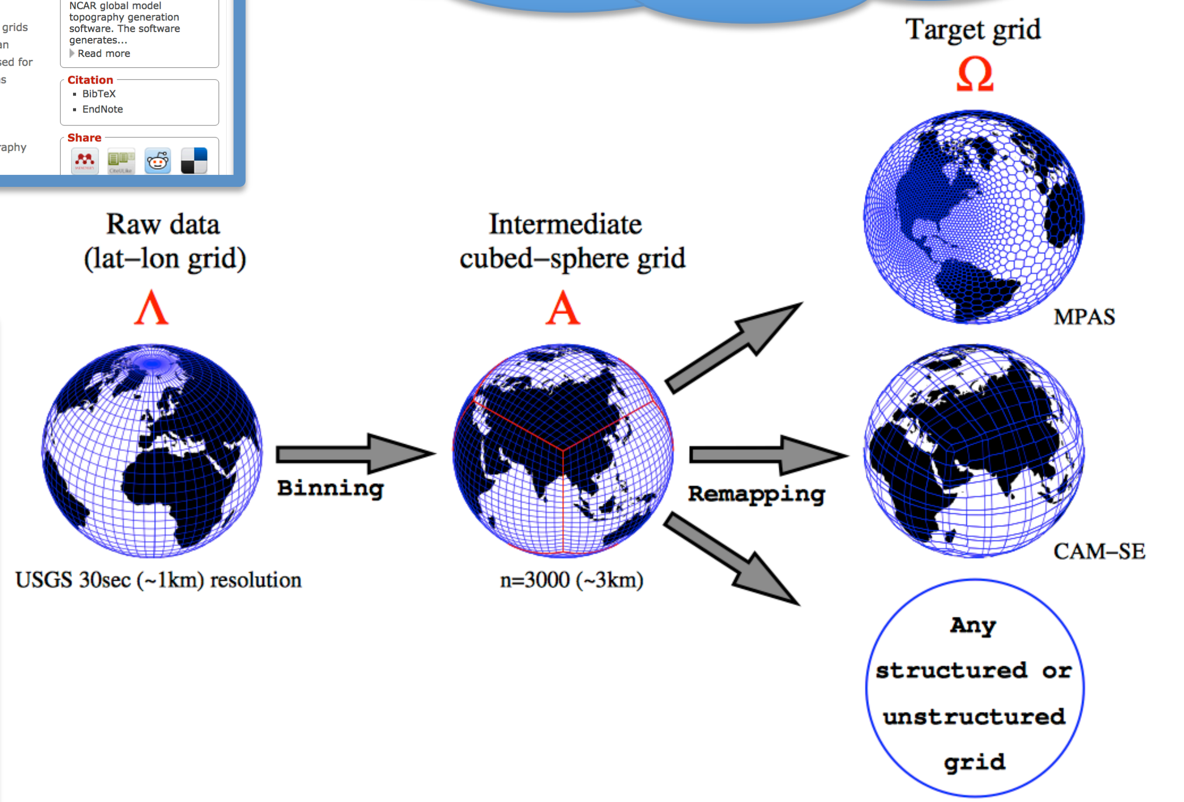
https://github.com/NCAR/Topo

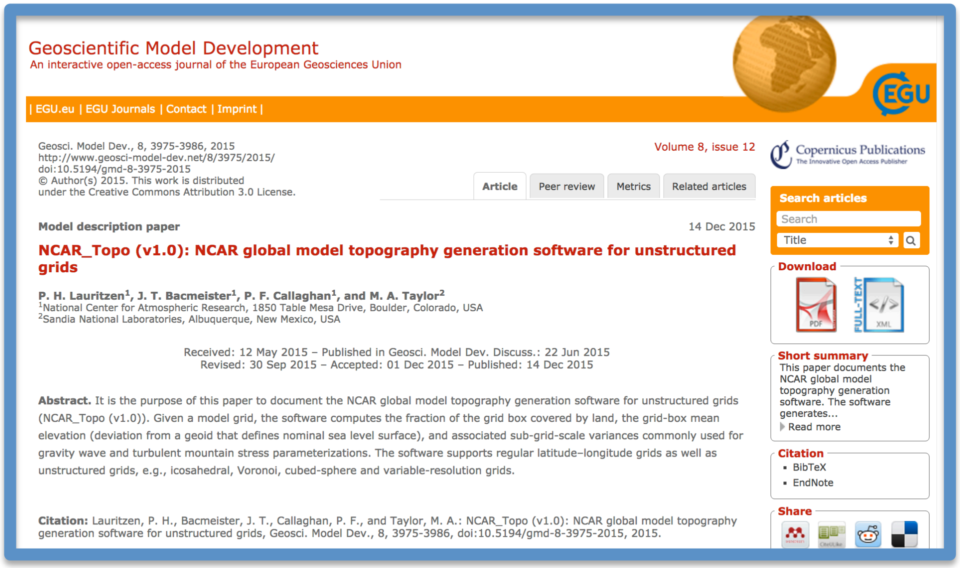
GTOPO30:

USGS ~1km dataset from 1996

http://pubs.usgs.gov/of/2011/1073/pdf/of2011-1073.pdf



variables:	variables:	variables:
h (height in m) LANDFRAC (land fraction [0,1])	PHIS (surface geopotential) LANDFRAC SGH30 (standard deviation of 30sec h)	PHIS LANDFRAC SGH30 SGH (standard deviation of ~3km cubed–sphere h)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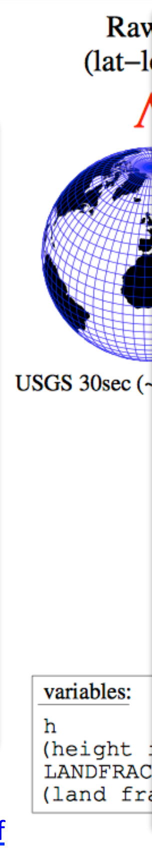
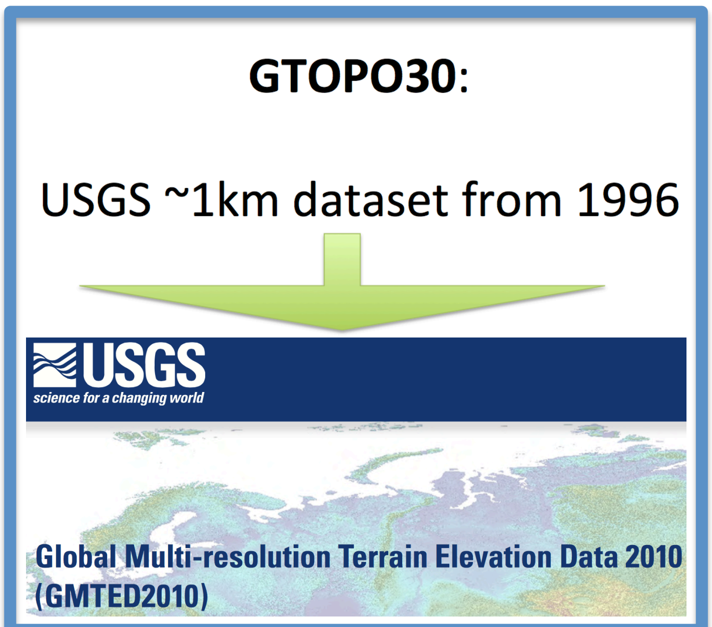
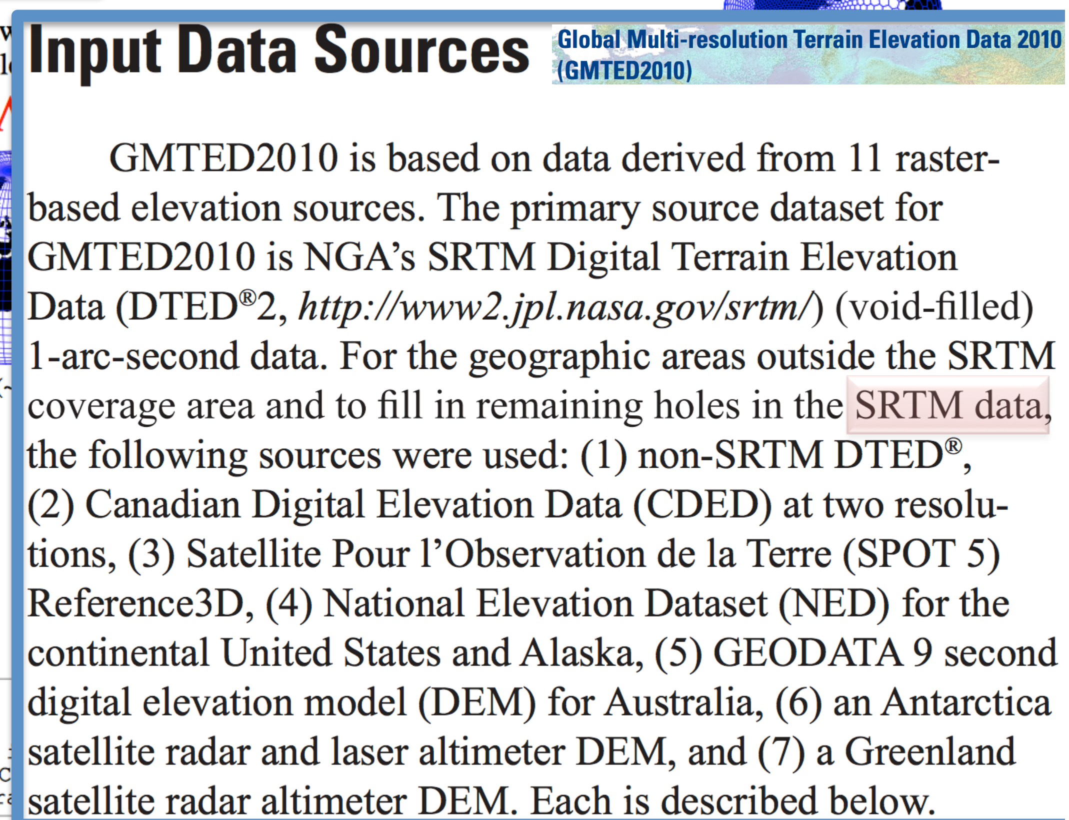




