Modeling the Changing Earth System: Prospects and Challenges

William D. Collins

Head, Climate Sciences Department, Berkeley Lab

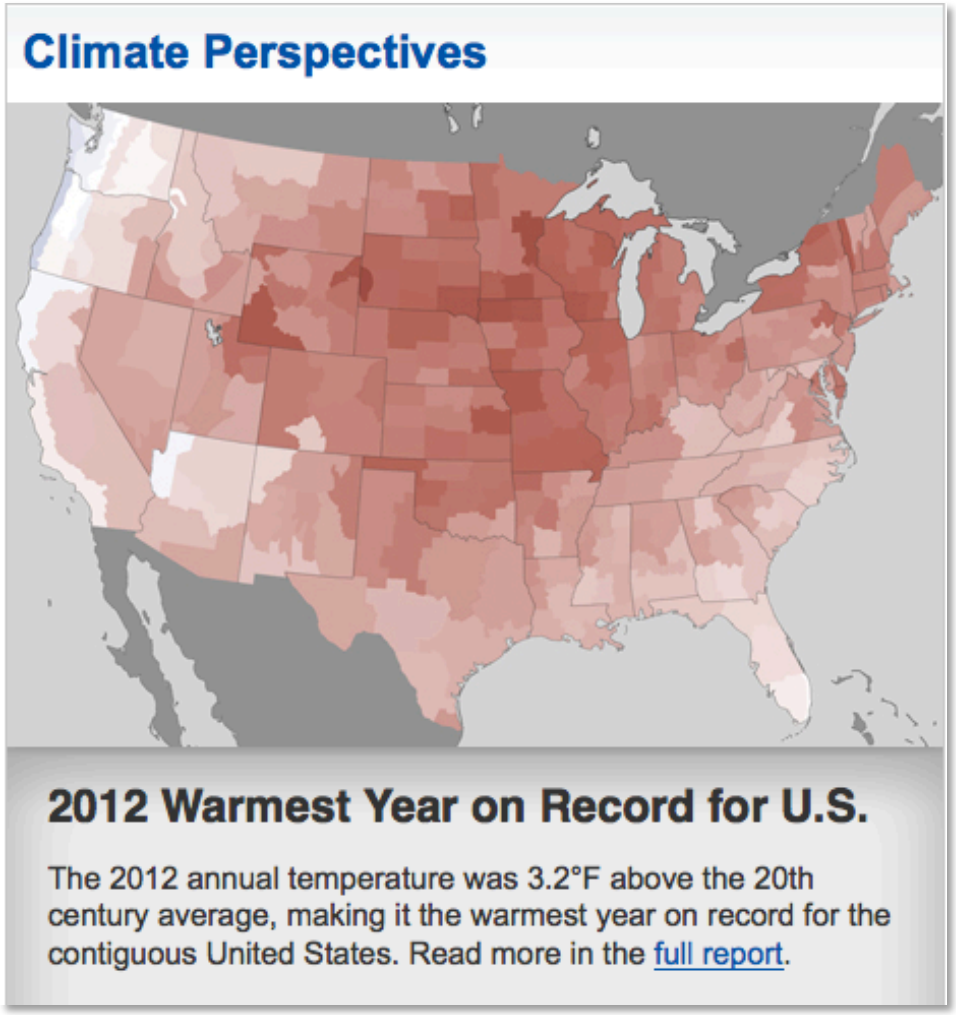
Professor in Residence, UC Berkeley

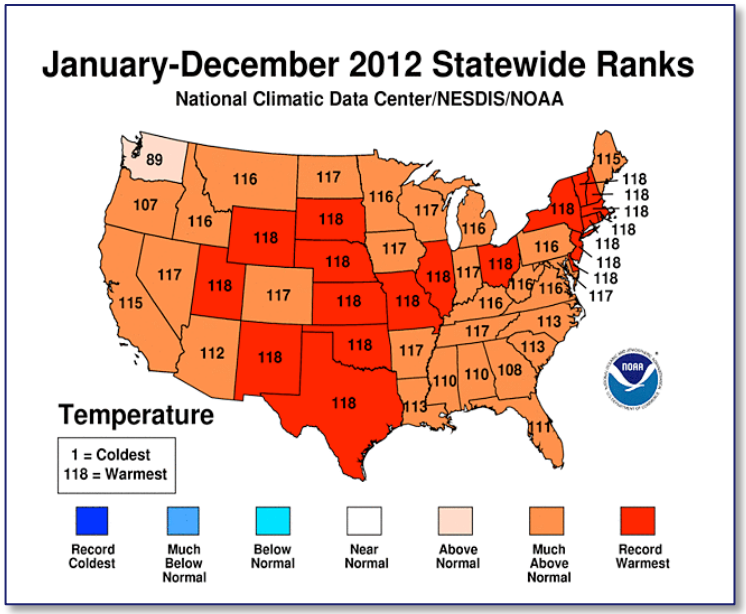
DOE's Chief Scientist for Climate Modeling

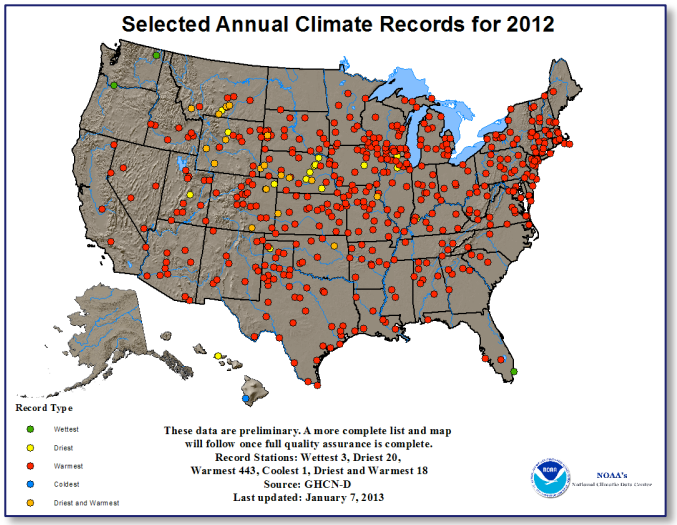




U.S. is getting hotter







http://www.ncdc.noaa.gov/

California is in midst of drought

2014

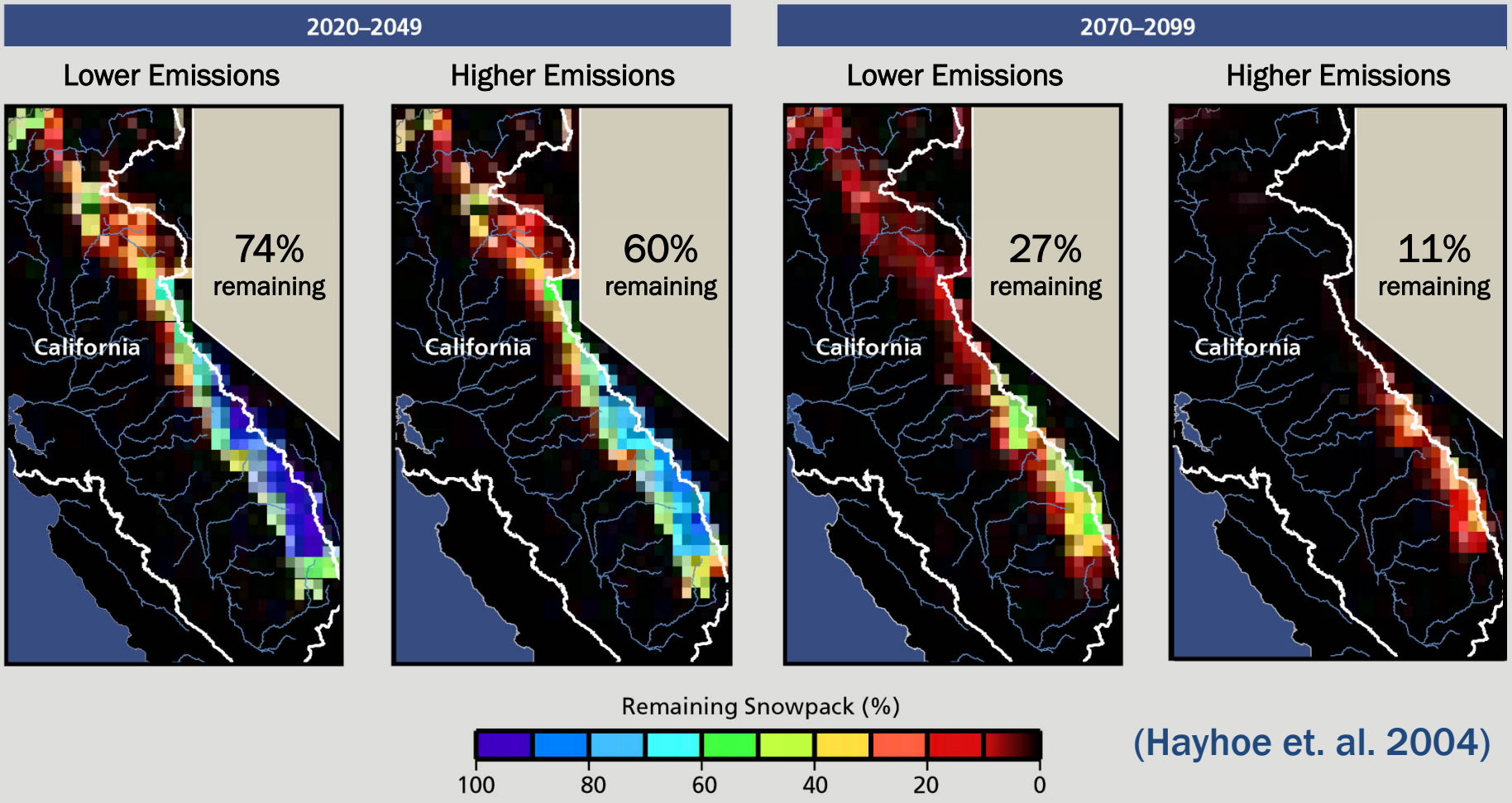


2013



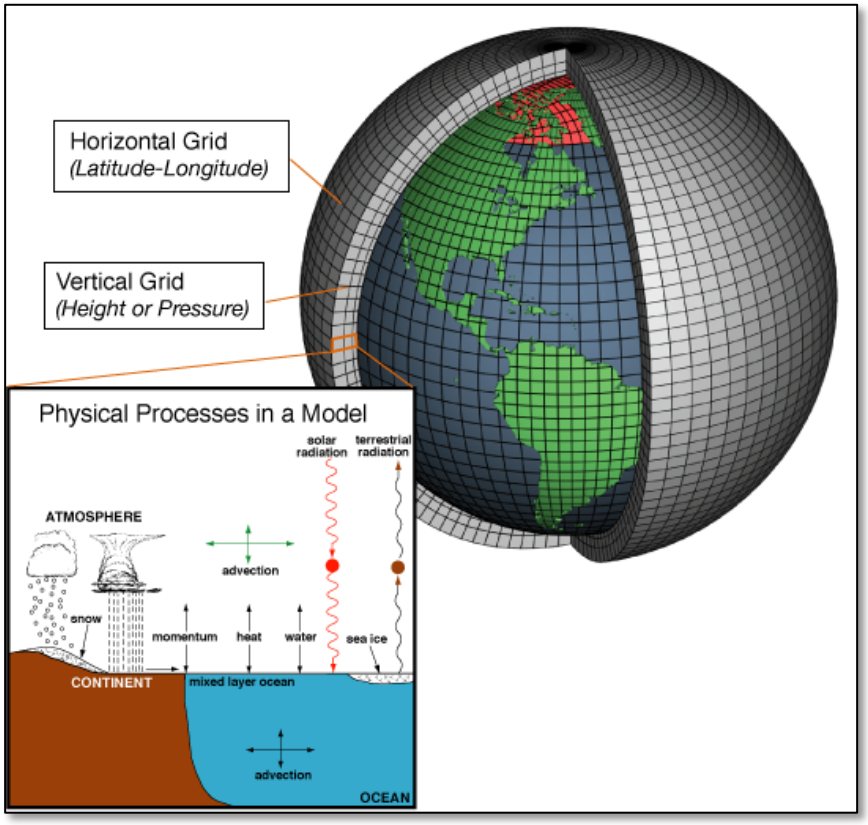
NASA MODIS

Projections for California's Snowpack



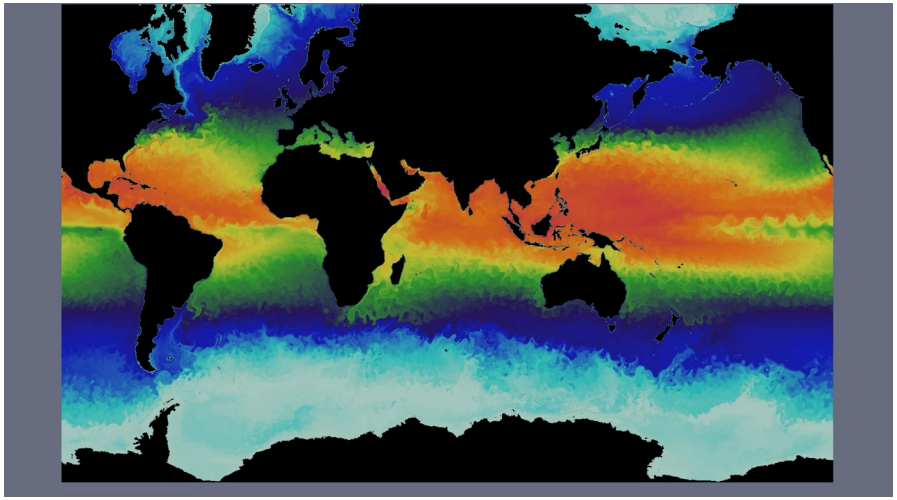
(Hayhoe et. al. 2004)

