Space-Time Adaptivity For Exascale Climate

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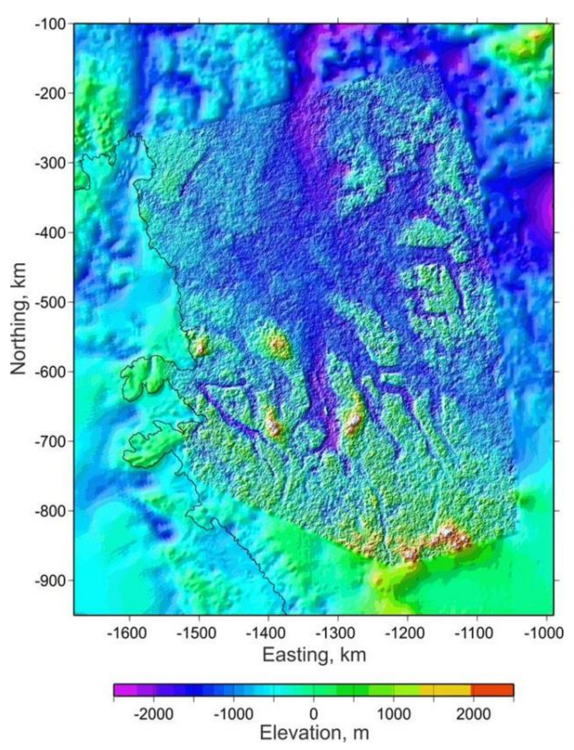
Need for Adaptivity in Climate

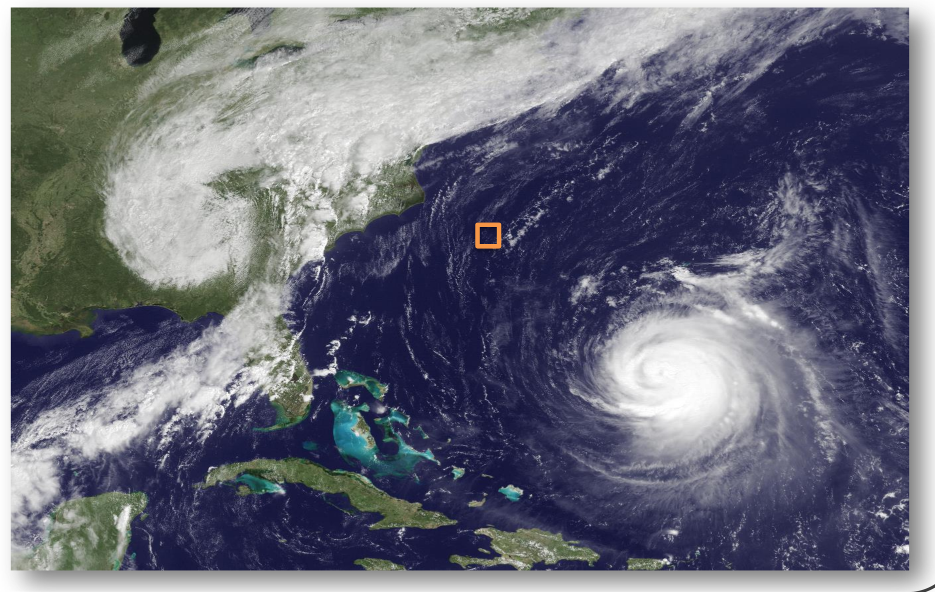


Many problems in climate exhibit large variations in spatial and temporal scales. At the same time, complex climate science applications typically use all the available computing resources to resolve features, dynamic processes, and assumptions.

Space-time adaptivity will benefit climate codes running on exascale machines by:

- More-efficient use of resources by deploying computational effort where needed
- Greater resolution of dynamic features (squall lines, atmospheric rivers, grounding lines)
- Grid refinement studies for new physics models (parameterizations) and geographic features
- Evaluation of time discretization errors

ABOVE: Thwaites Glacier (Antarctica) -- high-resolution (250 m) inner bed grafted onto lower-resolution 1km-resolution Bedmap2 bed.



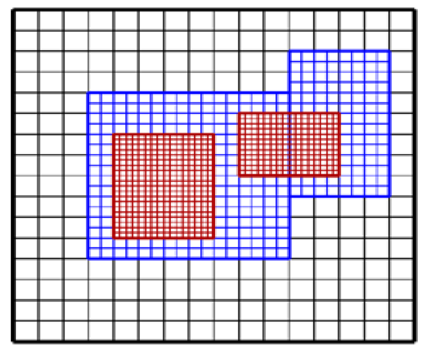
RIGHT: Tropical cyclones Lee and Katia (on 9/6/11). The box is the typical grid cell of a global climate model (~150km), too coarse to accurately predict TC dynamics. This can bias the spatial distribution of important climate statistics.