http://pubs.usgs.gov/of/2011/1073/pdf/of2011-1073.pdf



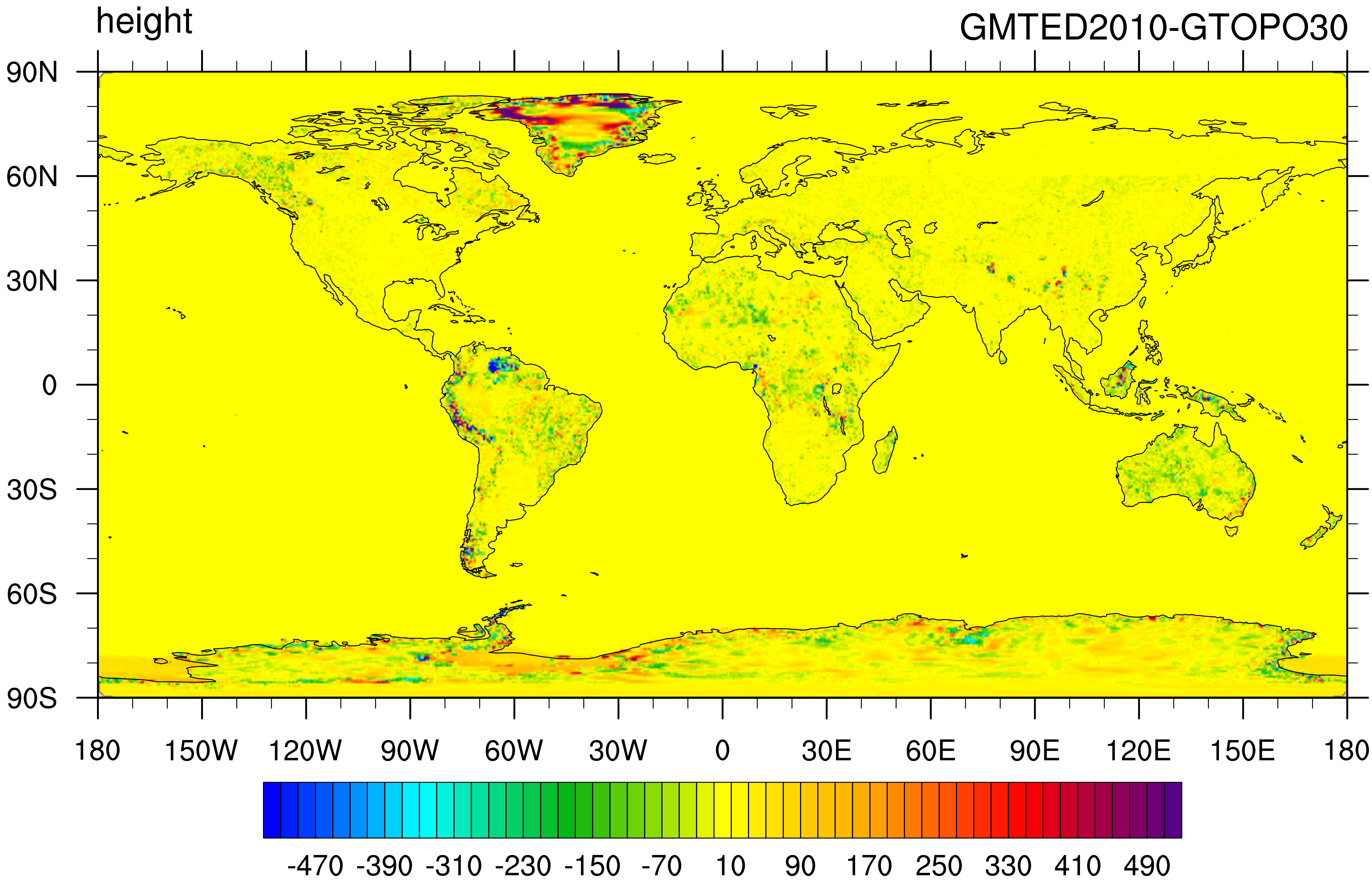
Input Data Sources

Global Multi-resolution Terrain Elevation Data 2010 (GMTED2010)

GMTED2010 is based on data derived from 11 raster-based elevation sources. The primary source dataset for GMTED2010 is NGA's SRTM Digital Terrain Elevation Data (DTED®2, *http://www2.jpl.nasa.gov/srtm/*) (void-filled) 1-arc-second data. For the geographic areas outside the SRTM coverage area and to fill in remaining holes in the SRTM data, the following sources were used: (1) non-SRTM DTED®, (2) Canadian Digital Elevation Data (CDED) at two resolutions, (3) Satellite Pour l'Observation de la Terre (SPOT 5) Reference3D, (4) National Elevation Dataset (NED) for the continental United States and Alaska, (5) GEODATA 9 second digital elevation model (DEM) for Australia, (6) an Antarctica satellite radar and laser altimeter DEM, and (7) a Greenland satellite radar altimeter DEM. Each is described below.

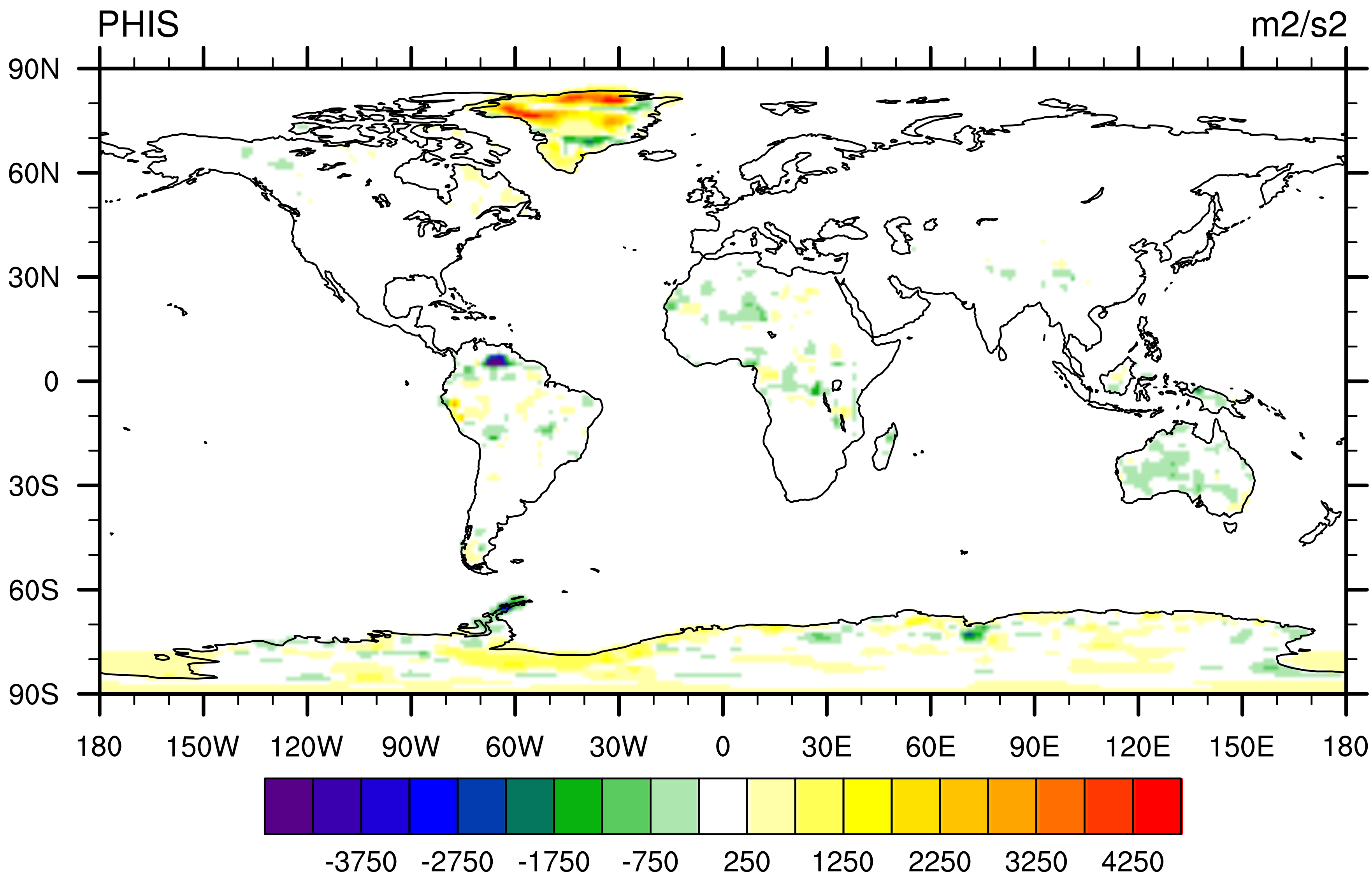
Elevation differences [meters]

(on 3km cubed-sphere grid)



Geopotential height differences

(on FV 1 degree grid with topo smoothing)