Climate models serve to project Earth's future



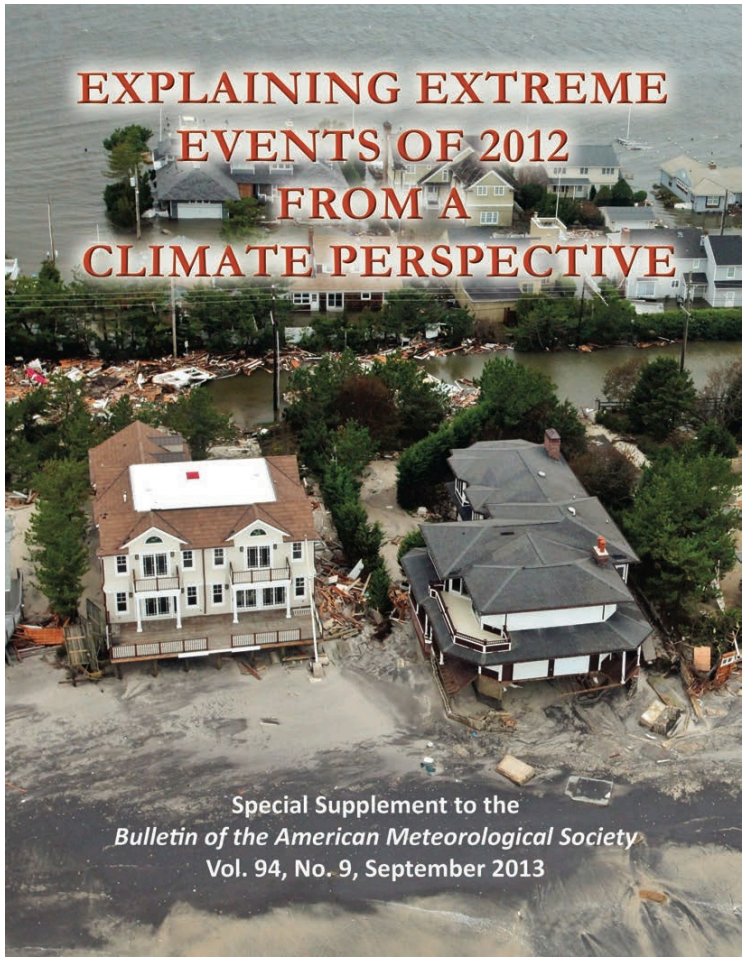
Credit: NOAA

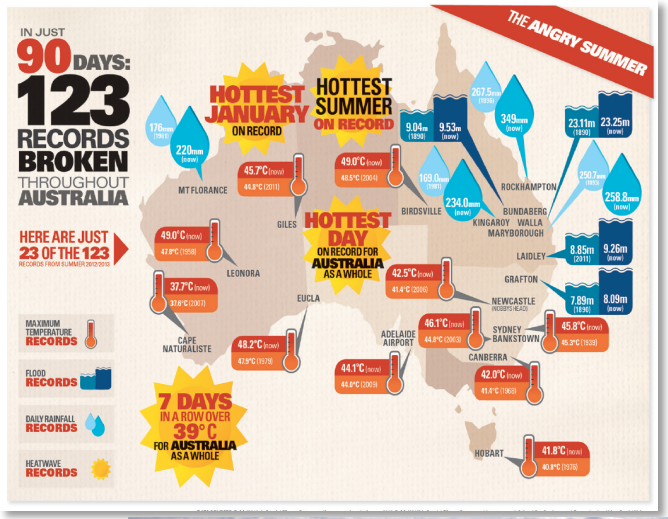
- Tool for predicting the future
- Tool for understanding the past
- Numerical "parallel Earth"



Credit: LANL

Extremes are a growing research focus

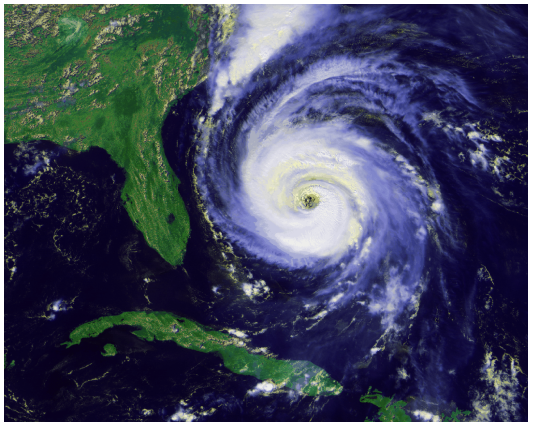






Can we predict climate change at the timescales of extreme climate events?

- **Projections suggest:**
  - More intense hurricanes
  - More intense downpours
  - Stronger storms

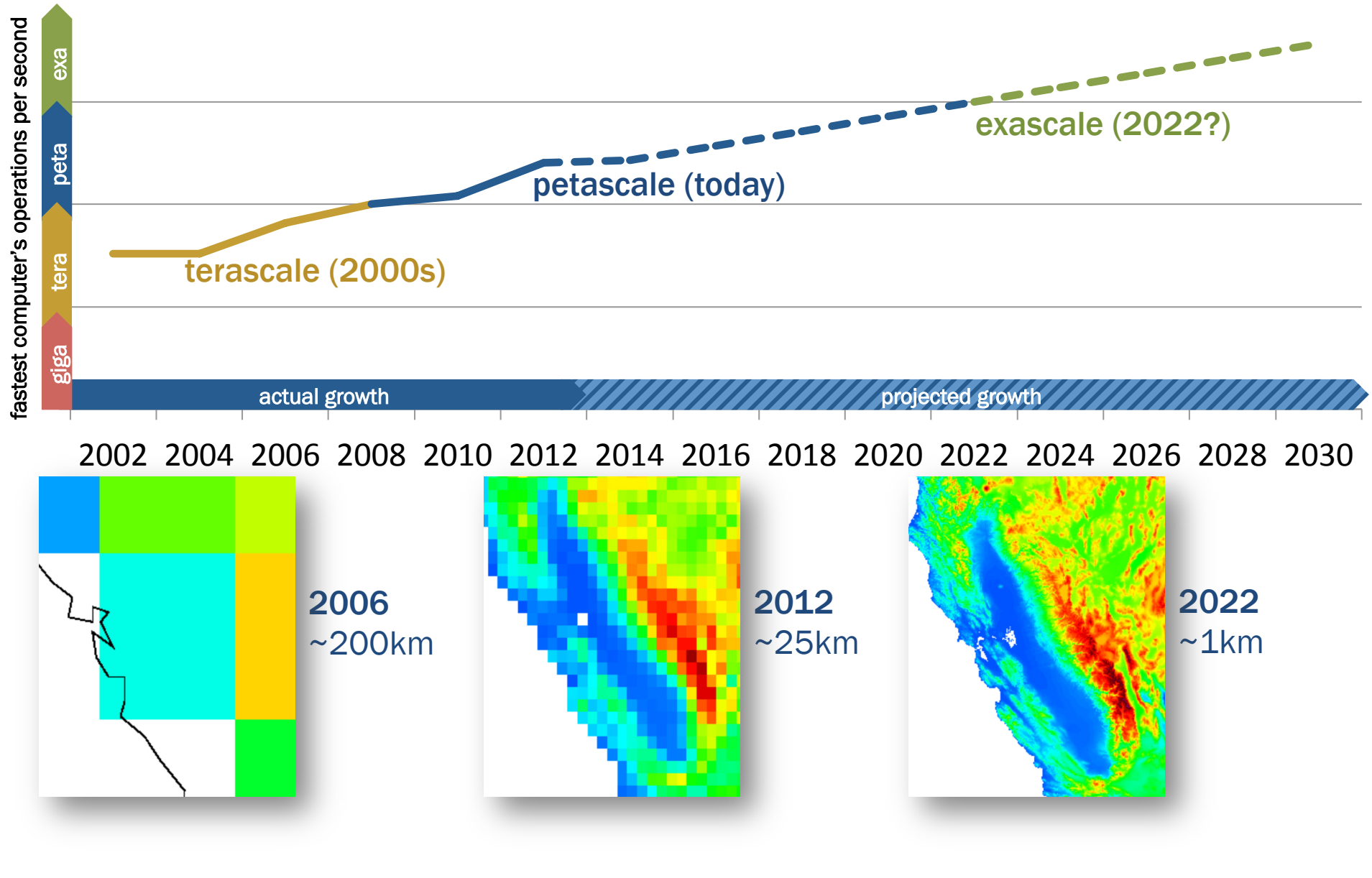


- These require ***ultra high*** resolution to detect and track storms in ***centuries to millennia*** of climate projections.