AMR + Higher-order for Efficiency

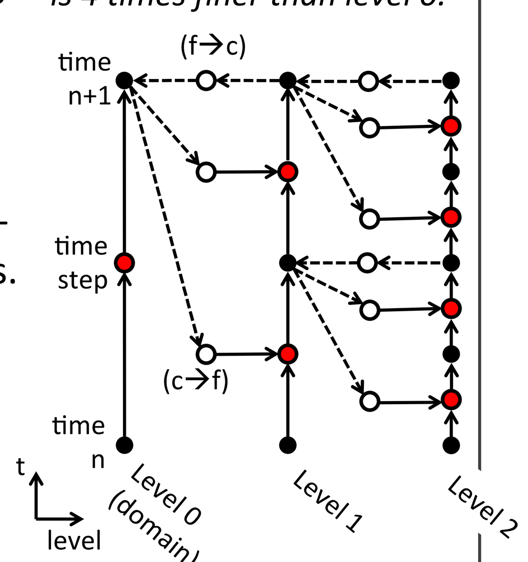
Many climate applications have localized requirements for high spatial and temporal resolution, making them ideal candidates for Adaptive Mesh Refinement (AMR). AMR dynamically refines computational meshes where needed to improve accuracy and resolve local dynamics, leading to more efficient usage of computational resources.

- Block-structured AMR can be made very efficient by using logically-rectangular mesh patches, so that regular-mesh operations make up the majority of the computation.
- Irregular operations confined to enforcing relevant coupling between coarse and fine meshes at coarse-fine interfaces.
- Use of higher-order (4th-order) discretizations increases floating-point intensity and improves errors significantly.
- Complex geometry can be represented using an Embedded-Boundary (EB) cut cell approach with AMR, to reduce errors.
- Block-structured AMR can refine in time, too: fine-mesh solutions are updated using a finer timestep (for accuracy and stability) without limiting the time step for the entire domain (due to the stability requirements).

Chombo (http://chombo.lbl.gov) is a high-order massively scalable finite-volume framework for robust and accurate solution of PDE's in arbitrary geometry. Chombo also provides a block-adaptive adaptive mesh refinement (AMR) capability for feature isolation and tracking.



ABOVE: Sample AMR meshes – black mesh is base level (0), blue mesh (level 1) is a factor of 2 finer, while red (level 2) is 4 times finer than level 0.

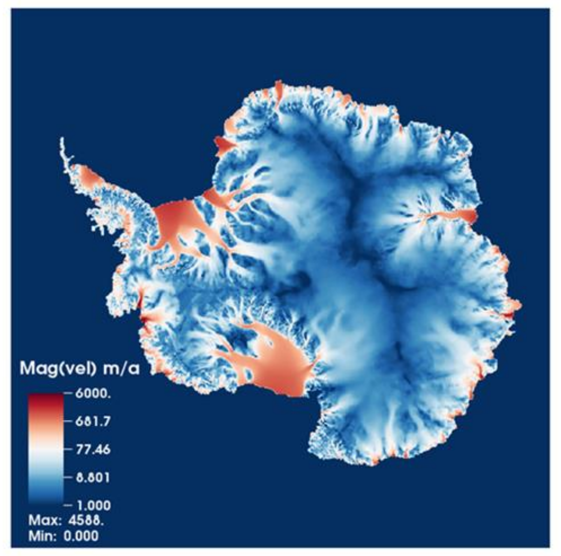


ABOVE: Space and time refinement creates complex communication and computation dependencies, implemented in Chombo.

The Case for AMR: Ice Sheet Dynamics

Resolution and Sea Level Rise: Mass loss from the large ice sheets of Antarctica and Greenland is expected to be a major contributor to sea level rise (SLR) over the next century and beyond.