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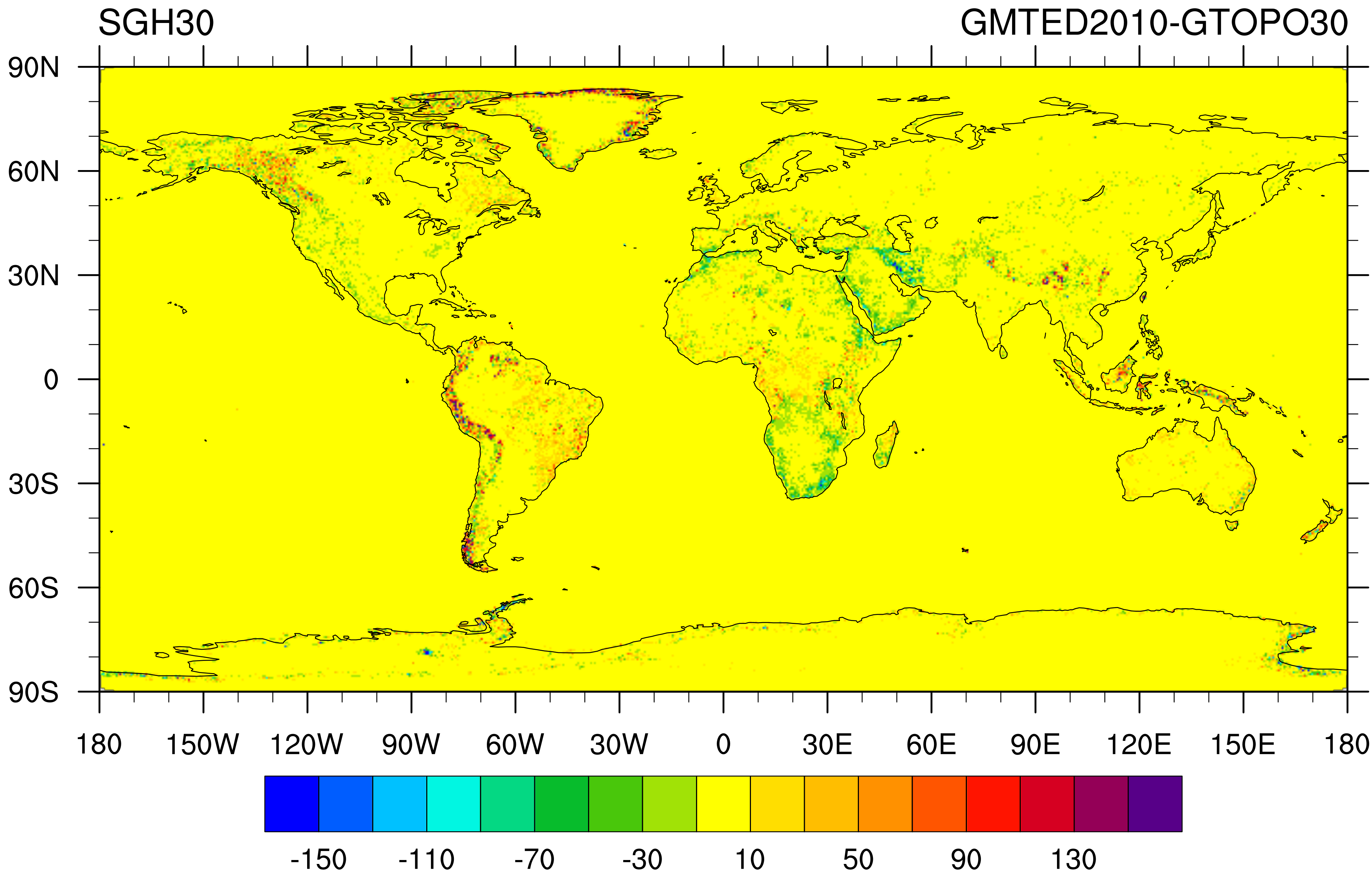
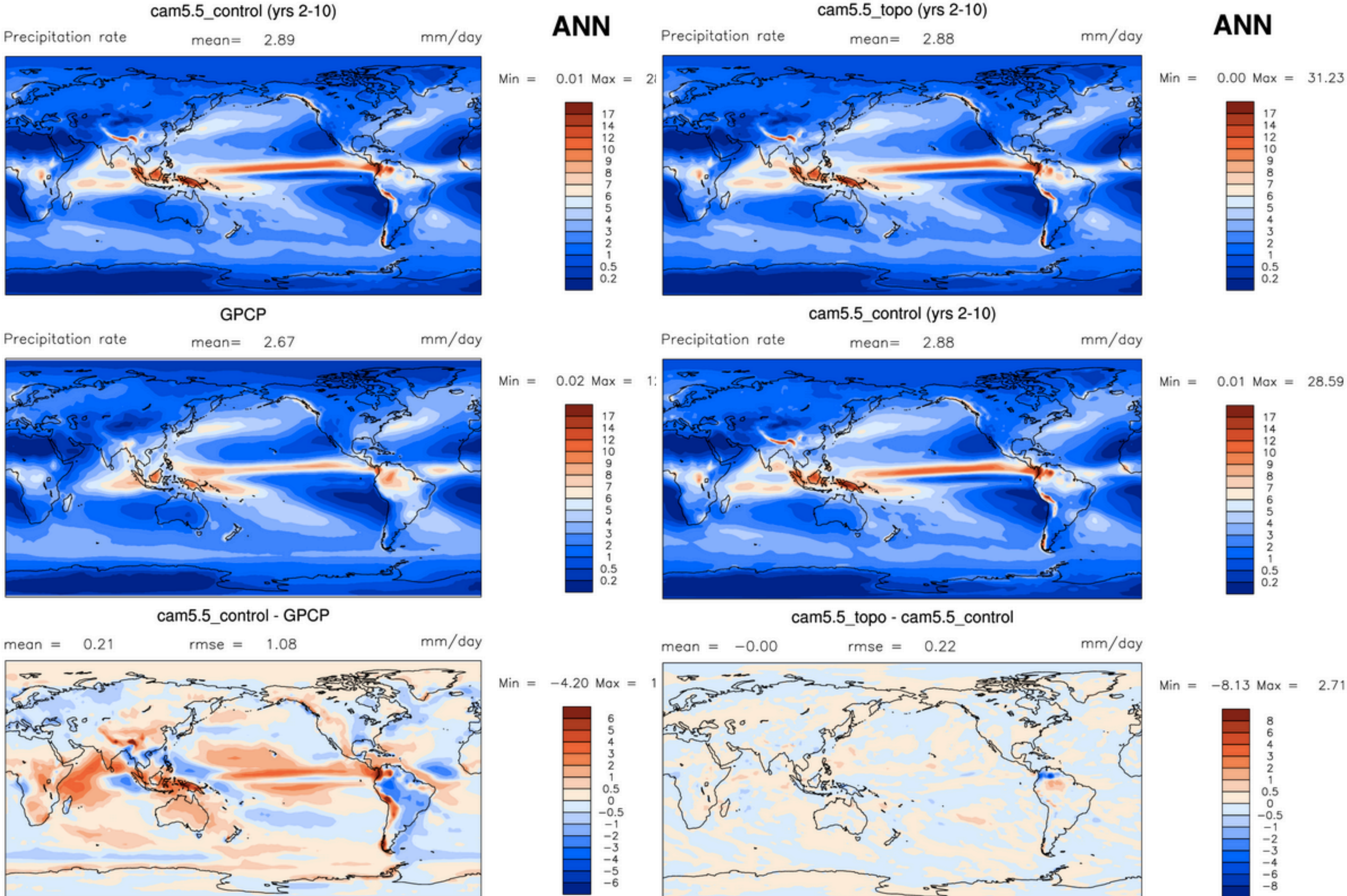