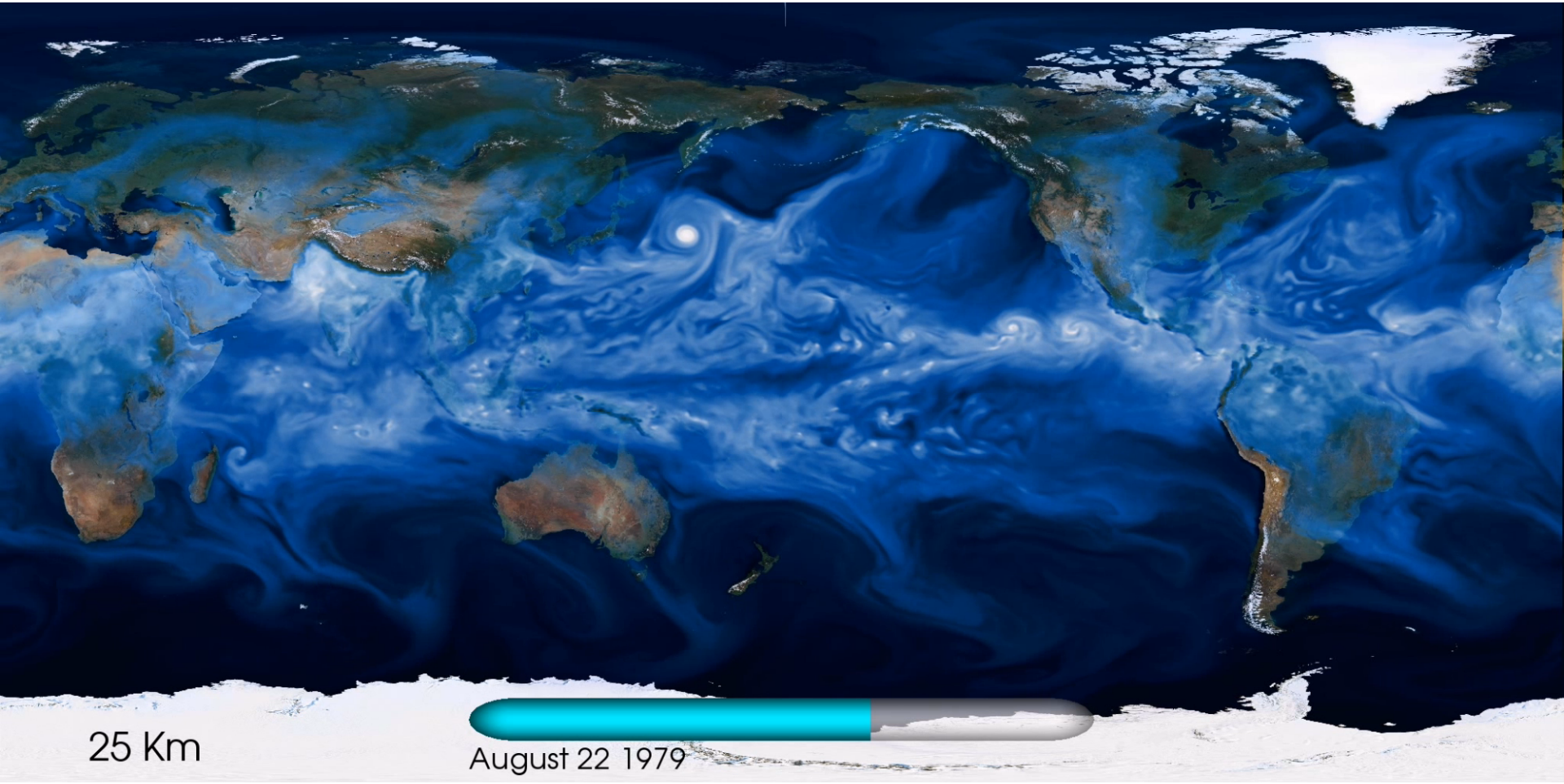




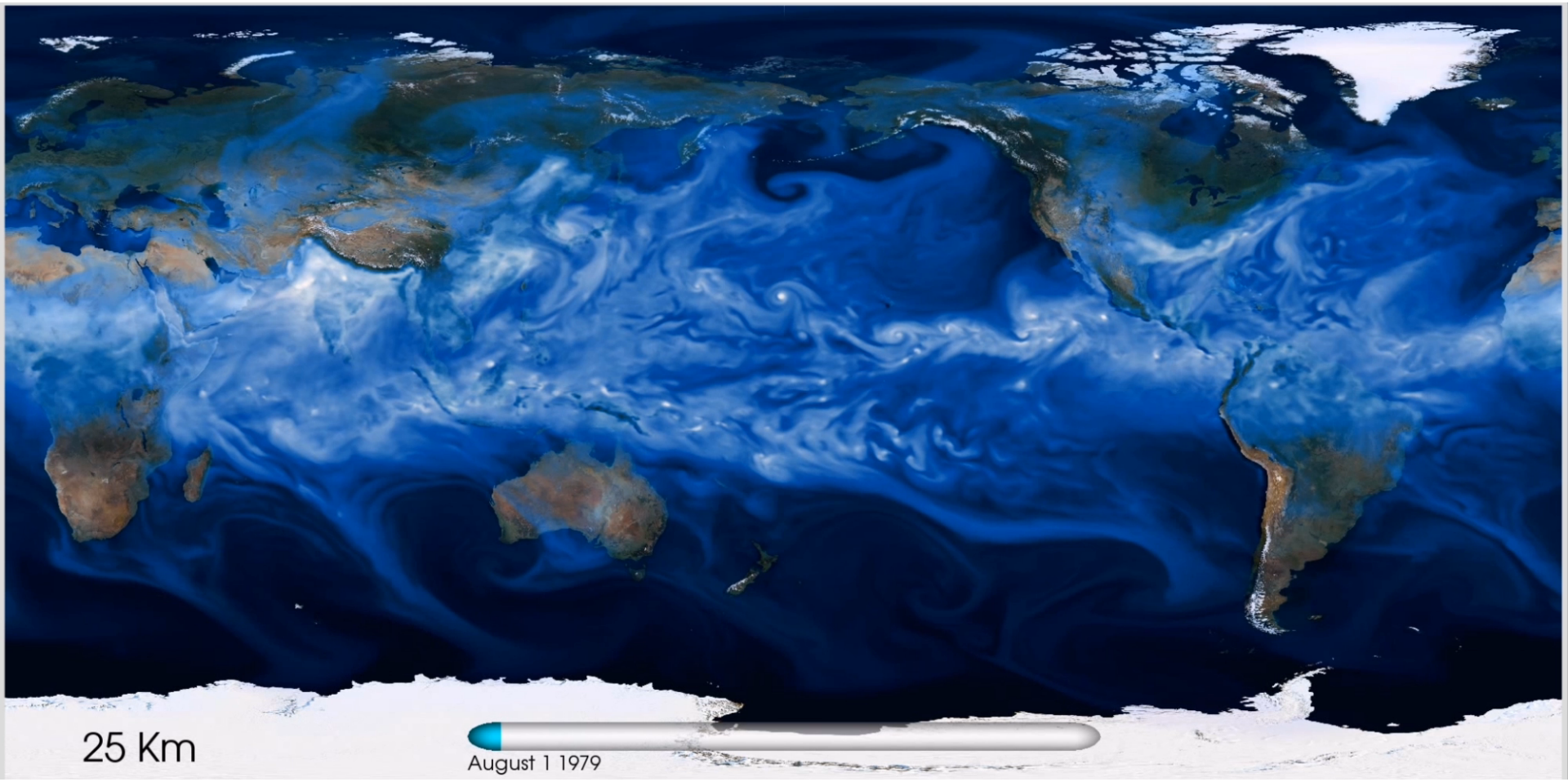
Extreme computing will transform projections



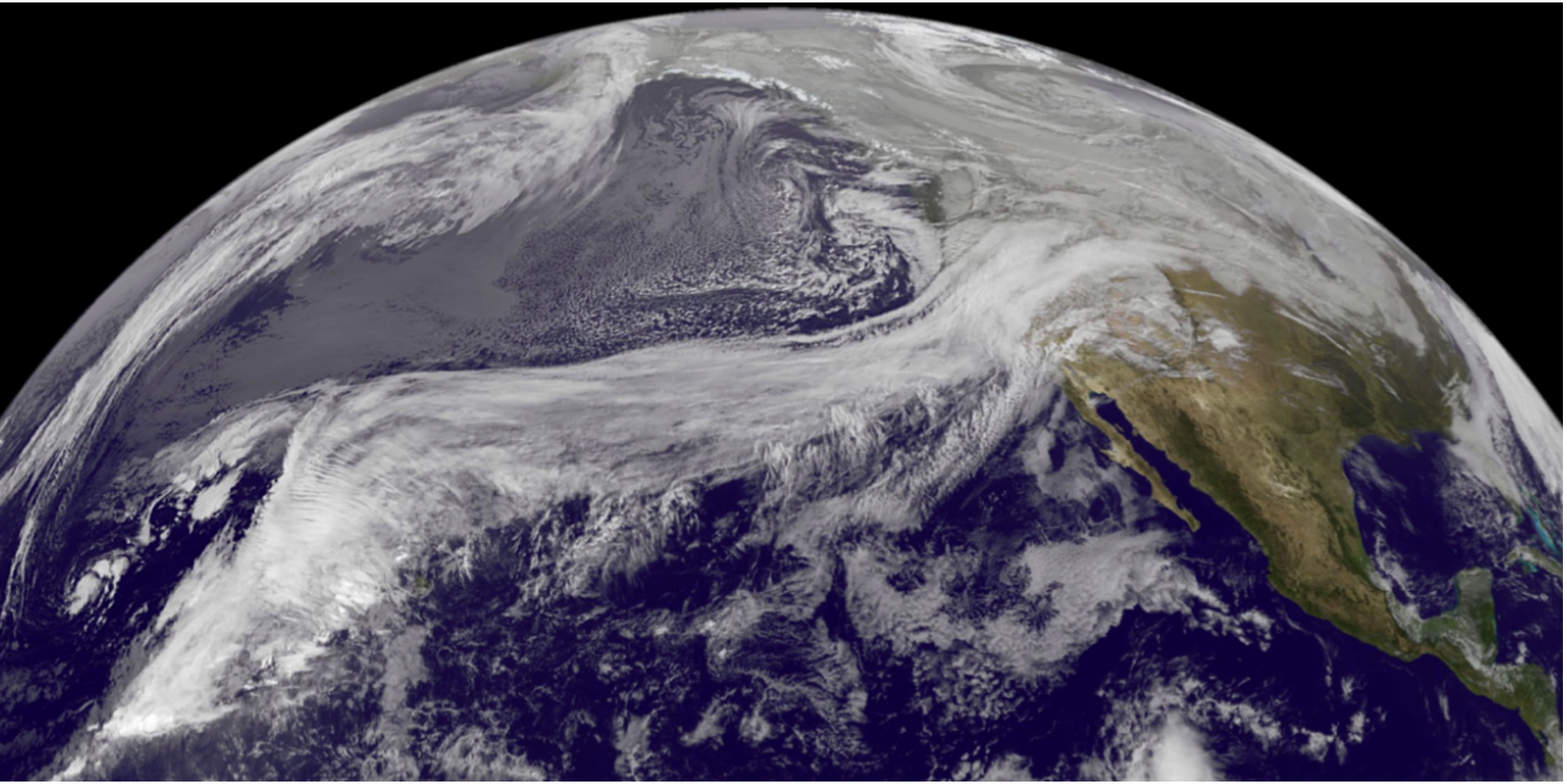
Simulating extreme weather events



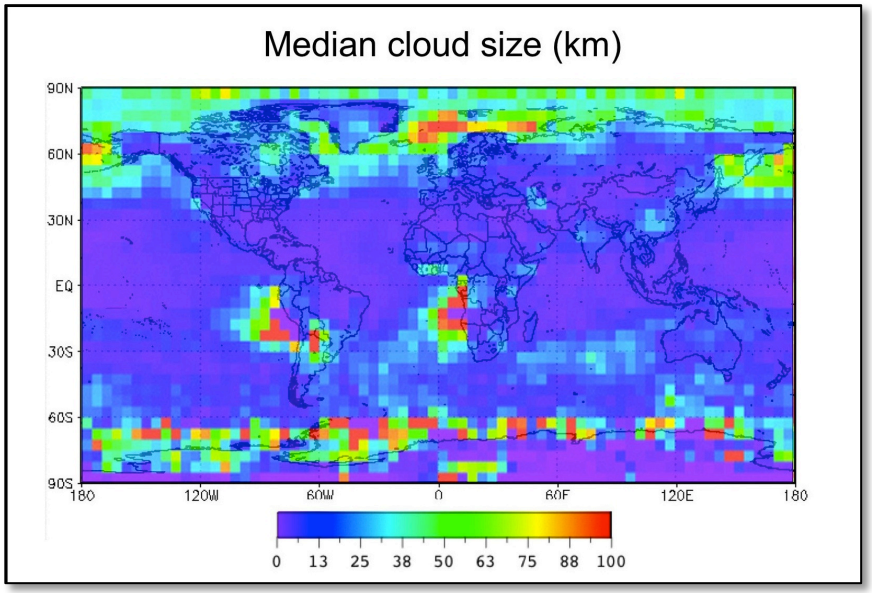
Big data challenges for extreme weather

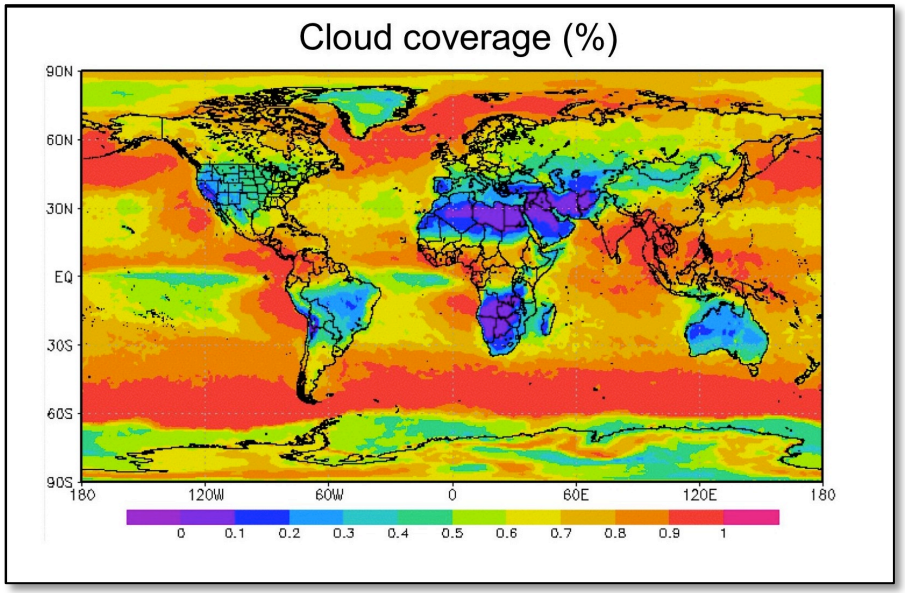


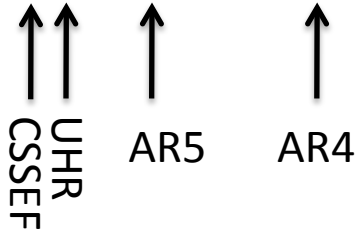
Simulating atmospheric rivers



Clouds scales and model resolution







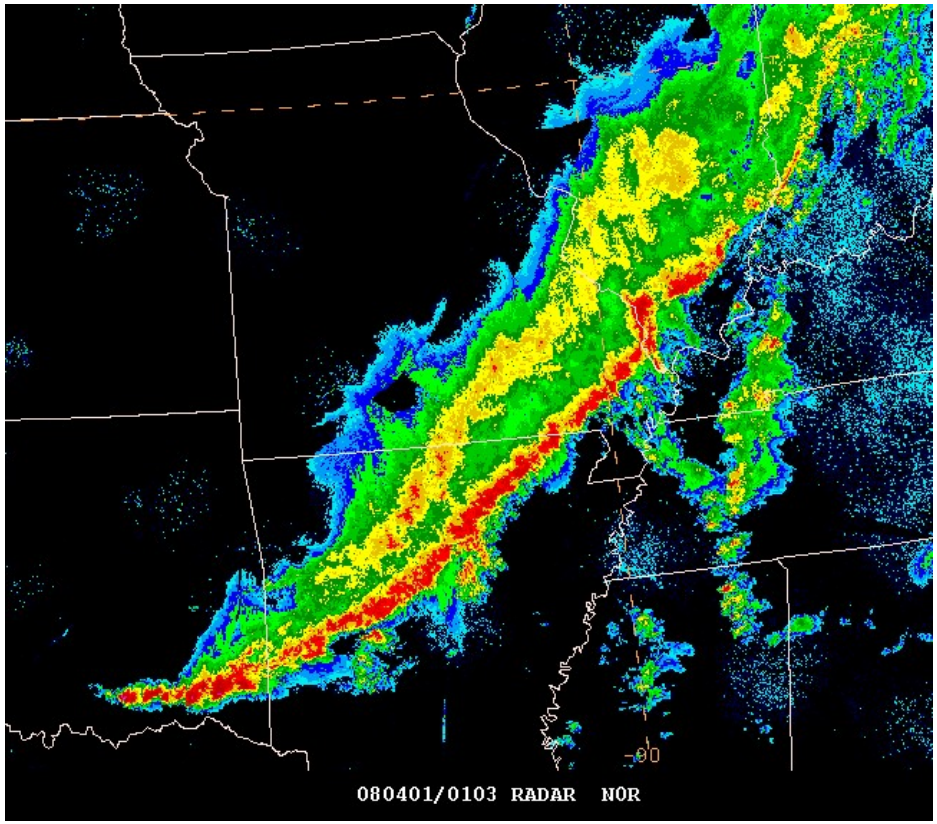
Potential of adaptive atmospheric dynamics

- Many meteorological features are localized in space and time
- Features can be: stationary, move at advected speeds, or evolve from wave dynamics
- Refinement can greatly reduce computational resources needed

Examples:

- Tropical cyclones
- Squall lines / storm fronts
- Atmospheric rivers
- Sporadic “burst” events

→ Refine where/when required



Radar image of a squall line over central US

Why non-hydrostatic?