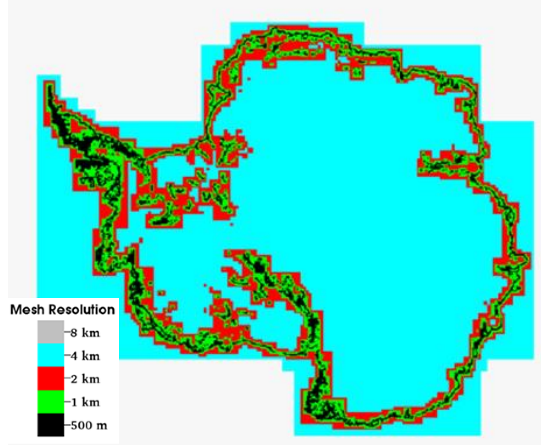
- The West Antarctic Ice Sheet (WAIS) is a *marine ice sheet* - organized into fast-flowing ice streams flowing to the ocean, eventually crossing the *grounding line (GL)* (where the ice begins to float), and feeding into enormous floating ice shelves, which buttress and hold back the feeder streams.
- Antarctic response to climate forcing is dominated by marine ice sheet instability -- warm-water incursion into subshelf cavities melts and eventually destroys ice shelves, weakening buttressing, which causes increased flow speeds, ice sheet thinning, and grounding-line retreat.
- Much of WAIS sits on bedrock below sea level, making it extremely vulnerable. ***3-5m of SLR*** is possible from WAIS collapse alone.
- Very fine spatial resolution (better than 1 km) is needed to resolve dynamic features like grounding lines and ice streams – under-resolution has been demonstrated to *under-predict* GL retreat and contribution to SLR. (Cornford, Martin, et al, 2016, Pattyn, et al, 2013)
- High cost of such fine resolution combined with large regions where such fine resolution is unnecessary – ***variable resolution*** is essential.
- Rapid and unpredictable GL retreat (potentially sweeping all of WAIS) – ***dynamic adaptivity (AMR)*** also essential.



BISICLES Antarctic ice velocities.

AMR for Ice Sheets: BISICLES

- **BISICLES** is a Chombo-based scalable AMR ice sheet model able to apply very fine mesh resolution only where needed to resolve ice sheet dynamics.
- Recent work (Cornford, Martin, *et al*, 2016) demonstrates importance of sufficient resolution and AMR.



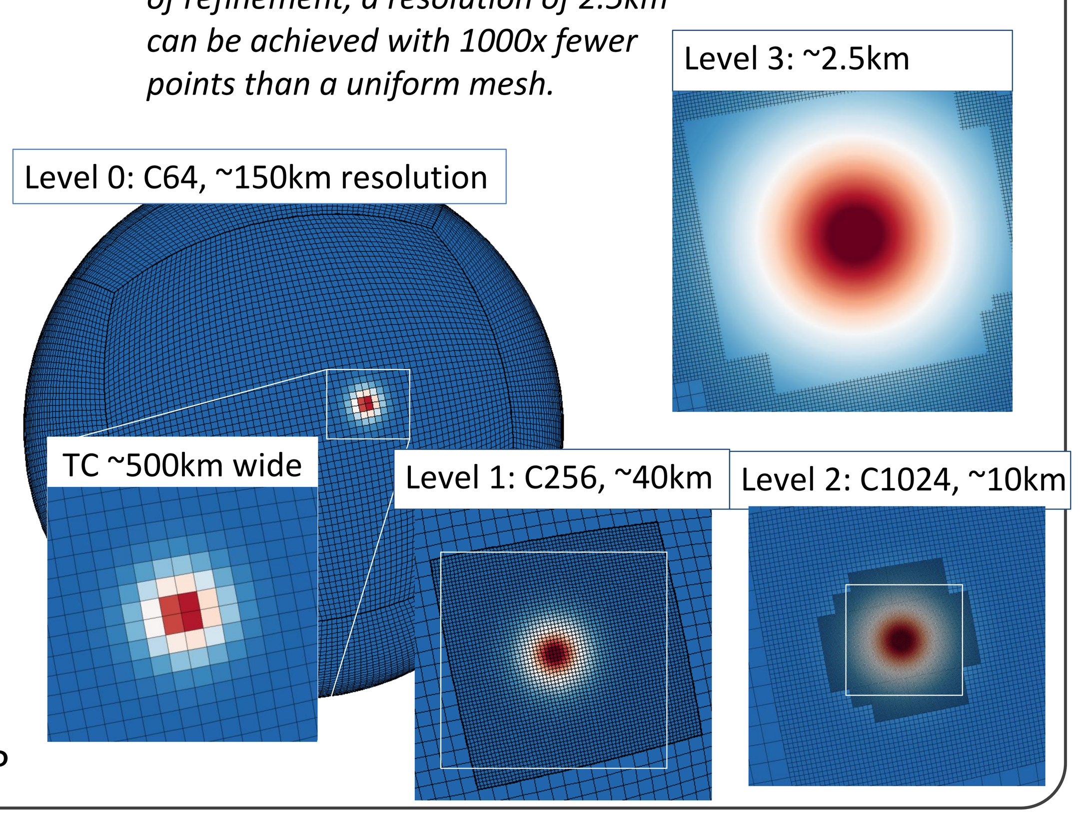
AMR benefits: Only ~1% of domain is covered with 500m mesh (in black). In many scenarios, refined meshes sweep over much of the WAIS as they follow retreating grounding lines.