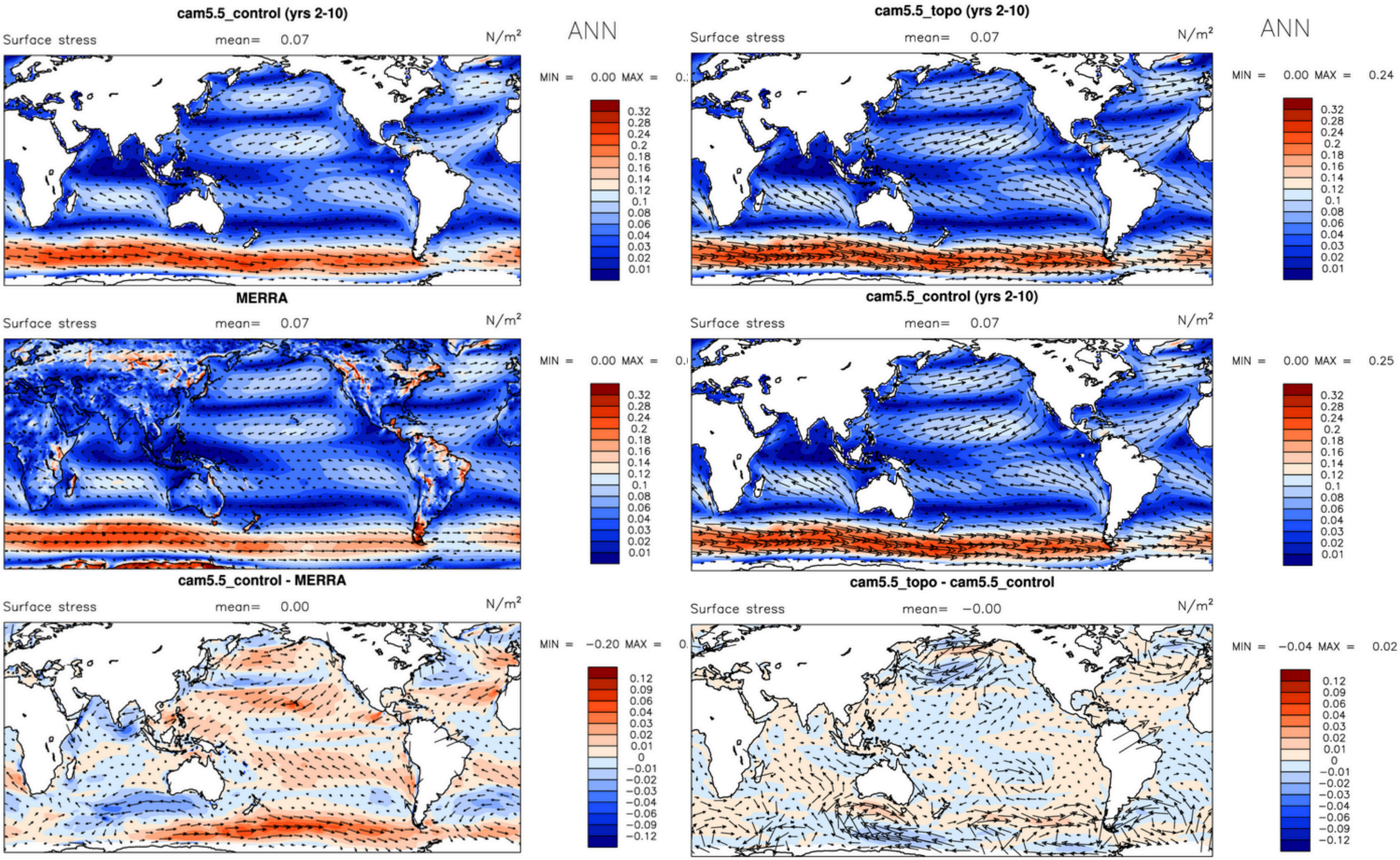
Rasta plot on 3km cubed-sphere grid

PRECT

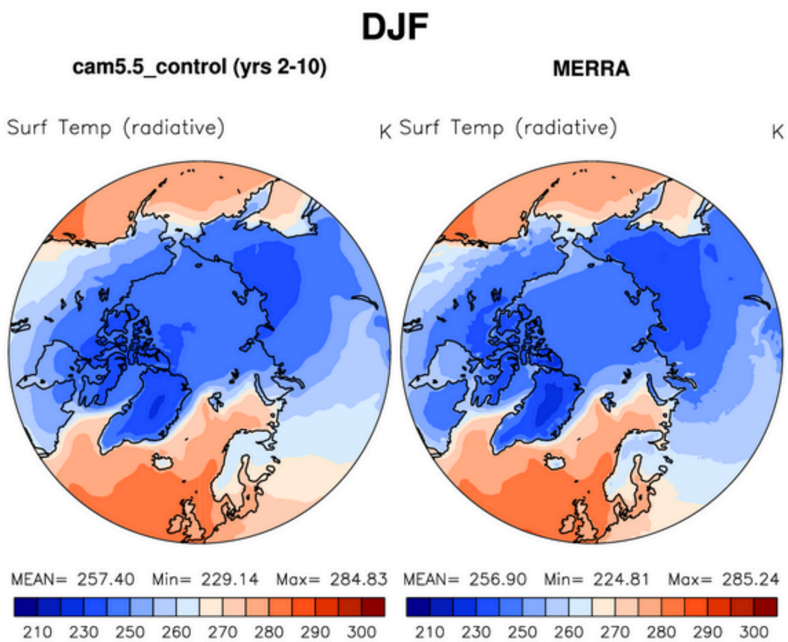


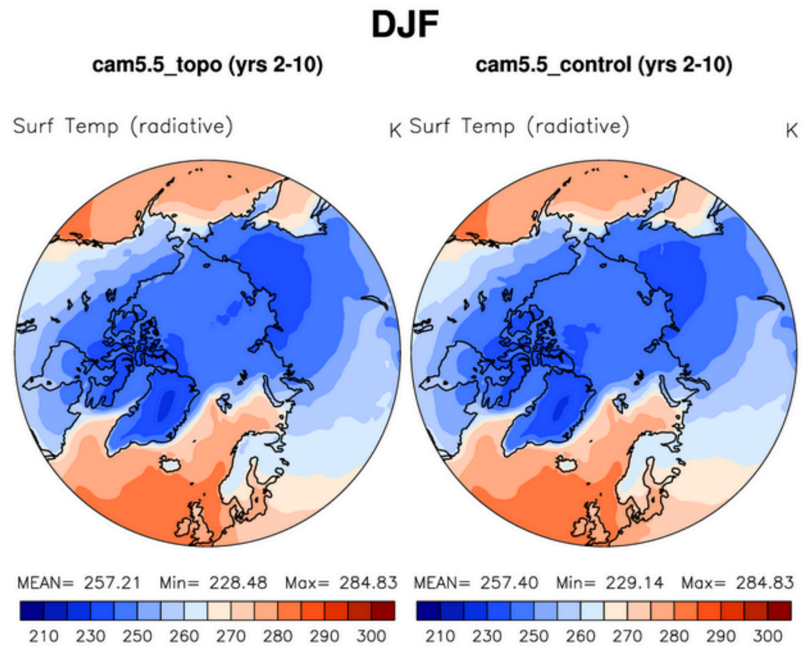
ANN
cam5.5_control (yrs 2-10)
Precipitation rate mean= 2.89 mm/day
Min = 0.01 Max =
17 14 12 10 9 8 7 6 5 4 3 2 1 0.5 0.2
cam5.5_topo (yrs 2-10)
Precipitation rate mean= 2.88 mm/day
ANN
Min = 0.00 Max = 31.23
17 14 12 10 9 8 7 6 5 4 3 2 1 0.5 0.2
GPCP
Precipitation rate mean= 2.67 mm/day
Min = 0.02 Max =
17 14 12 10 9 8 7 6 5 4 3 2 1 0.5 0.2
cam5.5_control (yrs 2-10)
Precipitation rate mean= 2.88 mm/day
Min = 0.01 Max = 28.59
17 14 12 10 9 8 7 6 5 4 3 2 1 0.5 0.2
cam5.5_control - GPCP
mean = 0.21 rmse = 1.08 mm/day
Min = −4.20 Max =
6 5 4 3 2 1 0.5 0 −0.5 −1 −2 −3 −4 −5 −6
cam5.5_topo - cam5.5_control
mean = −0.00 rmse = 0.22 mm/day
Min = −8.13 Max = 2.71
8 6 4 3 2 1 0.5 0 −0.5 −1 −2 −3 −4 −6 −8

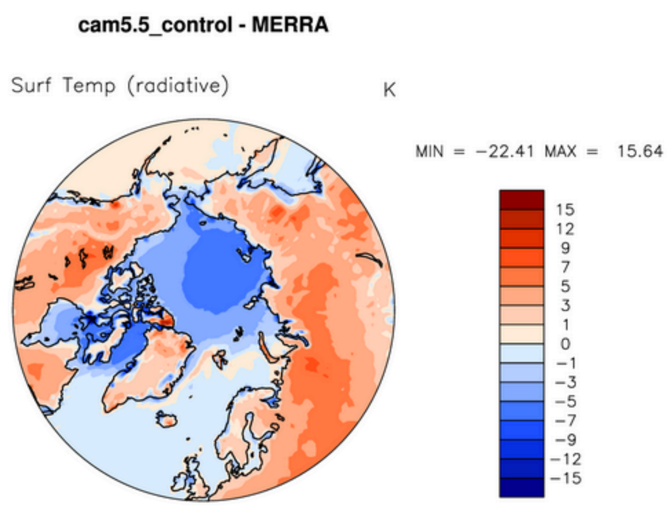
Surface wind stress

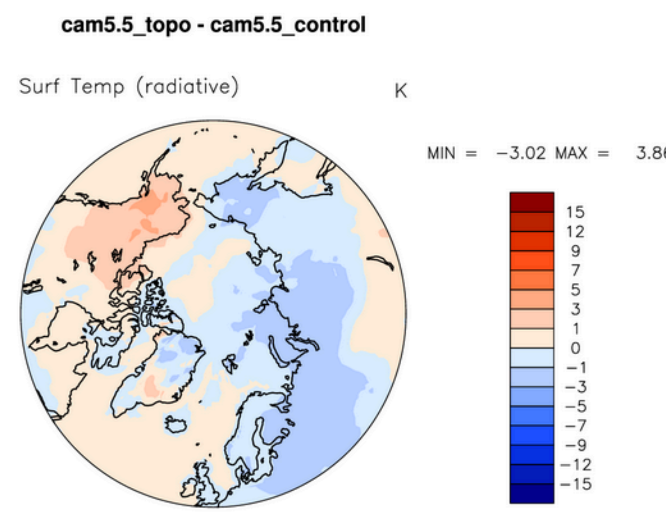


Surface temperature (TS)









Part II

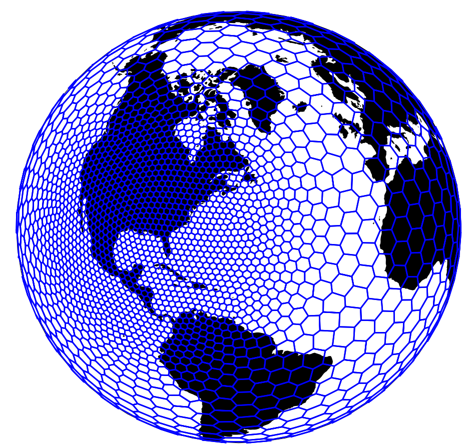
Dynamical core(s) development

Getting away from CAM-FV ...

CAM-SE **(spectral elements)**

Taylor et al., (1997)

Dennis et al., (2012)



CAM-FV **(finite volume)**

Lin (2004)

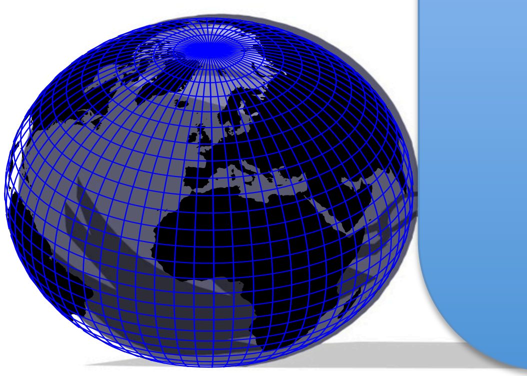
CAM-MPAS **(Model for Prediction Across Scales)**

Skamarock et al., (2012)

Getting away from CAM-FV …

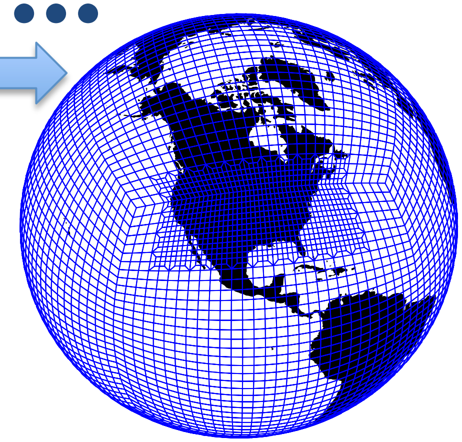
CAM-EUL
(spectral transform)

CAM-SLD
(spectral transform semi-Lagrangian)



CAM-FV **(finite volume)**
Lin (2004)

- **CAM-SE and CAM-MPAS are actively being developed at NCAR (with collaborators) both in terms of numerical methods and code optimization (with CISL)**
- **SE and MPAS represent two very different numerical methods and grids – there is no agreement (but many opinions) in the community on which method/grid is "best"**



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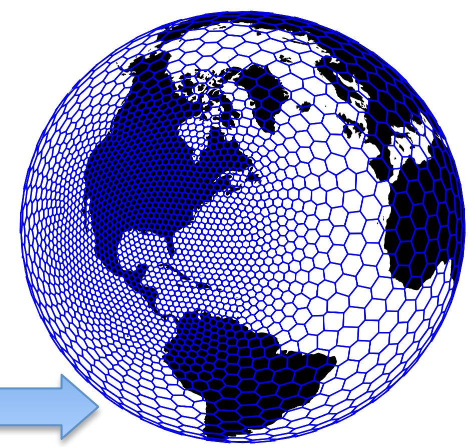
Dennis et al., (2012)



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(spectral transform semi-Lagrangian)

Not being developed further at NCAR in terms of numerical methods

CAM-FV
(finite volume)
Lin (2004)

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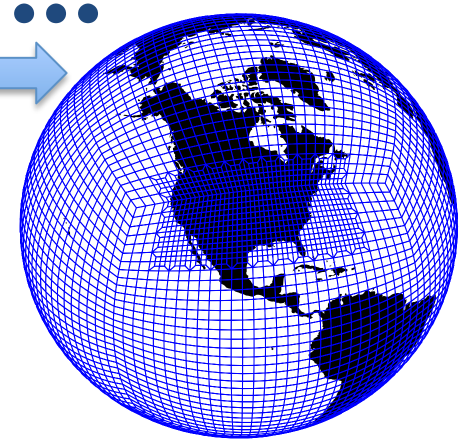

CAM-SE **(spectral elements)**
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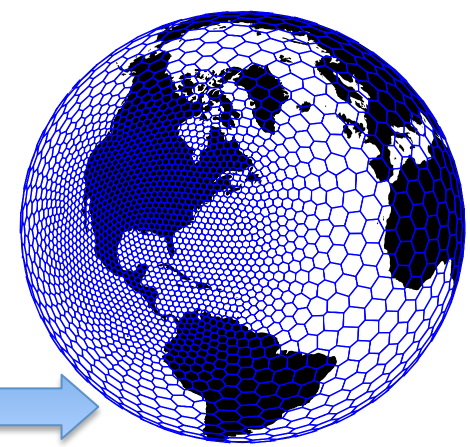

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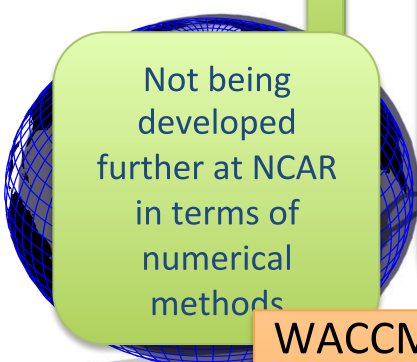