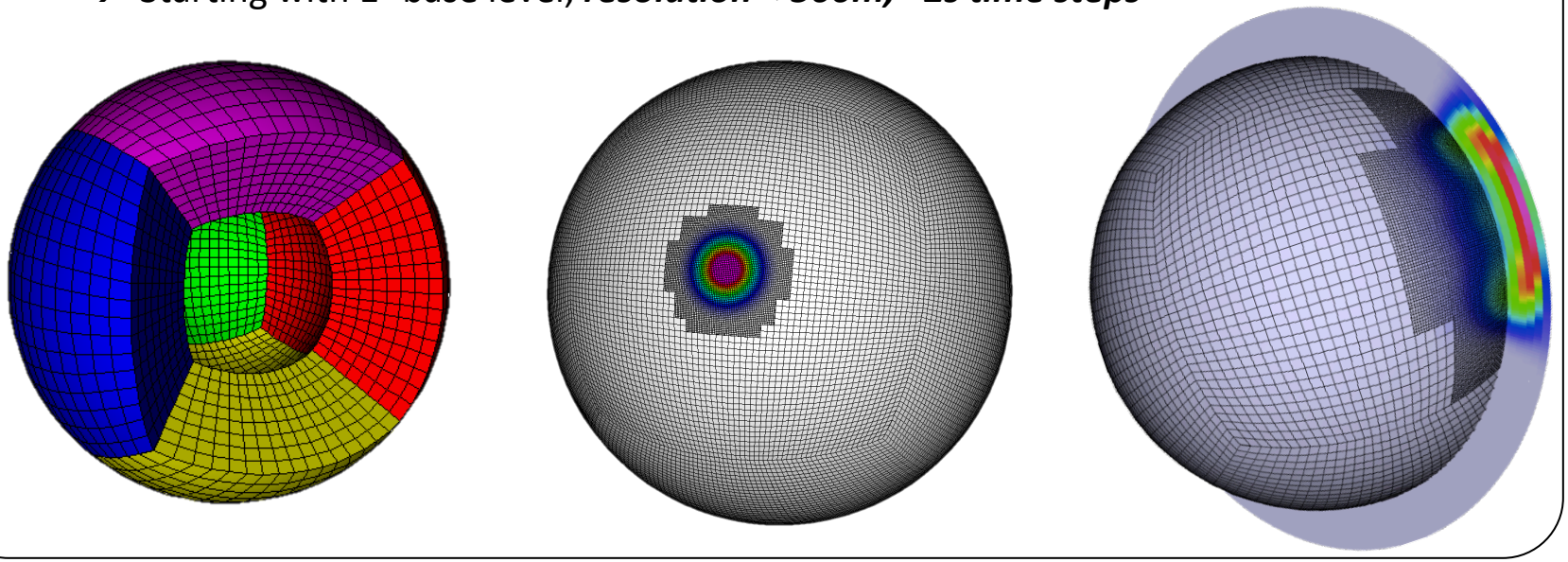


- Below 20km resolution, non-hydrostatic effects begin to emerge
- Overall, low-*Mach* number is the appropriate regime, but little benefit due to fast gravity waves
- Cloud-resolving models, etc. are growing trends in GCM, NWP
- DNS baselines will be needed for stochastic / PDF formulations in the (not so distant) future
- Refinement (ad nauseum) tests the "convergence" of physics models and time coupling

Goals of dynamic AMR atmospheric simulations

Create a high-resolution, high accuracy dycore to *eliminate local numerical errors*

- Fully non-hydrostatic dynamics (4^{th}-order in space and time)
- Excellent scaling (100k+ cores) without vertical explicit acoustic CFL limitation
- Anisotropic adaptive mesh refinement in space, refinement in time
  - → 3 levels with 4x refinement produces > ***5 more digits*** of accuracy
  - → Starting with 1° base level, ***resolution < 500m, ~2s time steps***



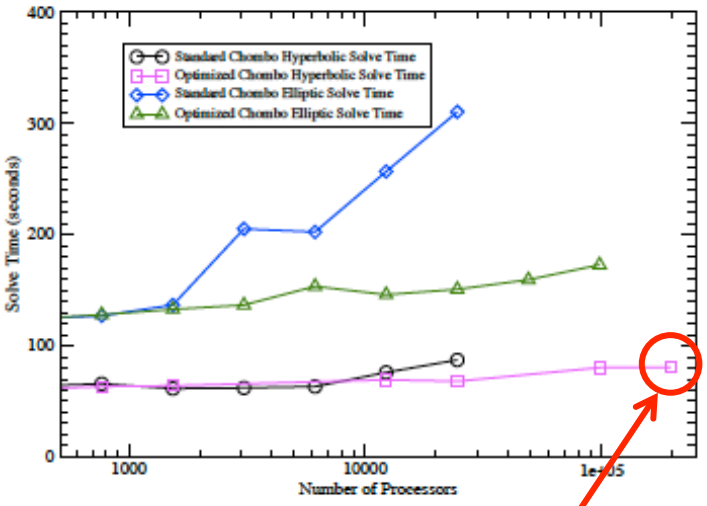
Chombo AMR code is well-established, scalable

Broad set of applications leveraging Chombo framework with complex physics:

- MHD for tokamaks (R. Samtaney, PPPL)
- Cosmology: CFD + particles (Miniati, ETH)
- Space plasmas: compressible CFD electromagnetic, kinetic effects (G. Zank, UA)
- Astro. MHD turbulence (McKee / Klein, UCB)
- SF Bay Hydrology modelling (CA DWR)
- Microscale fluids (UNC / UCD / LBNL EFRC)
- Heat transfer in nuclear reactors (LBNL)
- Nuclear reactor safety - hydrogen combustion entrainment models (Calhoun, CEA-Saclay)
- Type II Supernovae (Woosley, UCSC, LLNL)
- 4D gyrokinetic tokamak edge plasmas (LLNL) …

Long-term ASCR investment: SciDAC, FastMATH …

→ Target platforms extreme-scale / DoE LCF's



200k processor benchmark, nearly ideal weak scaling on similar hyperbolic problems! [EuroPar2011]

BISICLES: Dynamic AMR for Ice Sheets

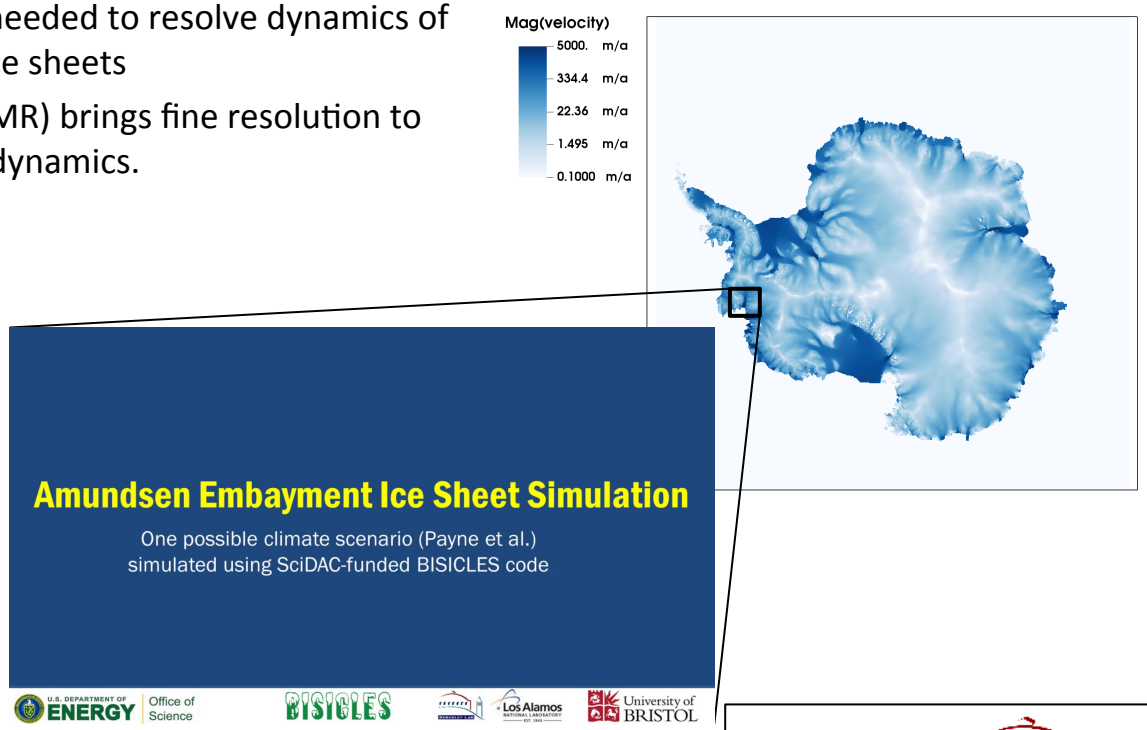
Objectives

- Understanding ice sheet dynamics is crucial for credible predictions of future sea level rise (SLR)
- Very fine resolution (better than 1 km) needed to resolve dynamics of grounding lines – unfeasible for entire ice sheets
- Dynamic Adaptive Mesh Refinement (AMR) brings fine resolution to bear only where needed to resolve the dynamics.

Impact

- Enables modeling grounding line dynamics of marine ice sheets with sufficient spatial resolution to correctly model advance or retreat.
- AMR models dynamics correctly (vs. lo-res reduced or no mobility)
- Enables continental-scale modeling of ice sheets at the resolution / computational cost for global climate models (GCMs).

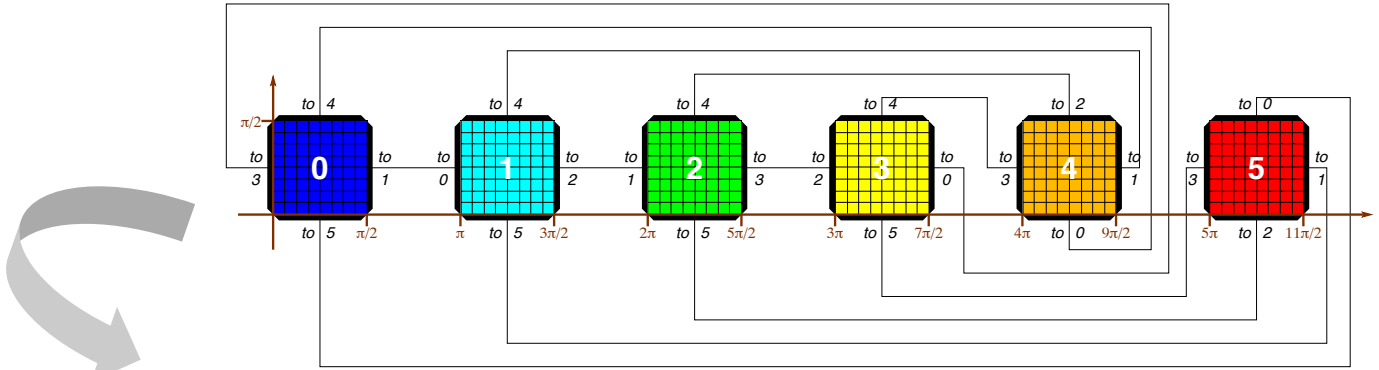
(below) Computed ice velocity for Antarctica, mesh and grounding line for Pine Island Glacier.

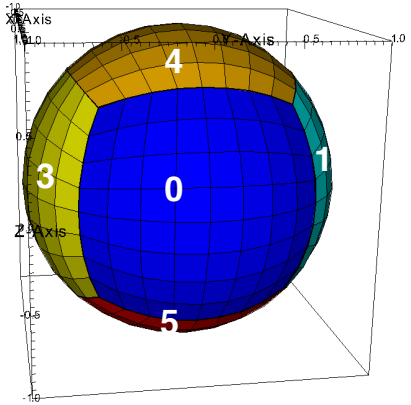


BISICLES
BERKELEY LAB
Los Alamos NATIONAL LABORATORY EST. 1943
University of BRISTOL

Cubed Sphere Formulation

- Use a “multi-block” mapping between rectangular index space and CS panels
- Use an arbitrary stretched grid in the radial direction (pressure coordinate, etc.)





Conservative FV on Cubed Sphere "Shells"

- Riemannian form of compressible Euler [Ullrich Jabl. JCP 2012]
- Conservative, in flux divergence form, with "~" indicating deviation from constant hydrostatic background state

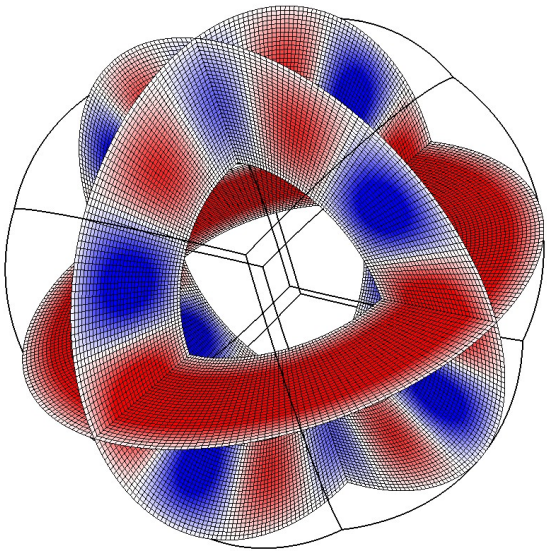
density $$\frac{\partial J\tilde{\rho}}{\partial t} = \dots$$

potential temp. $$\frac{\partial J\tilde{\Theta}}{\partial t} = \dots$$

humidity $$\frac{\partial J\tilde{Q}}{\partial t} = \dots$$

momentum $$\frac{\partial J\rho\mathbf{u}}{\partial t} = \dots$$

- Cubed sphere metrics calculated analytically, mapped to unit sphere
- "Shells" because we neglect the radial metric dependencies



$$\mathbf{u} = u^{\alpha}\mathbf{g}_{\alpha} + u^{\beta}\mathbf{g}_{\beta} + u^{\xi}\mathbf{g}_{\xi}$$

What makes this harder than hydrostatic?