The Case for AMR: Atmospheric Dynamics

AMR is being evaluated for atmospheric dynamics using a suite of 2D and 3D test problems, to verify accuracy and robustness.

- Non-hydrostatic Euler on cubed sphere mesh
- 4th-order, conservative spatial discretization
- Implicit-explicit time integration scheme for acoustic wave stability
- Adaptive refinement in both space and time
- Strong scaling to 100k cores with MPI+OpenMP

BELOW: AMR-based simulations can greatly improve resolution of a tropical cyclone. With only 3 levels of refinement, a resolution of 2.5km can be achieved with 1000x fewer points than a uniform mesh.



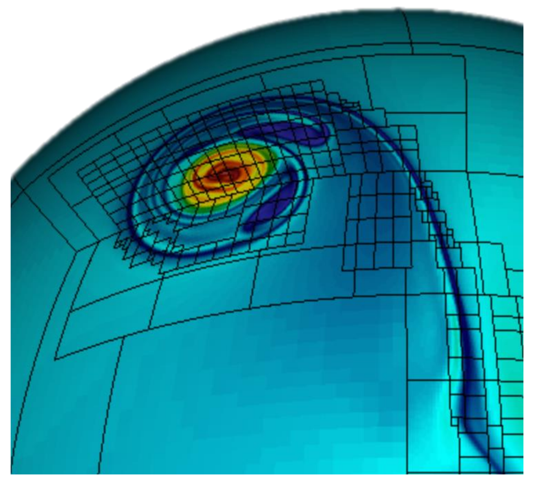
Benefits and Challenges

Next-generation exascale computing promises a revolution in our ability to fully resolve the processes which define our climate, if we use AMR methods:

- Uniform refinement over the entire domain wastes computational resources and leaves the solution under-resolved, thus requiring sub-grid parameterizations.
- Higher-order methods combined with AMR can ensure that computational resources are used as efficiently as possible to fully-resolve the relevant physics, while dynamically adapting to changes in the system.
- Efficient, high-order adaptive finite-volume methods can more accurately represent orography (with cut cells) and boundaries.
- Greater space-time resolution of dynamic features and extreme events becomes possible.

Primary challenges for AMR techniques include:

- Software infrastructure to support complexity
- High-resolution observational data sets for initialization, boundary conditions, and validation.
- Efficient refinement criteria for multi-physics
- Weak scaling for some operations, load balancing



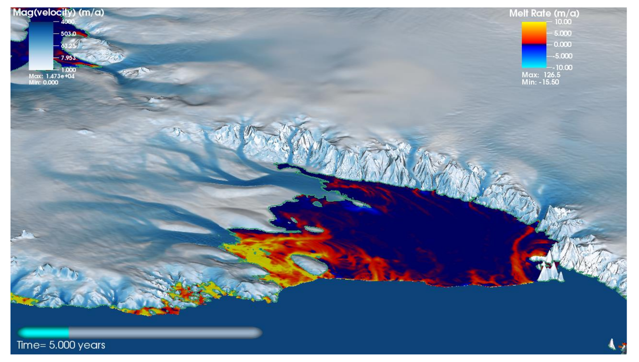
ABOVE: AMR-based simulations of vortex interactions in a shallow water equation simulation.

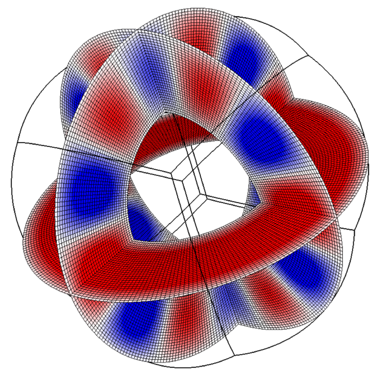
Exascale Research Directions

Future opportunities for this technology in climate applications include surface/subsurface hydrology, oceanography, and extreme weather.

To ensure that AMR remains computationally efficient at scale on emerging architectures, research directions must include:

- Load balancing dynamic calculations, mitigated by asynchronous communication.
- Better strong scaling for coarse grid work (solvers, coarse time step advances, etc.)
- Better algorithms for blocking/collectives (regridding, time step synchronization, etc.)
- Efficient implementations of mixtures of regular and irregular calculations as they arise in multiblock, AMR, and cut-cell discretizations
- Effective use of hierarchical parallelism, performance portability across many-core and GPU-based architectures





Above: Frame from POPSICLES coupled Antarctic ice-ocean simulation.
Left: Cut-away of a cubed sphere atmospheric test problem.

For More Information

Contact Dan or Hans via email (above), or follow this QR code:

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