Not being developed further at NCAR in terms of numerical methods

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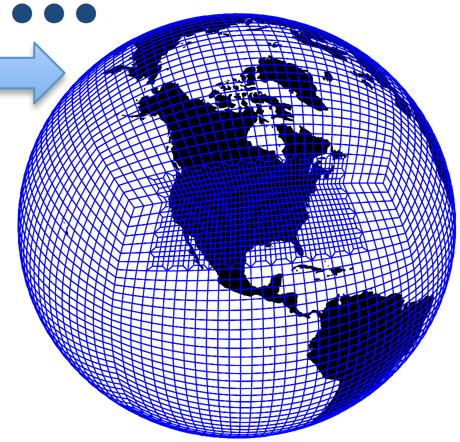
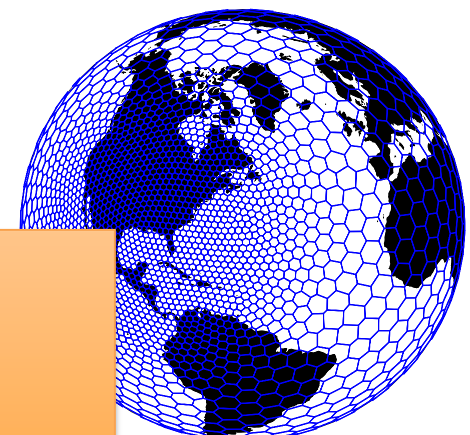


CAM-SE (spectral elements)
Taylor et al., (1997)
Dennis et al., (2012)



WACCM-X: Issues with representing thermosphere (1) Specific heat dry air gas constant (R*/mbar), and kappa (R/Cp) are variables (2) Correction to thermodynamic equation in terms of potential temperature.
Hanli Liu (HOA, NCAR)

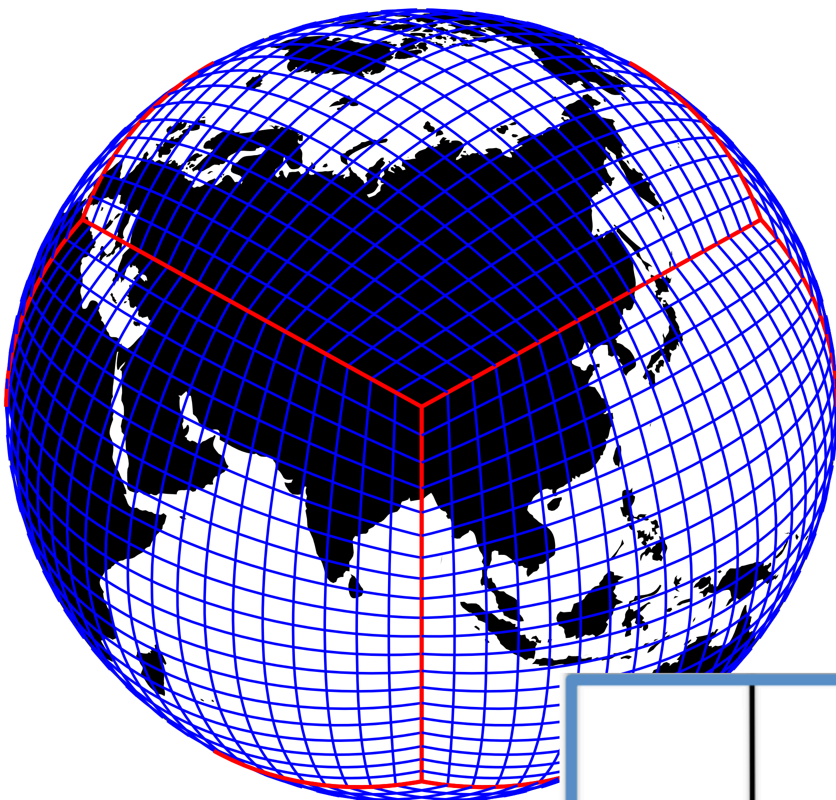
CAM-FV
(finite volume)
Lin (2004)

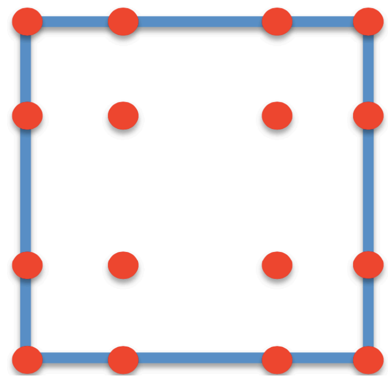
rediction Across Scales)
Skamarock et al., (2012)

CAM-SE development

- Separating physics and dynamics grids
  - presented at 2014 AMWG meeting
- More accurate and faster (if enough tracers) tracer transport scheme
  (CSLAM: Conservative semi-LAgrangian Multi-tracer scheme)
  - consistent coupling between spectral-element dry mass and CSLAM dry mass fields was presented at 2015 CESM meeting in Breckenridge
- Change to dry mass vertical coordinates
- Explicitly represent condensate loading the dynamical core (high resolution)

CAM-SE-physgrid configuration

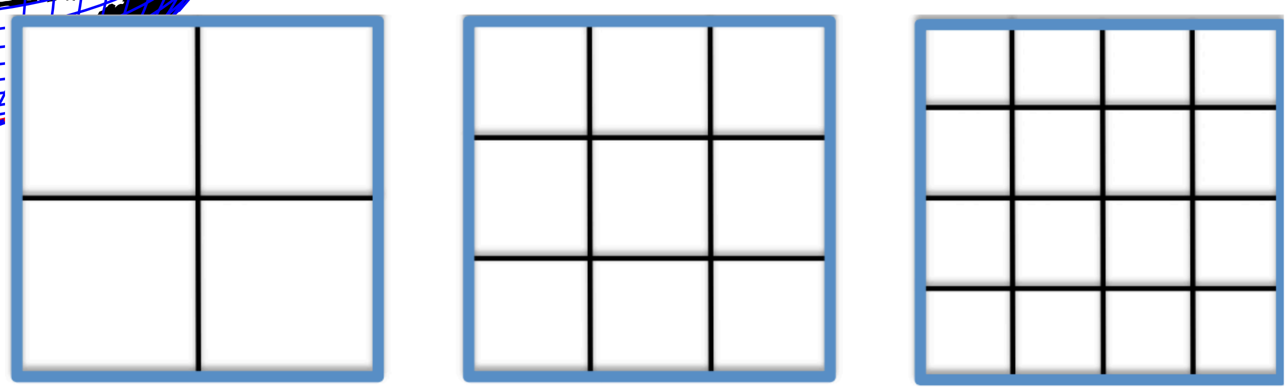




Dynamics: Spectral-element dynamics on Gauss-Lobatto-Legendre (GLL) nodal values

(4x4 GLL point in each element; degree 3 Lagrange polynomials)

Physics: Coarser, same or finer resolution cell-average grid



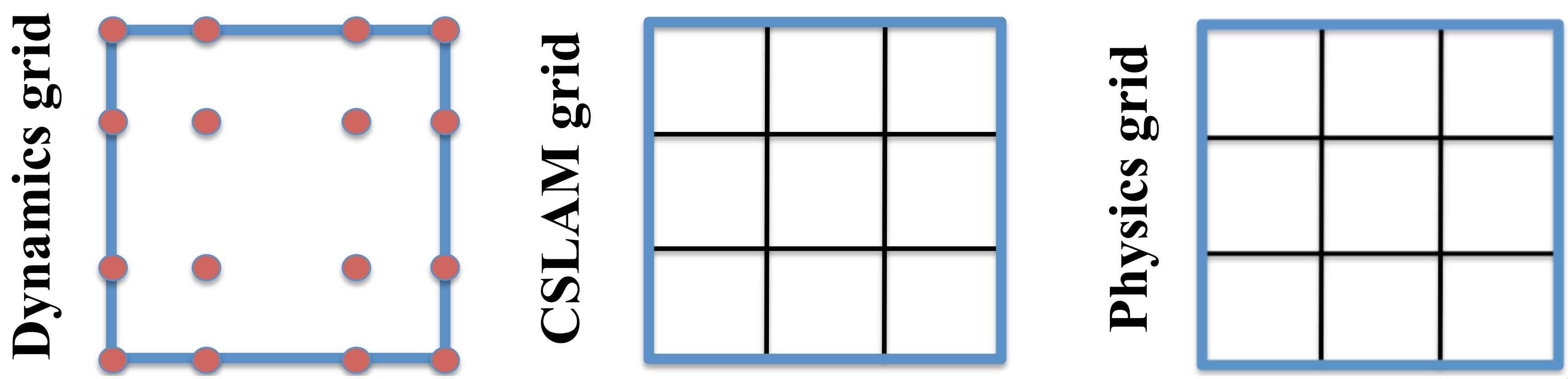
CAM-SE-CSLAM configuration

A new model configuration based on CAM-SE:

- **SE**: Spectral-element dynamical core solving for $\vec{v}$, T, p_s **+ dry eta**

  (Dennis et al., 2012; Evans et al., 2012; Taylor and Fournier, 2010; Taylor et al., 1997)
- **CSLAM**: Semi-Lagrangian finite-volume transport scheme for tracers

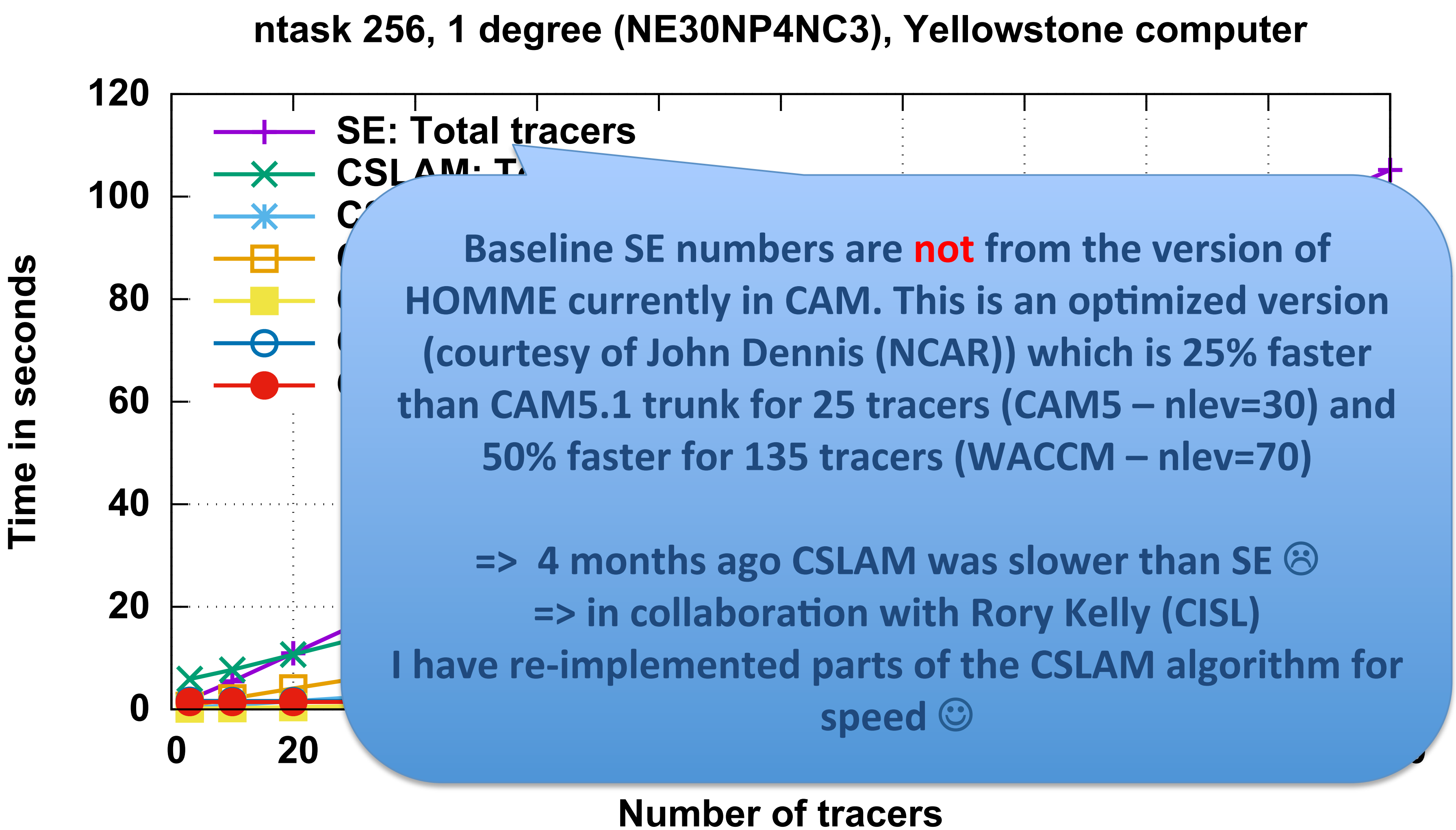
  (Lauritzen et al., 2010; Erath et al., 2013, 2012; Harris et al., 2010) **+ new consistent coupling version**
- **Phys-grid**: Separating physics and dynamics grids, i.e. ability to compute physics tendencies based on cell-averaged values within each element instead of quadrature points