- At 1° resolution, lower atmosphere cells can have ~1000:1 aspect ratio
- Euler has (fast) acoustic waves, (almost as fast) gravity waves

- Sound wave-based CFL for explicit methods → 1000x smaller time step
- Need an alternative to explicit time integration in the vertical direction!

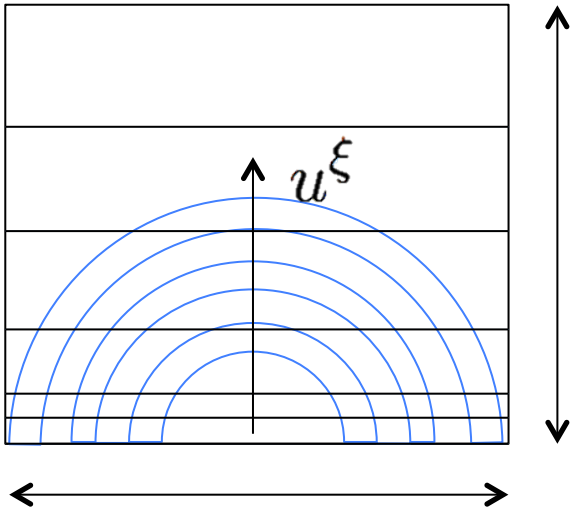
$$\frac{\partial J\tilde{\rho}}{\partial t} + \frac{\partial}{\partial \xi}(J\bar{\rho}u^{\xi}) = \dots$$

$$\frac{\partial J\tilde{\Theta}}{\partial t} + \frac{\partial}{\partial \xi}(J\bar{\Theta}u^{\xi}) = \dots$$

$$\frac{\partial J\bar{\rho}u^{\xi}}{\partial t} + \frac{\partial}{\partial \xi}(JG^{\xi\xi}\tilde{p}) = \dots$$

$$\frac{\partial J\tilde{p}}{\partial t} + \gamma J\bar{p}\frac{\partial u^{\xi}}{\partial \xi} = \dots$$

$$p = p_0\left(\frac{R_d\rho\theta}{p_0}\right)^{\gamma}$$



Vertical acoustic waves cross thin cells too quickly for explicit CFL!

Horizontal acoustic waves ok within a wide aspect ratio cell

Tricks from aero / combustion CFD

- Equation of state is used to derive an equivalent equation for the pressure perturbation:
- If we evolve this separately from Θ they will diverge, so connect with a Lagrange multiplier to EoS:

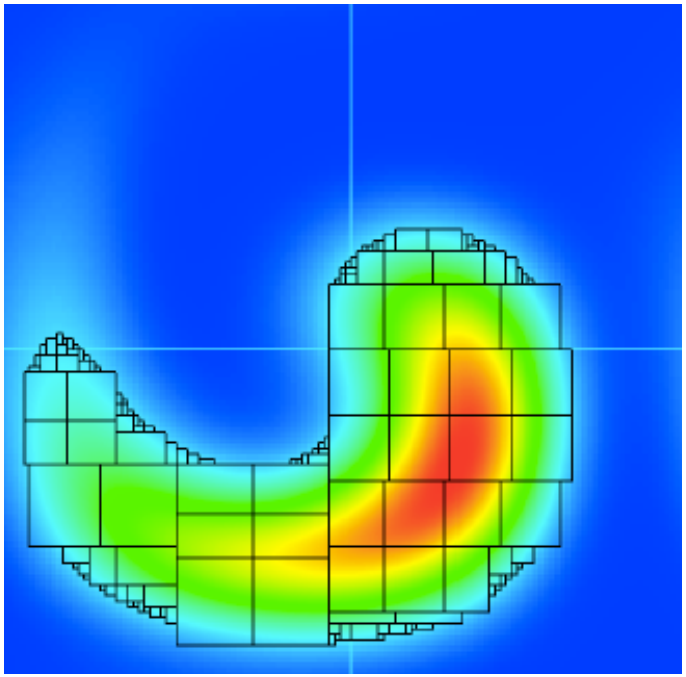
$$\frac{\partial J\tilde{p}}{\partial t} + \gamma\left(\bar{p}+\tilde{p}\right)\frac{\partial}{\partial x^k}(Ju^k) + Ju^k\frac{\partial \tilde{p}}{\partial x^k} - Ju^\xi\frac{\bar{\rho}g}{H} = J\eta\left(P(\Theta)-p\right)$$

- To isolate vertical acoustic waves, separate out acoustic terms against hydrostatic background (since in general $\tilde{\rho} \ll \bar{\rho}$

$$\frac{\partial J\tilde{\rho}}{\partial t} + \frac{\partial}{\partial \xi}(J\bar{\rho}u^\xi) = \dots$$
$$\frac{\partial J\tilde{\Theta}}{\partial t} + \frac{\partial}{\partial \xi}(J\bar{\Theta}u^\xi) = \dots$$
$$\frac{\partial J\bar{\rho}u^\xi}{\partial t} + \frac{\partial}{\partial \xi}(JG^{\xi\xi}\tilde{p}) = \dots$$
$$\frac{\partial J\tilde{p}}{\partial t} + \gamma J\bar{p}\frac{\partial u^\xi}{\partial \xi} = \dots$$

This linear system approximates vertical acoustic waves vs. hydrostatic balance, so if we treat it implicitly, vertical CFL ok

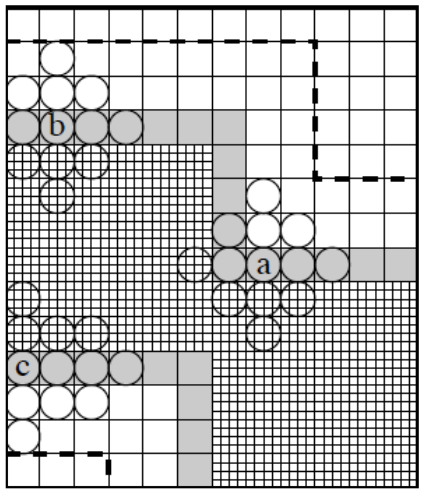
Adaptive Mesh Refinement

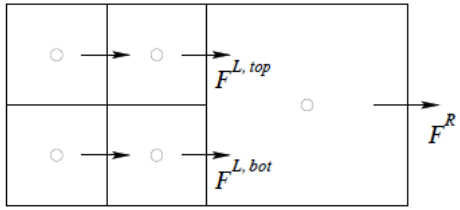


3-level AMR stiff Advection-Diffusion

To achieve 4th-order accuracy in space on *adaptive* mapped grids:

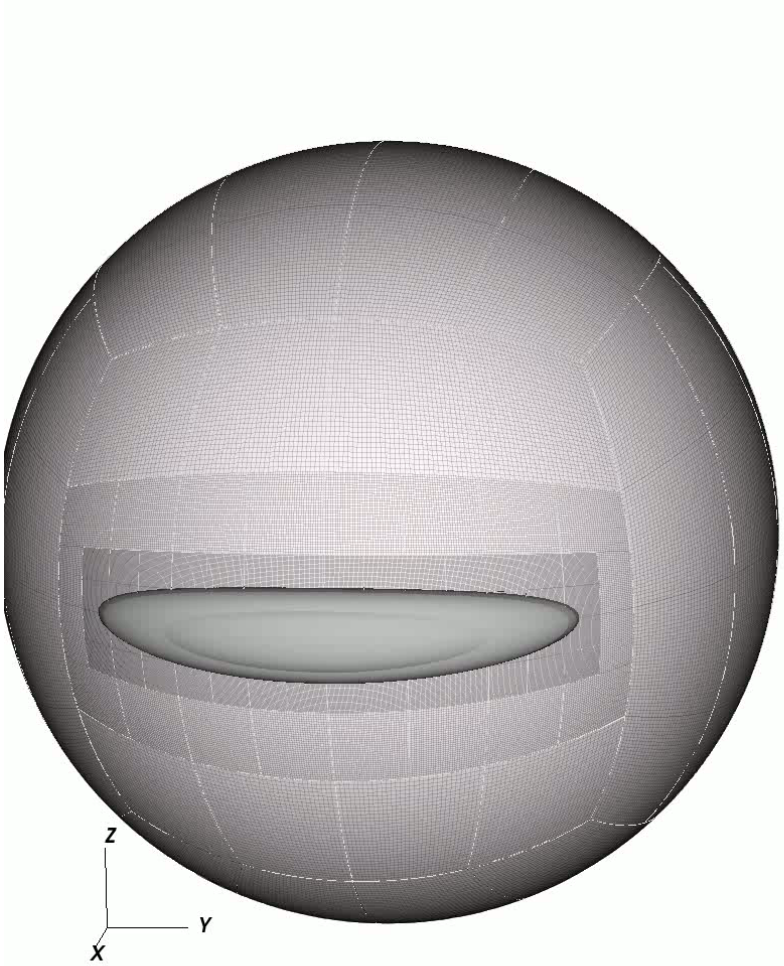
- Interpolate *coarse* to *fine* "ghost cells" in space (4th-order least-squares) and time
- Algorithm advances *fine* level in time
- Covered *coarse* solution is average of *fine*
- Coarse fluxes must be "corrected" with *fine*





Demo calculation

- **Dynamics:** **Prescribed Hadley circulation**
- **Physics:** **Large-scale condensation**
- **Lower boundary:** **Aquaplanet**
- **H2O processes:** **Advection & condensation**
- **Movie:** **3D vapor and surface rainfall**
- Simulation time: 30 days
- AMR grid: 0.7° resolution,
  3 mesh tiers



Near-term Future Plans for AMR

What are we hoping to accomplish?

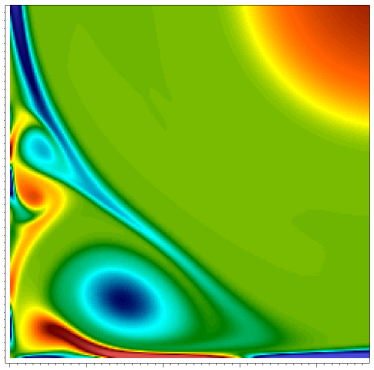
- 4^{th}-order in space and time, without limitation of vertical explicit CFL
- Near-perfect scaling (CHOMBO explicit implementations have gone to 100k+)
- Anisotropic adaptive mesh refinement, 4^{th}-order in space, refinement in time

→ 4 levels of 4x refinement produces almost ***5 more digits*** of accuracy

→ 1° base level, that would be ***< 500m resolution***, not feasible with uniform grid

Future plans:

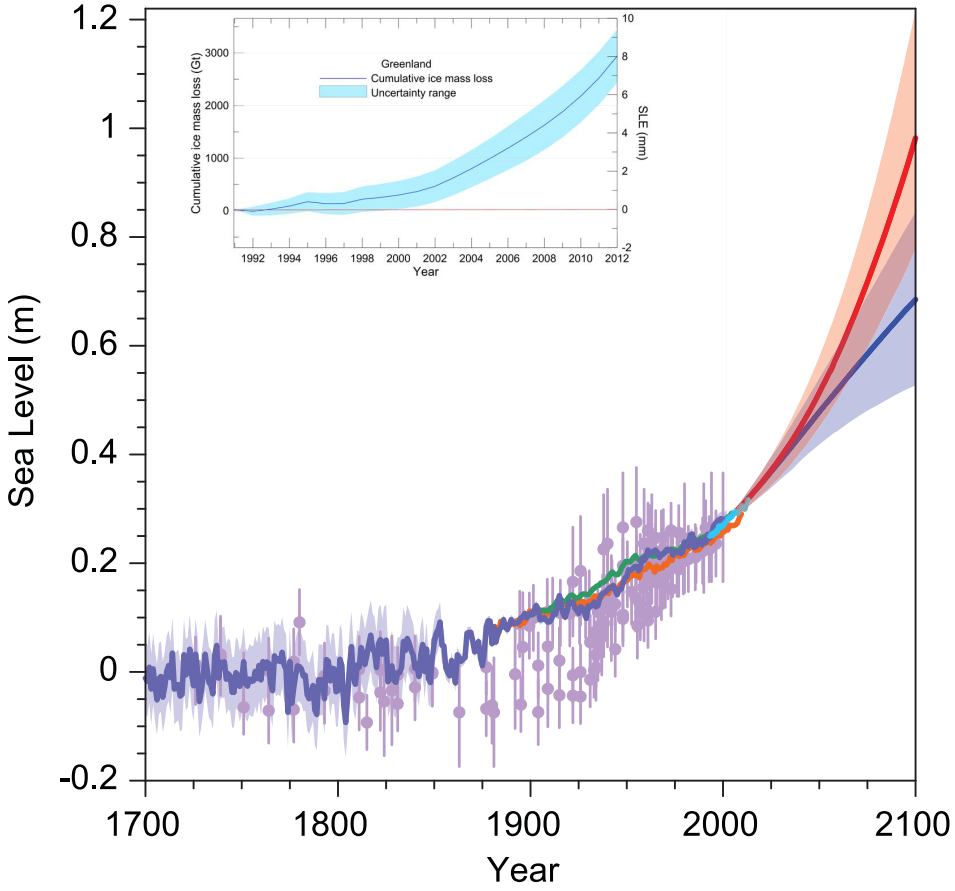
- Finish non-hydrostatic implementation,
- Add orography
- Integrate with various "column physics" to observe refinement behavior
- Support "grid insensitive," time-accurate physics parameterizations



Projections of Sea Level Rise



IPCC Sea-Level Projections



- Projections 3x over AR4.
- Land ice sheets contribute 1/3 of total by 2100.
- Land ice contributes are dominant on long term.
- Long-range sea-level rise is about 2.3 meters/^{o}C.

IPCC AR5 Fig. 13.27

Motivation: Future Sea Level Rise (SLR)

Projections: For RCP8.5, [projected] global mean SLR for 2081–2100 (relative to 1986–2005) [is] 0.45–0.81 m … range at 2100 is 0.53–0.97 m

Based on current understanding, only the collapse of marine-based sectors of the Antarctic ice sheet, if initiated, could cause [21st century *SLR*] substantially above the likely range

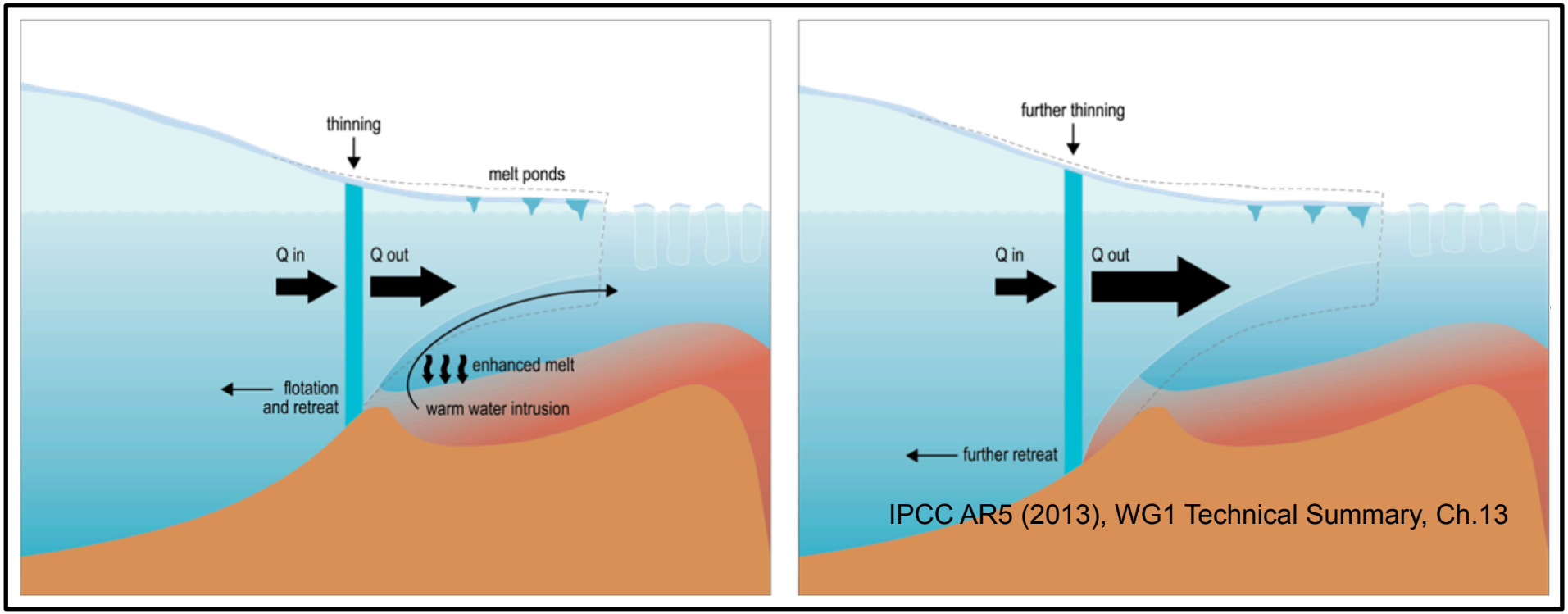
Paleoclimate record:

Pliocene warm intervals: CO_2 levels 250-400 ppm; temperatures 2°C to 3.5°C warmer than pre-industrial; records suggest deglaciation of West Antarctica and parts of East Antarctica *with global mean sea level not >20 m above present*

Last Interglacial: global temperatures were not more than 2°C above pre-industrial; global mean sea level at least 5 m higher than present; Greenland likely contributed 1.4 - 4.3 m*, implying a contribution from Antarctica*

IPCC AR5 (2013), WG1 Technical Summary

Motivation: Future Sea Level Rise (SLR)



Observations and modeling argue for the importance of ice-ocean interactions in causing changes in submarine melt rates, with consequent dynamic ice sheet response, including grounding line retreat and increased mass flux to the oceans.[1, 2]

[1]Joughin & Alley (*Nat. Geosc.*, **4**, 2011) [2] Straneo et al. (*BAMS*, **94**, 2013)

Previous Work (mainly Antarctic)

*** Previous work exploring coupled ice-ocean evolution:

- idealized, stand-alone ocean modeling
- idealized, stand-along ice sheet modeling
- realistic, low / high res., stand-alone ocean modeling
- realistic, low / high res., stand-alone ice sheet modeling
- idealized, fully coupled ice-ocean modeling

Goal of current work: realistic, high resolution, fully coupled ice-ocean modeling

*** Grosfeld et al. (1997); Holland & Jenkins (2001); Walker et al. (2007,2008); Losch (2008); Holland et al. (2008); Thoma et al. (2008); Pollard et al. (2009); Joughin et al. (2010); Yin et al. (2011); Cornford et al. (2012); Mueller et al. (2012); Schodlok et al. (2012); Heimbach & Losch (2012); Goldberg et al. (2012a,b); Gladish et al. (2012); Little et al. (2012); Hellmer et al. (2012); Timmerman et al. (2013); Kushara et al. (2013); Sergienko et al. (2013a,b); Parizek et al. (2013); Wilson (2013); Robinson (2013) … plus many more.

Ice Sheet Model: BISICLES

"L1L2" momentum balance [1]

- formally 1st-order approximation to Stokes equations [2]
- velocities: 2d elliptic solve + SIA vertical column solve

Block-Structured AMR for improved accuracy in regions of dynamic complexity (e.g., grounding lines)

MISMIP3d [3] – demonstrates grounding line "reversibility" with results very similar to simulations using high-resolution Stokes [4]

Optimization on sliding param. & ice softness to match obs. vels.

Coupled to Community Ice Sheet Model (CISM)

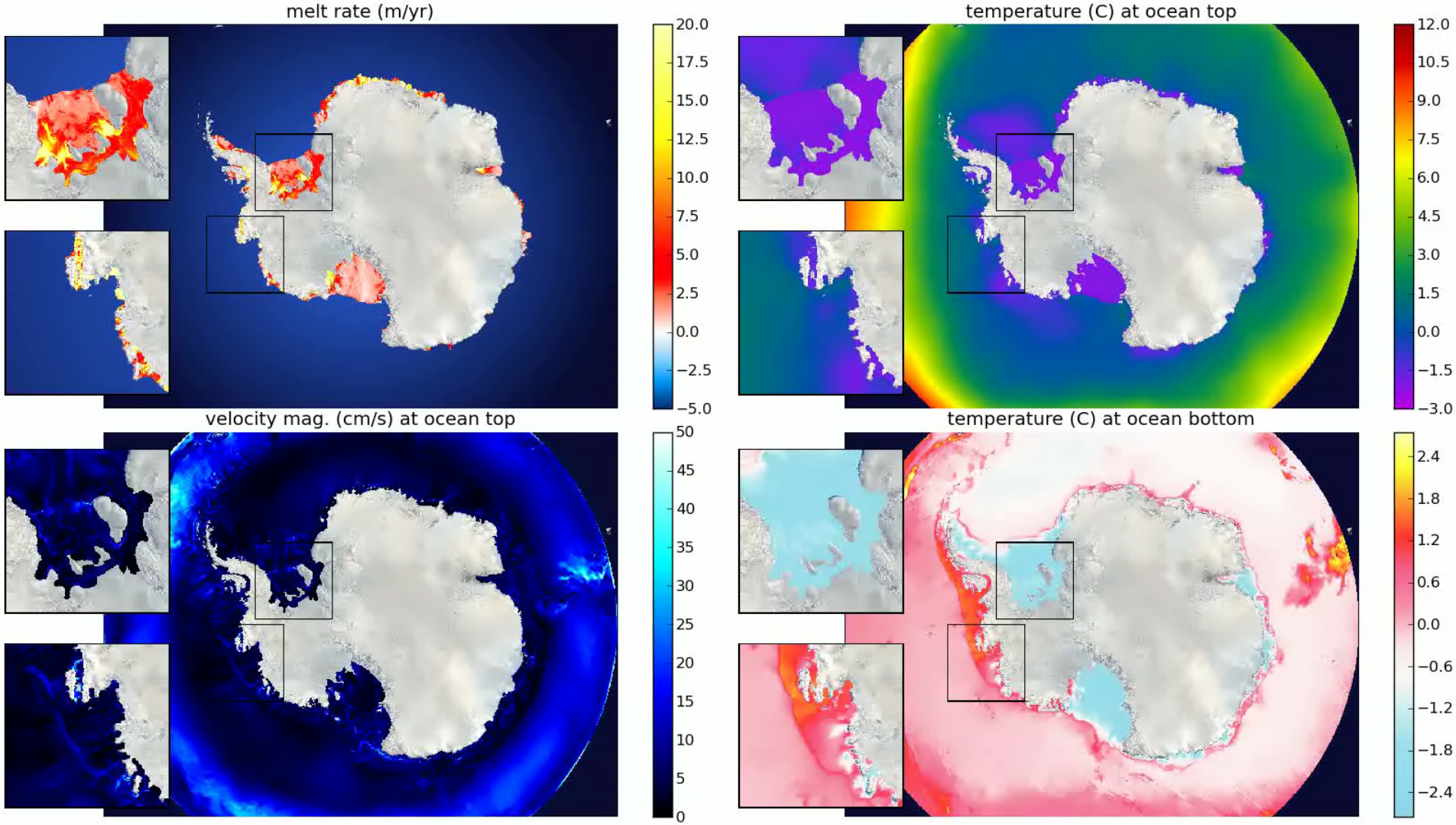
[1]Cornford et al. (2012); [2]Schoof and Hindmarsh (2010); [3]Pattyn et al. (2013); [4]Pattyn & Durand (2013)

Ocean Model: POP2x

- POP2 = **P**arallel **O**cean **P**rogram version 2 (hydrostatic, Boussinesq, primitive equations)[1]
- z-level vertical coordinate, partial bottom cells
- "x" = eXtended to include ice shelf cavity circulation using partial top cells[2]
- sub-shelf mixed layer thickness = dz (vert. mixing scheme[2], not physics based)
- For idealized experiments[2], sub-shelf circulation in POP2x compares very well with previously published results

[1]Smith et al., (2010); [2]Losch (2008)