NCAR

Lauritzen, Taylor, Overfelt, Ullrich and Goldhaber (2016, IN PREP)

Performance

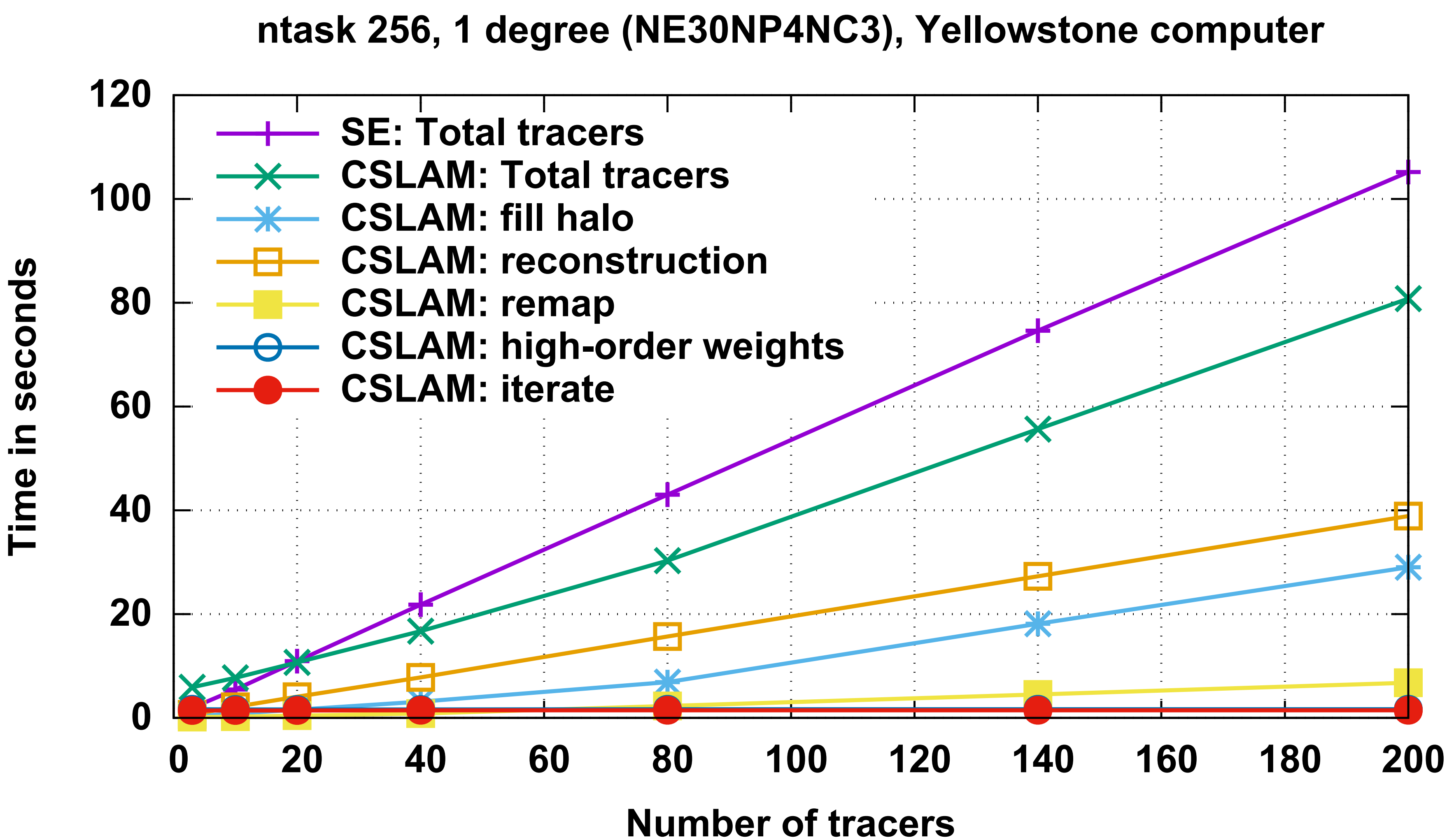


Baseline SE numbers are **not** from the version of HOMME currently in CAM. This is an optimized version (courtesy of John Dennis (NCAR)) which is 25% faster than CAM5.1 trunk for 25 tracers (CAM5 – nlev=30) and 50% faster for 135 tracers (WACCM – nlev=70)

=> 4 months ago CSLAM was slower than SE ☹
=> in collaboration with Rory Kelly (CISL)
I have re-implemented parts of the CSLAM algorithm for speed ☺

Thanks to Rory Kelly (CISL) for collaborating on code optimization

Performance



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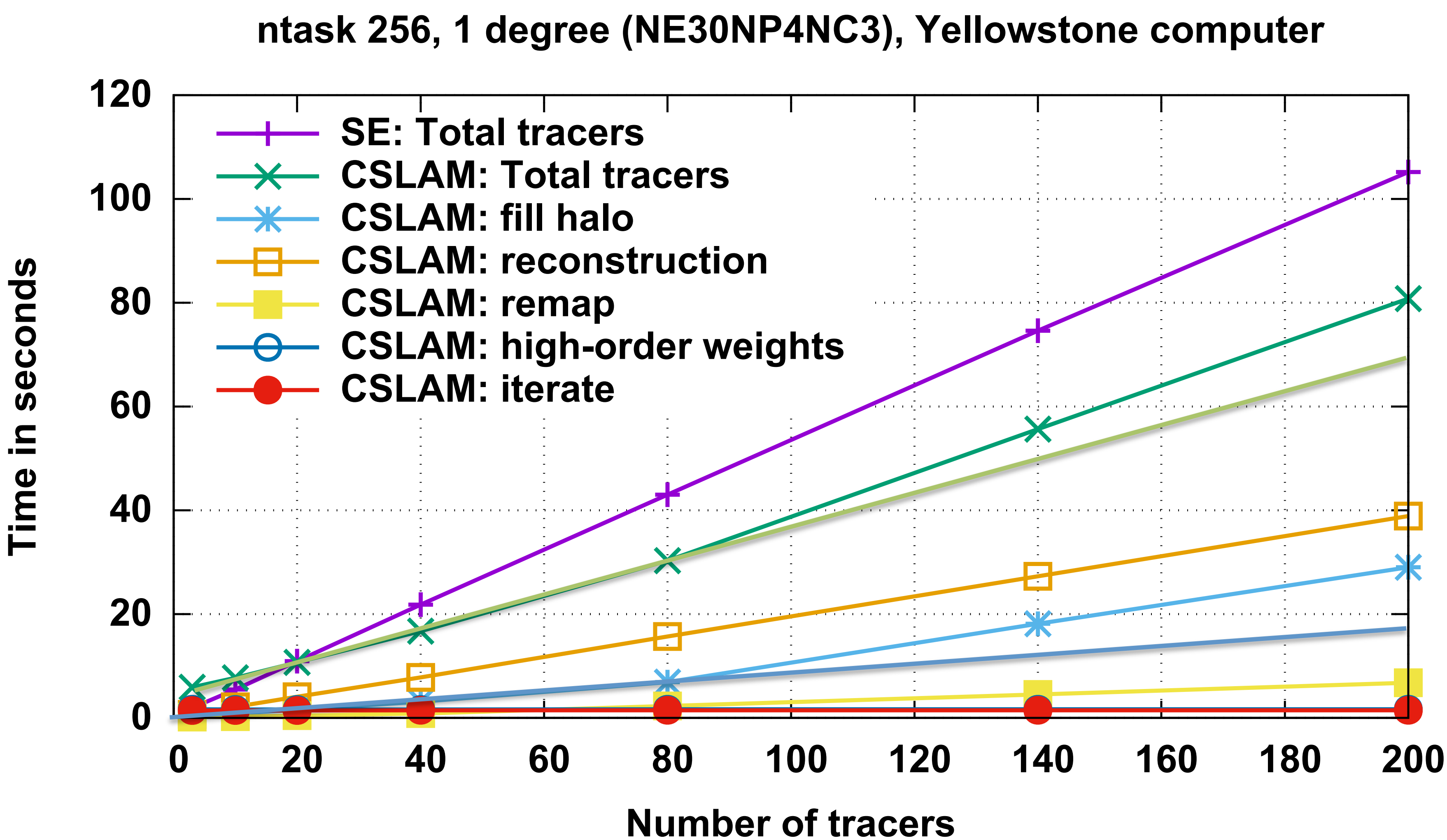
Performance