Realistic uncoupled experiments

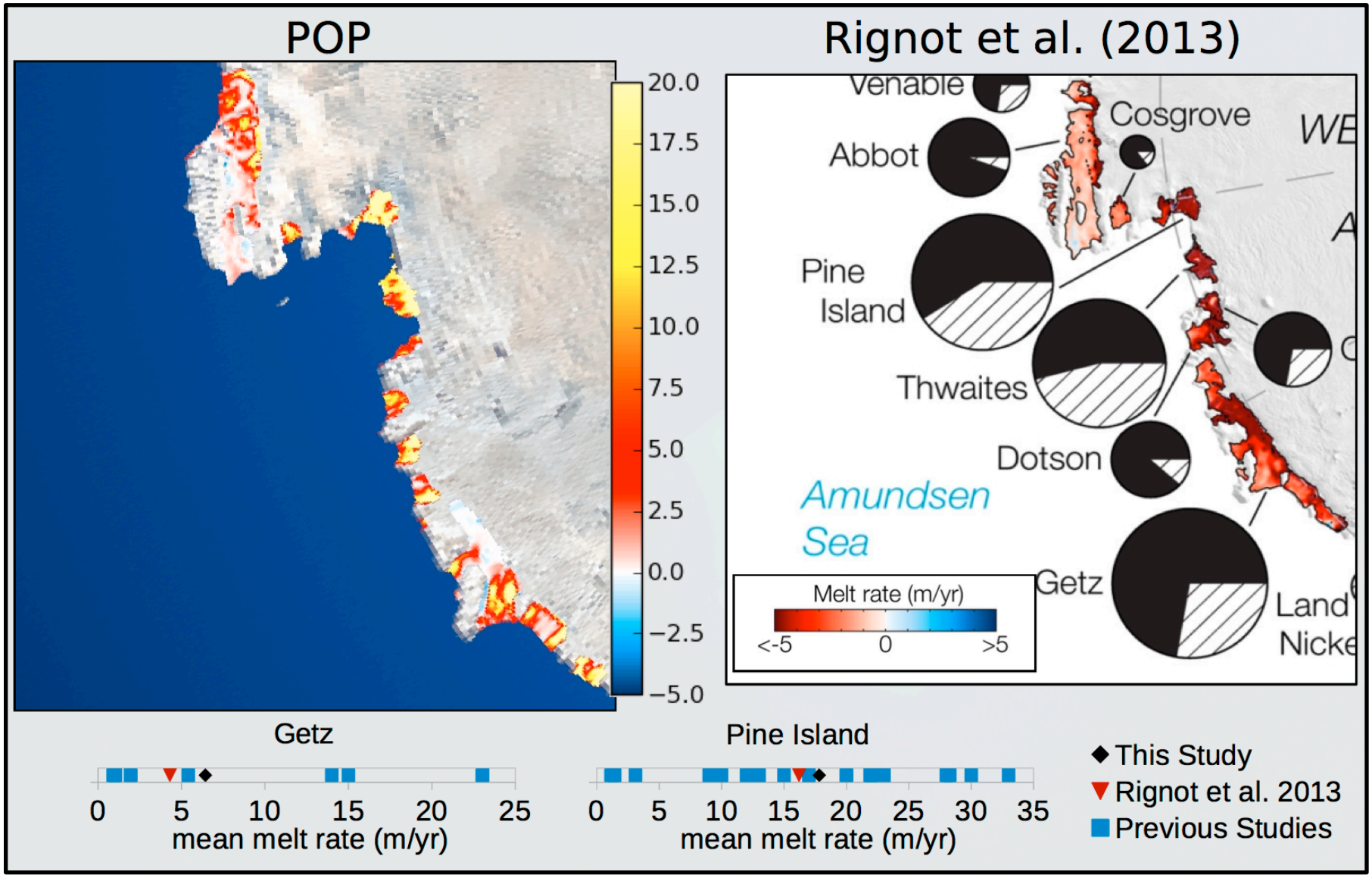


Amundsen Sea Embayment Simulation



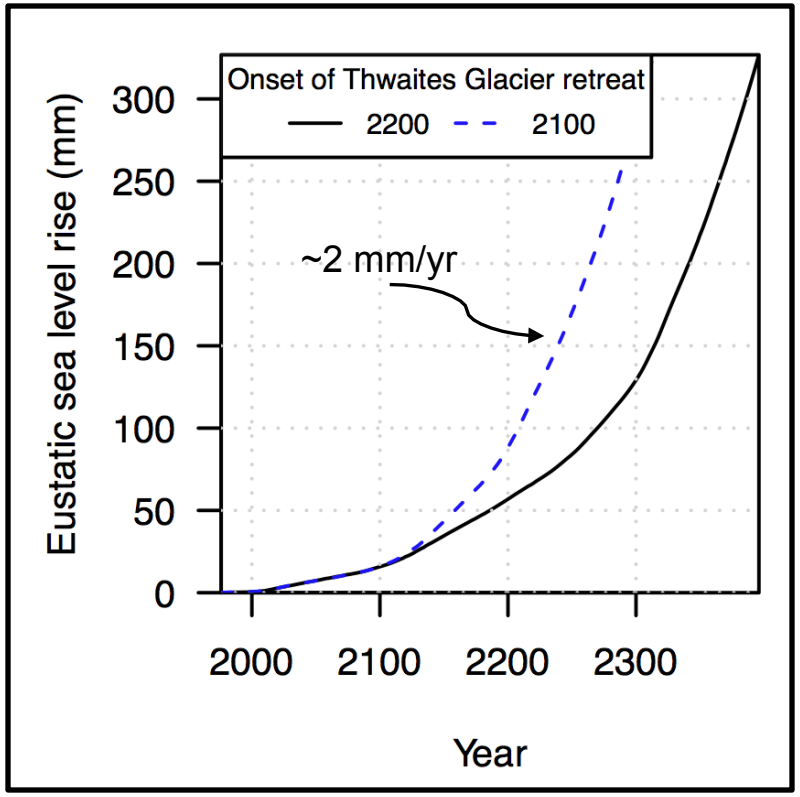
Movies courtesy of S. Cornford and D. Martin

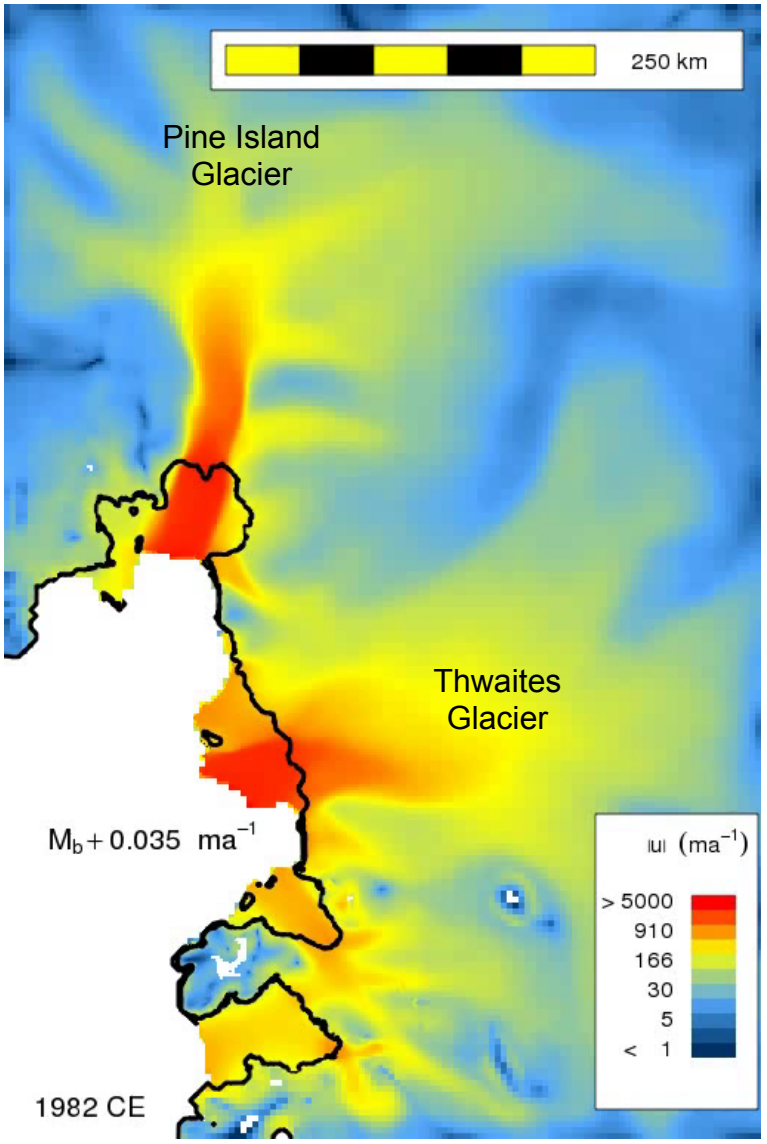
POP2x: realistic experiments (uncoupled)



Amundsen Sea Embayment Simulation

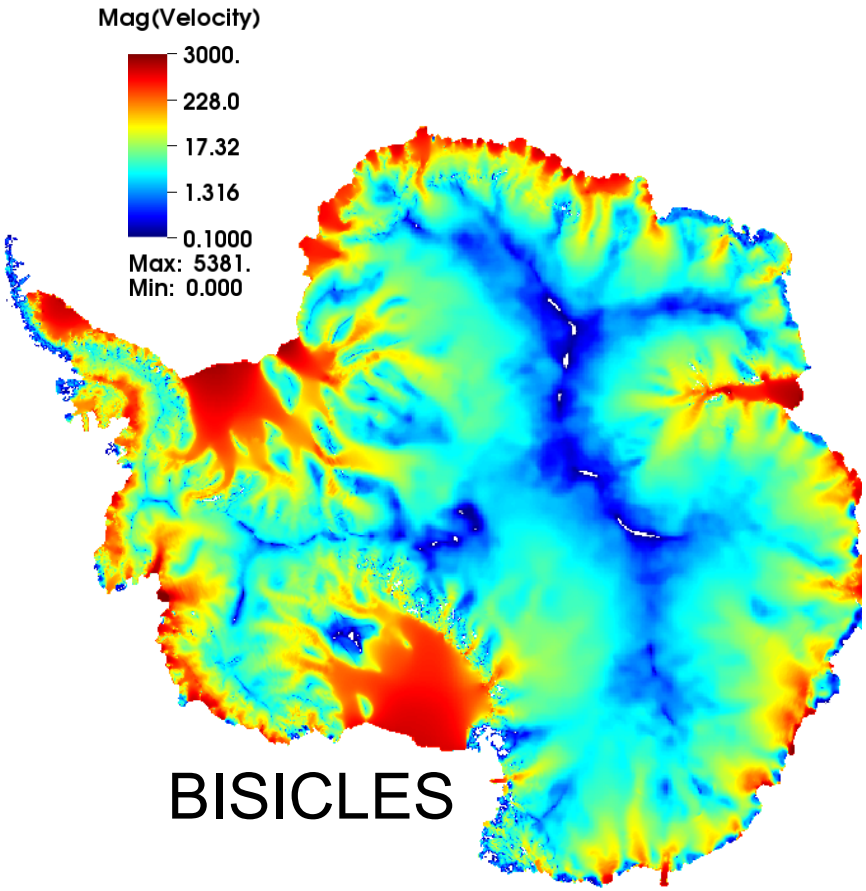
- Same forcing as previous run with submarine melting constant after 2200
- In +400 yr run, Thwaites fairly stable (until it's not)





Movies courtesy of S. Cornford and D. Martin

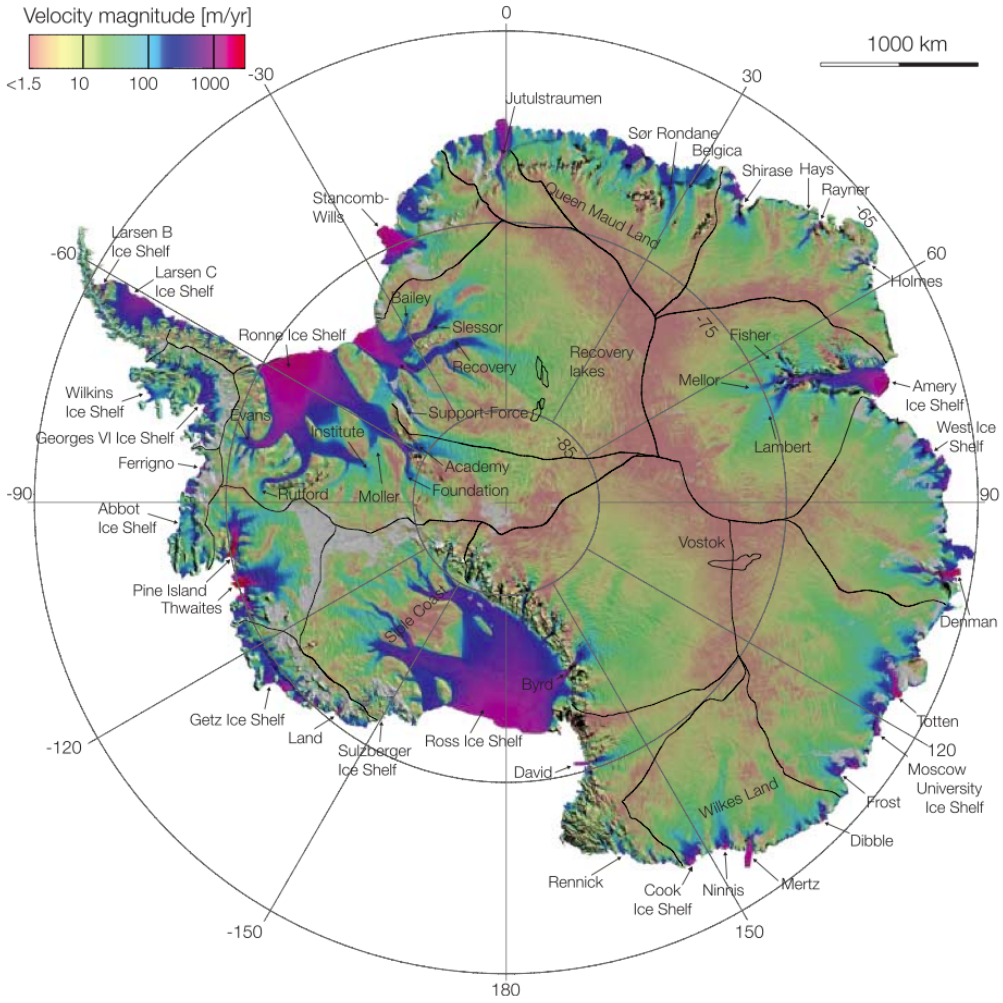
Whole Antarctic Ice Sheet Simulations



BISICLES

- base level res. of 5 km, refinement to 625 m -

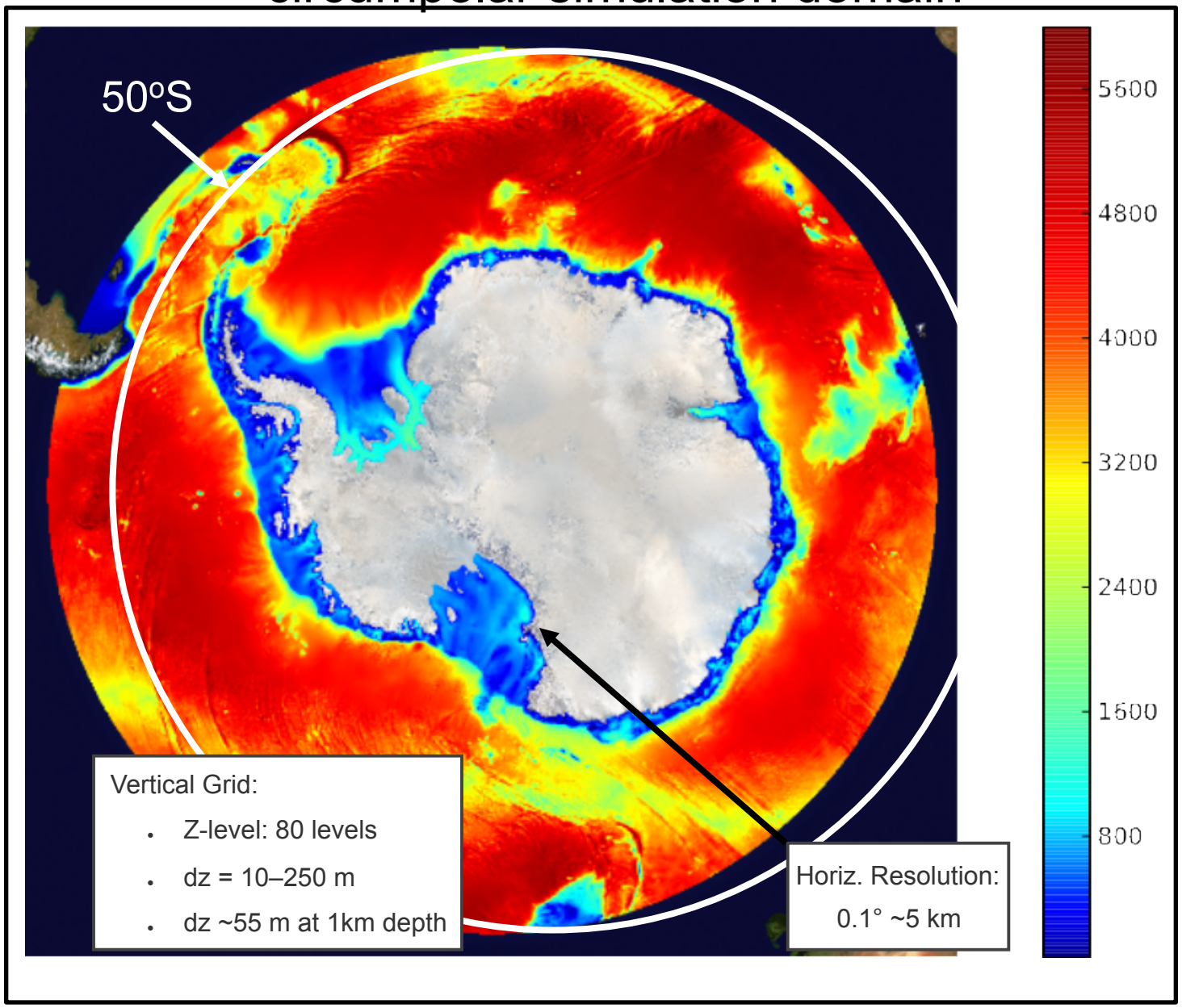
(courtesy of D. Martin & S. Cornford)