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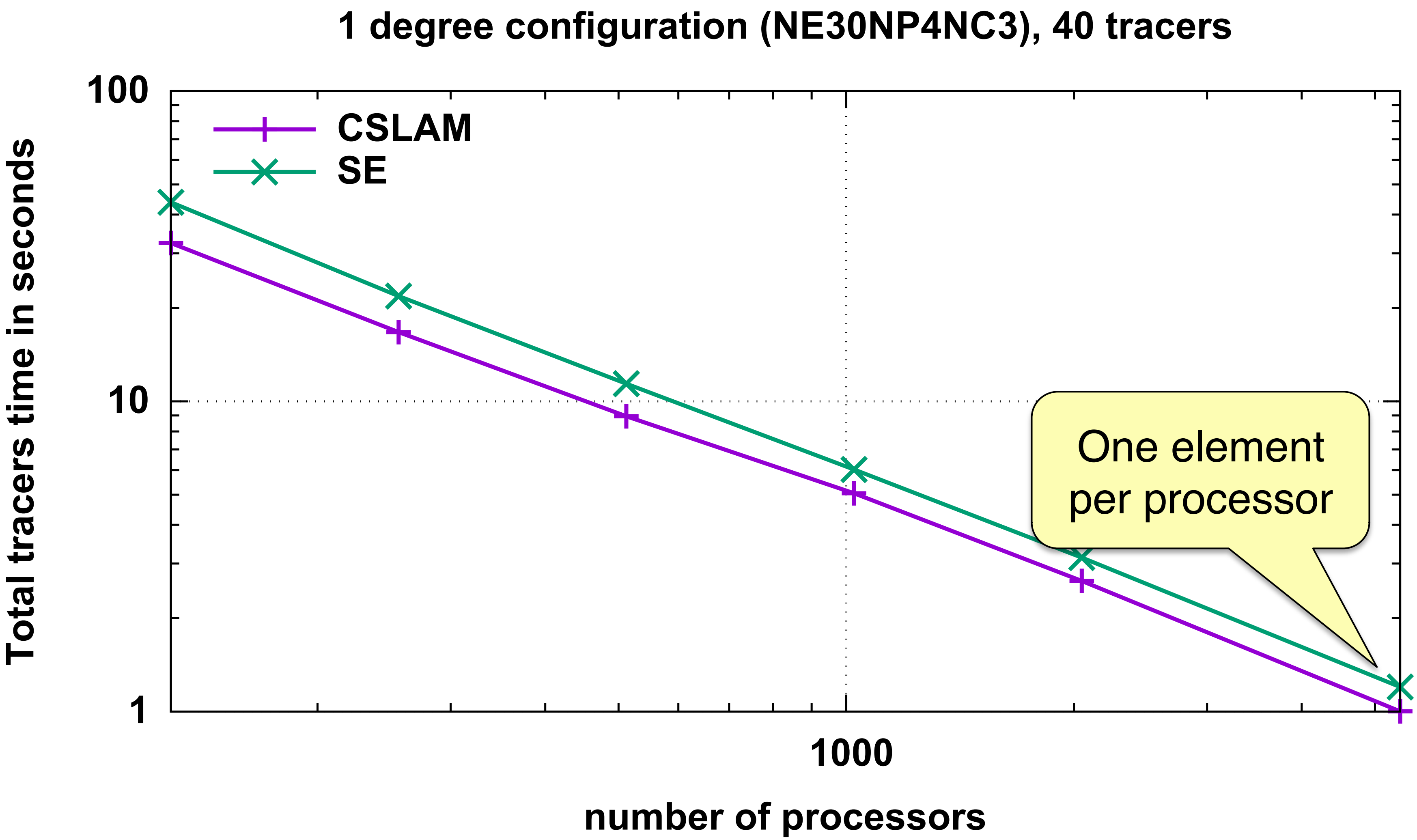
Performance



Thanks to Rory Kelly (CISL) for collaborating on code optimization

CAM-SE development: dry-mass eta

Consider a 'moist' η-coordinate system: The pressure is given by

$$p(\eta) = A(\eta)p_0 + B(\eta)ps,$$

where ps is 'moist' surface pressure.

In a floating η-coordinate system, $\dot{\eta} = 0$, the continuity equation for p can be written as

$$\frac{\partial}{\partial t}\left[\left(\frac{\partial p}{\partial \eta}\right)\right] + \nabla \cdot \left[\left(\frac{\partial p}{\partial \eta}\right)\vec{v}\right] = S^p,$$

where $S^p(q_v)$ is the source/sink term for pressure ($q_v \equiv$ specific humidity).

CAM-SE development: dry-mass eta

This source/sink (exists in CAM-FV and CAM-SE) term is problematic:

- Physics-dynamics coupling
  (violates energy conservation, mixing ratios must be adjusted to conserve mass)
- An inert tracer will have source/sink terms
- Complicates CSLAM-SE coupling in moist atmosphere

...he

...he

$$\frac{\partial}{\partial t}\left[\left(\frac{\partial p}{\partial \eta}\right)\right] + \nabla \cdot \left[\left(\frac{\partial p}{\partial \eta}\right)\vec{v}\right] = S^p,$$

where $S^p(q_v)$ is the source/sink term for pressure ($q_v \equiv$ specific humidity).

CAM-SE development: dry-mass eta

If one uses a dry mass vertical coordinate

$$p(\eta_d) = A(\eta_d)p_0 + B(\eta_d)ps_d,$$

where ps_d is dry surface pressure, then the continuity equation for pressure does not have sources/sinks

$$\frac{\partial}{\partial t}\left[\left(\frac{\partial p_d}{\partial \eta_d}\right)\right] + \nabla \cdot \left[\left(\frac{\partial p_d}{\partial \eta_d}\right)\vec{v}\right] = 0.$$

CAM-SE development: condensate loading

Momentum eqn's in moist vertical coordinates:

$$\frac{\partial u}{\partial t} + (\zeta + f)\,\hat{k} \times \vec{v} + \nabla\left(\frac{1}{2}\vec{u}^2 + \Phi\right) + \frac{R_d T_v}{p_{gas}} \nabla p_{gas} = 0.$$

Momentum eqn's in dry mass vertical coordinates:

$$\frac{\partial u}{\partial t} + (\zeta + f)\,\hat{k} \times \vec{v} + \nabla\left(\frac{1}{2}\vec{u}^2 + \Phi_d\right) + \frac{1}{\rho_d \left(1 + \sum_{X=(v,cl,ci)} m_X\right)} \nabla p_{gas} = 0,$$

where Φ_d is obtained from dry hydrostatic eqn

$$\frac{\partial \Phi_d}{\partial \eta_d} = -\frac{1}{\rho_d}\frac{\partial p_d}{\partial \eta_d},$$

and $m_v \equiv \frac{\rho_v}{\rho_d}$ is the dry mixing ratio for water vapor and the gas pressure (dry+water vapor) is

$$p_{gas} = p_{top} - \int_{\eta'=0}^{\eta'=\eta_d} \frac{\rho}{\rho_d}\left(\frac{\partial p_d}{\partial \eta_d}\right) d\eta',$$

$$= p_{top} - \int_{\eta'=0}^{\eta'=\eta_d} (1 + m_v)\left(\frac{\partial p_d}{\partial \eta_d}\right) d\eta'.$$

CAM-SE development: condensate loading

Maintains excellent CAM-SE axial angular momentum conservation properties (in a dry atmosphere)

...l coordinates:

$$\ldots \times \vec{v} + \nabla\left(\frac{1}{2}\vec{u}^2 + \Phi\right) + \frac{R_d T_v}{p_{gas}}\nabla p_{gas} = 0.$$

...ical coordinates:

$$\ldots \Phi_d\Big) + \frac{1}{\rho_d\left(1+\sum_{X=(v,cl,ci)} m_X\right)}\nabla p_{gas} = 0,$$

wh... ...drostatic eqn

$$\frac{\partial \Phi_d}{\partial \eta_d} = -\frac{1}{\rho_d}\frac{\partial p_d}{\partial \eta_d},$$

and $m_v \equiv \frac{\rho_v}{\rho_d}$ is the dry mixing ratio for water vapor and the gas pressure (dry+water vapor) is

$$p_{gas} = p_{top} - \int_{\eta'=0}^{\eta'=\eta_d} \frac{\rho}{\rho_d}\left(\frac{\partial p_d}{\partial \eta_d}\right) d\eta',$$

$$= p_{top} - \int_{\eta'=0}^{\eta'=\eta_d} (1+m_v)\left(\frac{\partial p_d}{\partial \eta_d}\right) d\eta'.$$

CAM-SE development: condensate loading

Note that the 'full' surface pressure is

$$ps = p_{top} - \int_{\eta'=0}^{\eta'=1} \frac{\rho}{\rho_d} \left(\frac{\partial p_d}{\partial \eta} \right) d\eta',$$
$$= p_{top} - \int_{\eta'=0}^{\eta'=1} (1 + m_v + m_{cl} + m_{ci} + ...) \left(\frac{\partial p_d}{\partial \eta} \right) d\eta',$$

where m_{cl} and m_{ci} are the mixing ratios for cloud liquid water and cloud ice, in other words, the density of air is the sum of the individual component masses

$$\rho = \rho_d + \rho_v + \rho_{cl} + \rho_{ci} + ...$$

but only gases (dry air and water vapor) exert a pressure in the pressure gradient force.

CAM-SE development: condensate loading

The thermodynamic equation

$$\frac{\partial T}{\partial t} + \vec{u} \cdot \nabla T - \frac{R}{c_p p_{gas}} \omega = Q,$$