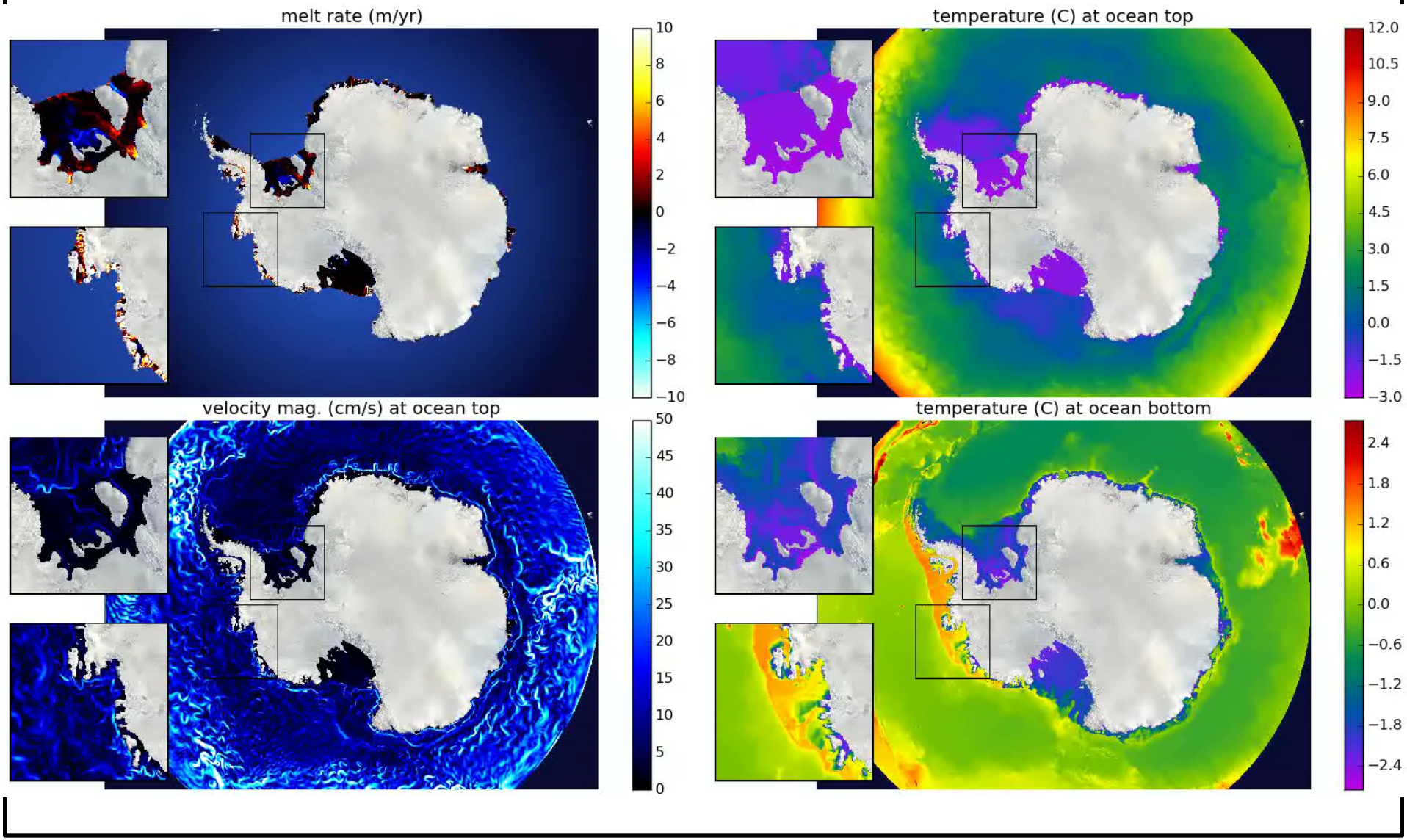
Rignot et al., *Science*, **333** (2011)

POP2x: realistic experiments (uncoupled)

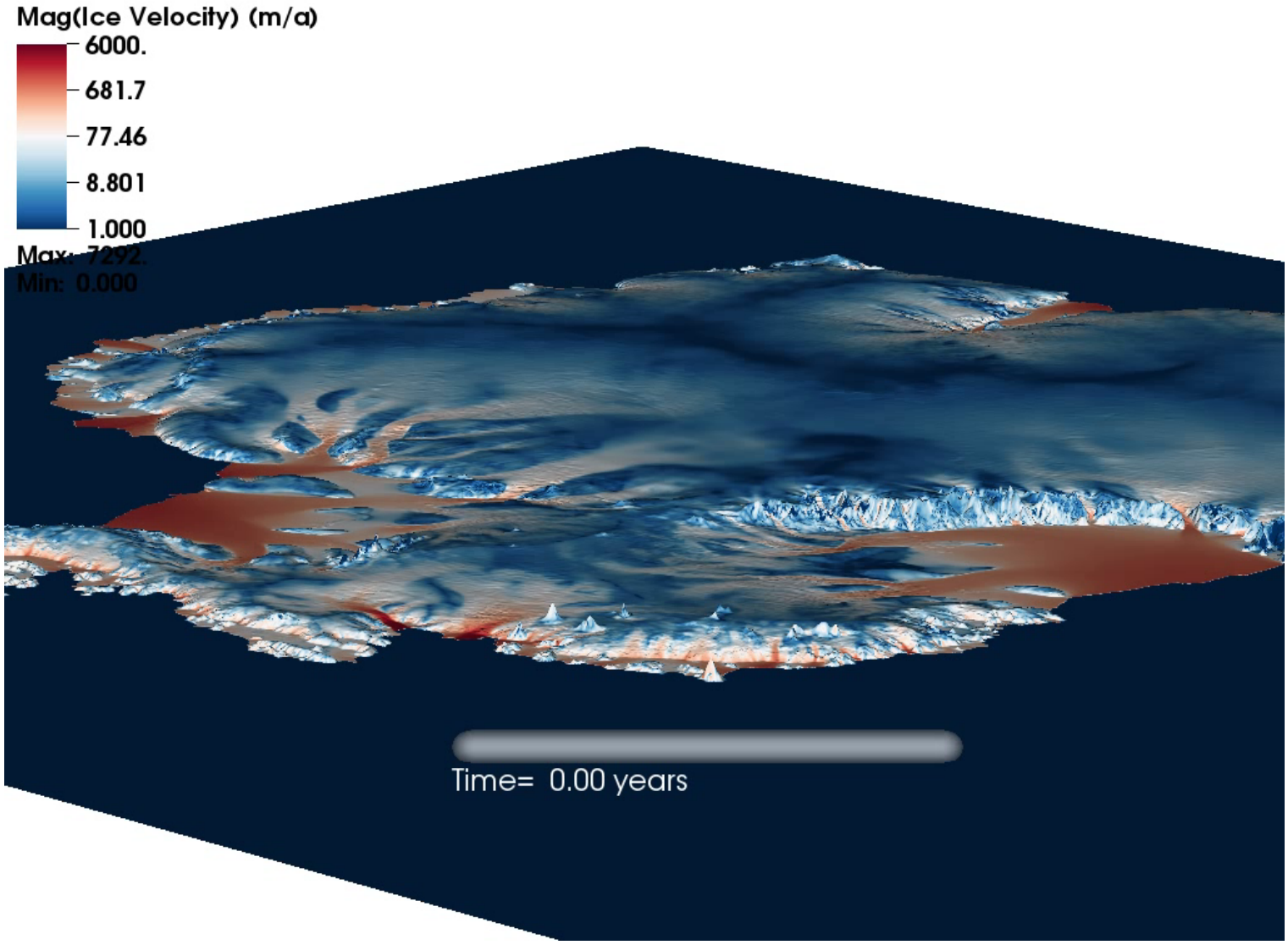
circumpolar simulation domain



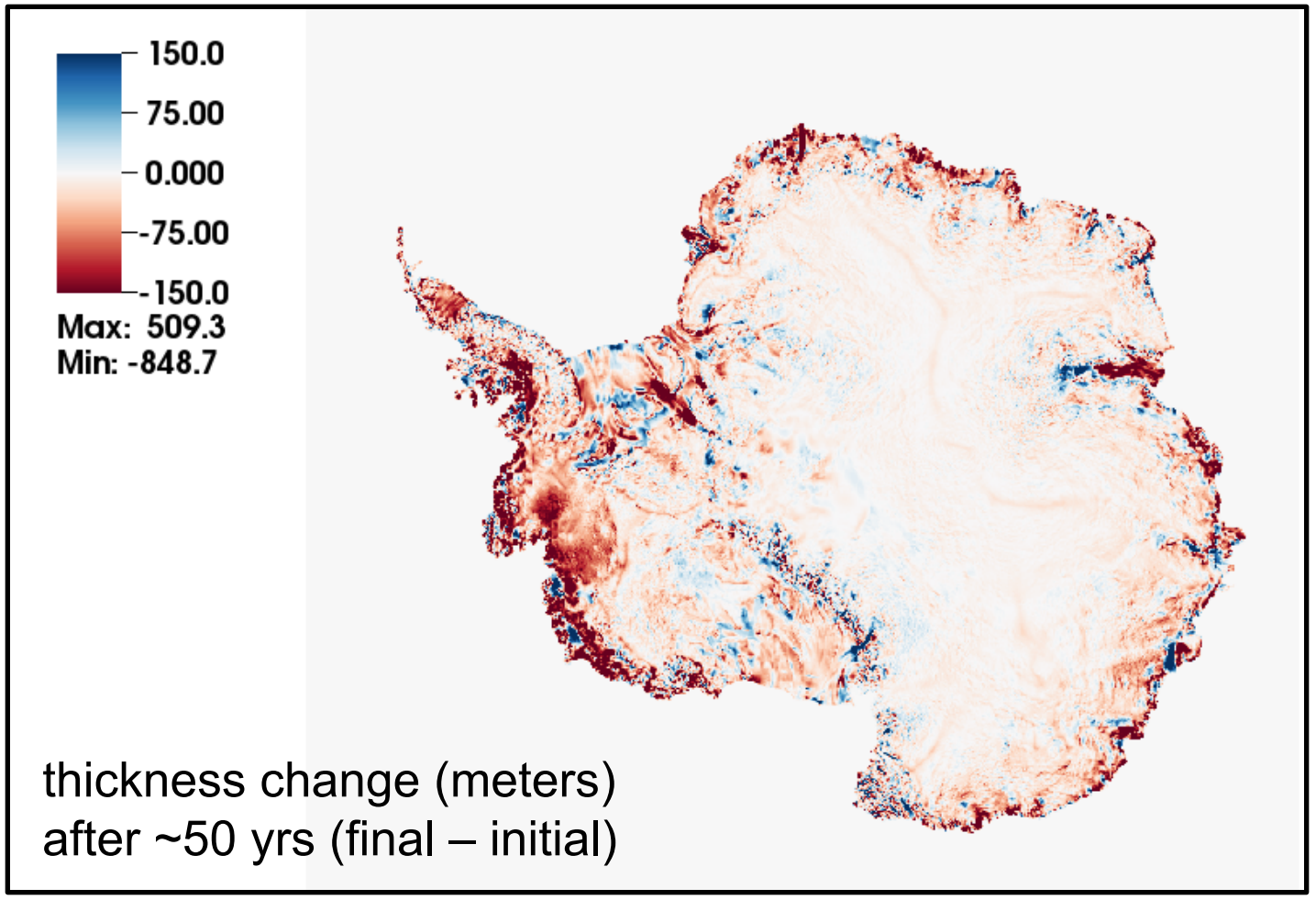
Fully coupled ocean/land-ice experiments



Coupled, realistic experiments (8 yrs)



Antarctic Volume Change: BISICLES + POP2x



Summary & Future Work

High-resolution, whole-Antarctic forward model integrations with realistic, large-scale ocean-model forcing are stable on decadal (to century?) timescales

Future work will focus on:

- Correcting ocean-model biases
- Validation of ice sheet, ocean, and coupled model output
- Coupled, forward model integrations under range of RCPs
- Static shelf coupling in CESM? (active ocean + data ice sheet)
- Development of ice-ocean coupling capability in MPAS-Ocean