where

$$R = R_d \frac{1 + \frac{1}{\epsilon} m_v}{1 + \sum_{X=(v,cl,ci)} m_X},$$

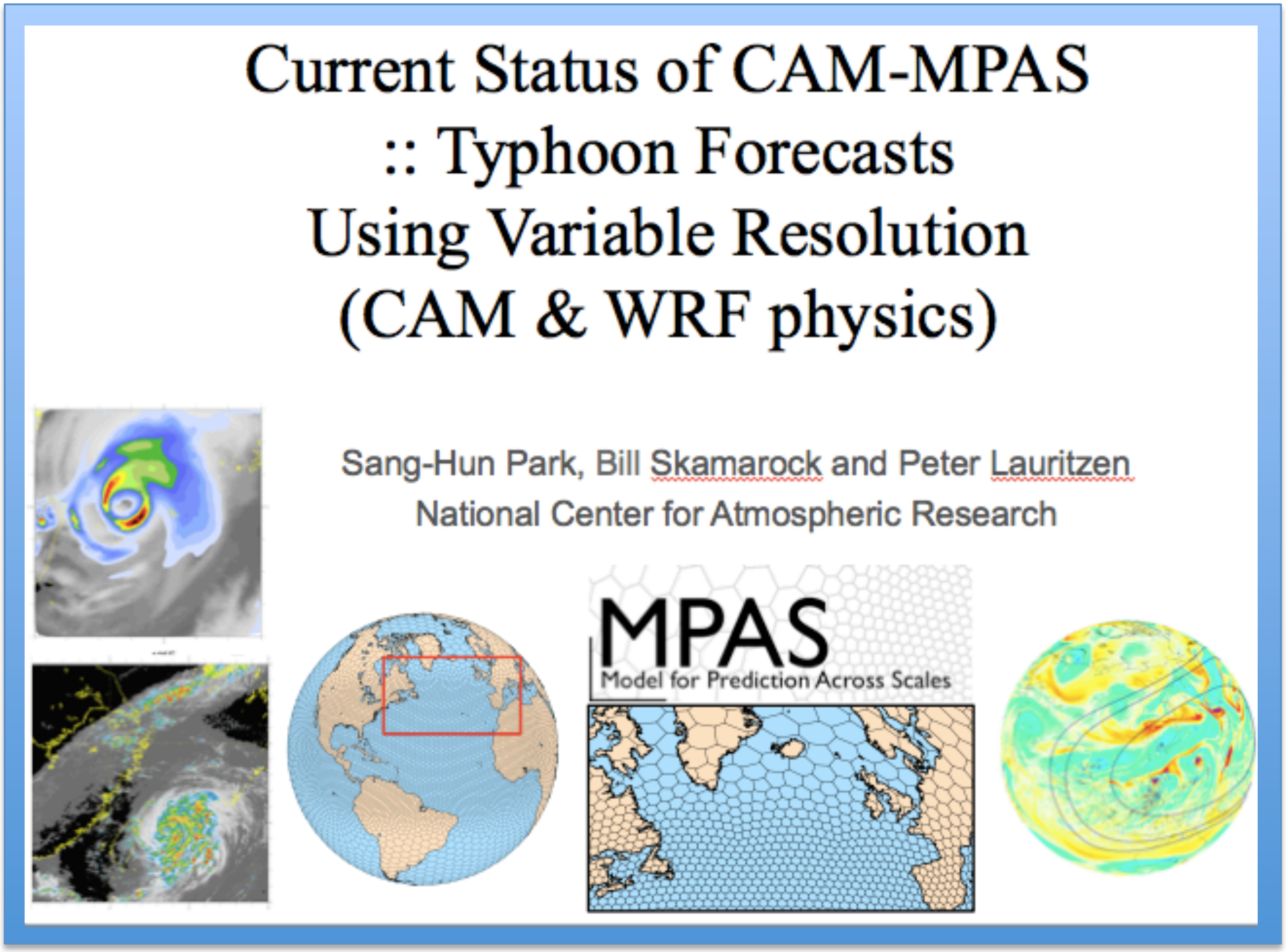
and

$$c_p = \frac{c_{pd} + m_v\, c_{pv} + m_{cl} c_{cl} + m_{ci} c_{ci}}{1 + \sum_{X=(v,cl,ci)} m_X}.$$

and $\epsilon = R_d/R_v$.

Thermodynamic equation has the same form for both moist and dry vertical coordinates (except for condensate loading terms in R and c_p).

CAM-MPAS development

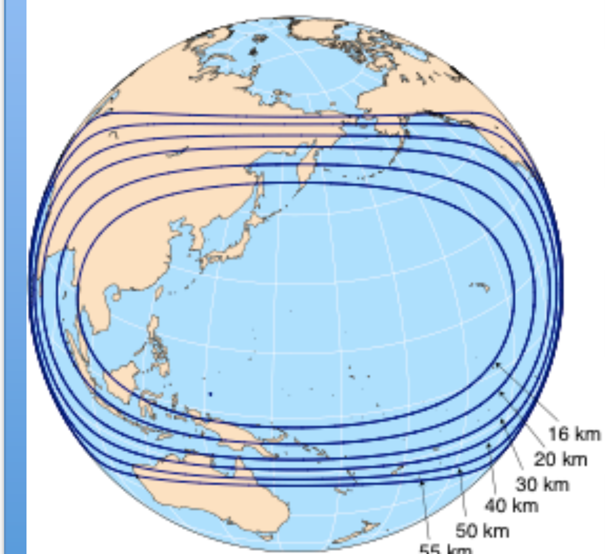


Slide courtesy of Sang-Hun Park (NCAR)

CAM-MPAS development

Forecast Configuration

MPAS-TC Mesh Contour



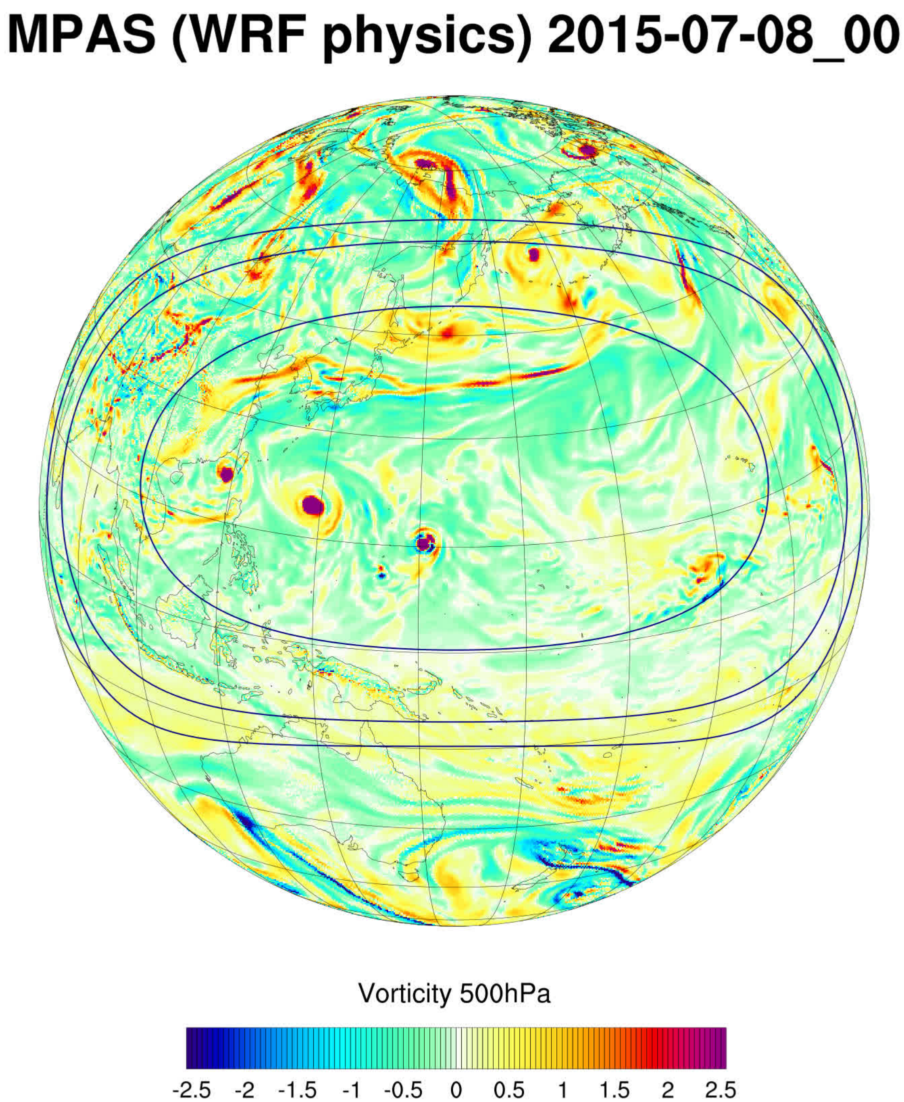
	WRF-MPAS	CAM-MPAS
Initial Data	GFS 15km F00 analysis	
SST	GFS 15km Skin temperature	NOAA OISST 1x1 deg. (weekly)
Run Time	10 Days	5 Days
Model Top	30 km (55 levels)	~45 km (30 levels)
Mesh Size	535554 Cells* (fine 15km ~ coarse 60km)	
DT for dynamical core	60s (RK3) (setting for fine resolution)	
DT for physics	Different depend on schemes	1800s

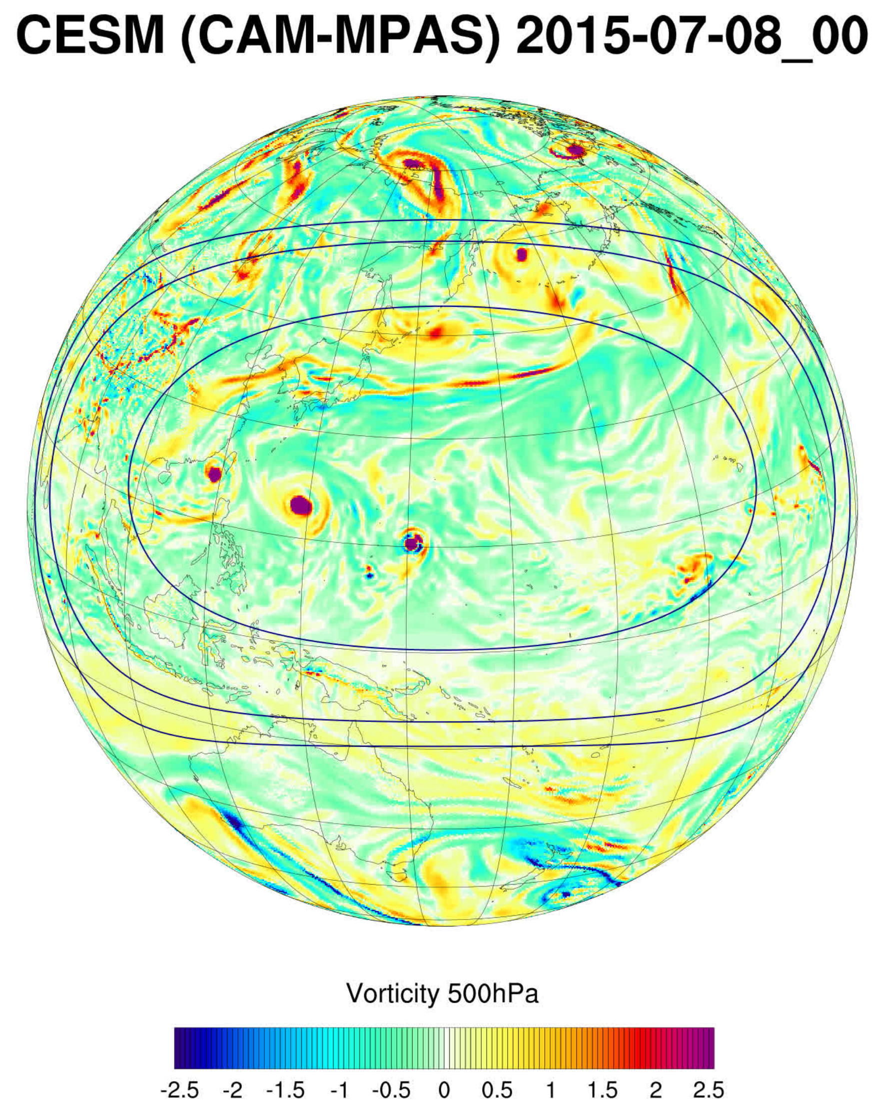
* uniform 30km :: 655362 Cells
uniform 15km :: 2621442 Cells

Slide courtesy of Sang-Hun Park (NCAR)

Slide courtesy of Sang-Hun Park (NCAR)

CAM-MPAS development





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