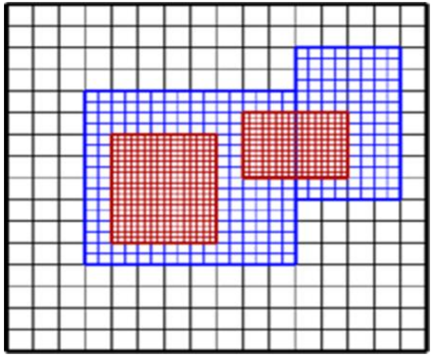
Space-Time Adaptivity for Climate Modeling

Daniel Martin[1], Hans Johansen[1], Will Thacher[1], Esmond Ng[1], Stephen Cornford[2], Edward Santilli[3], Alberto Scotti[4], James Parkinson[5]

1. Lawrence Berkeley National Laboratory, Berkeley, CA
2. Swansea University, Swansea, U.K.
3. Jefferson University, Philadelphia, PA,
4. University of North Carolina, Chapel Hill, NC,
5. Oxford University, Oxford, U.K.

Adaptivity for Accuracy and Efficiency

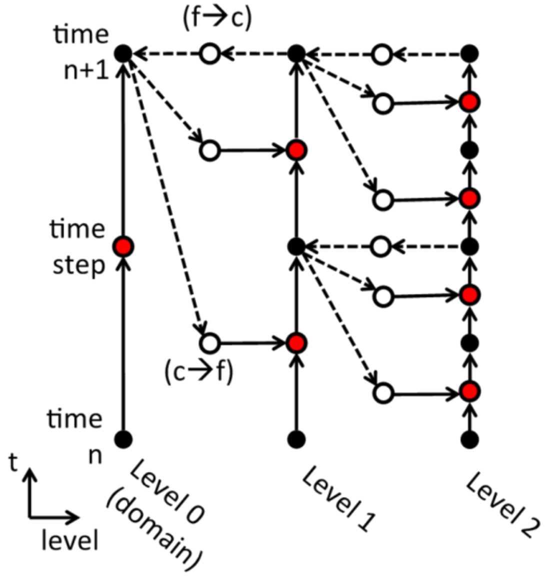
- **Many climate applications have localized requirements for high spatial and temporal resolution, making them ideal candidates for Adaptive Mesh Refinement (AMR). AMR dynamically refines computational meshes where needed to improve accuracy and resolve local dynamics, leading to more efficient usage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



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.

Adaptivity for Accuracy and Efficiency (cont)

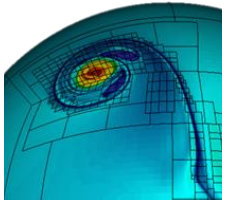
- **Complex geometry can be represented using an Embedded-Boundary (EB) cut cell approach with AMR, to reduce errors.**
- **Block-structured AMR can refine in time, too: fine-mesh solutions are updated using a finer timestep (for accuracy and stability) without limiting the time step for the entire domain (due to the stability requirements).**

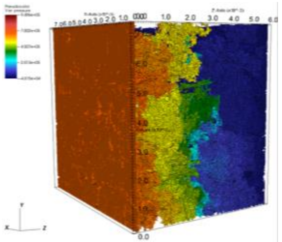


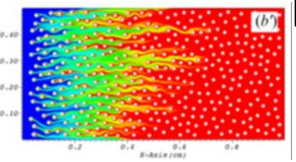
Space and time refinement creates complex communication and computation dependencies, implemented in Chombo

Chombo – Scalable Adaptive Mesh Refinement (AMR)

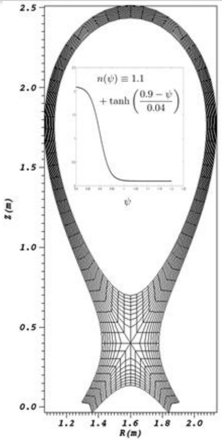
Scalable adaptive mesh refinement (AMR) framework.
Enables implementing scalable AMR applications with support for complex geometries.

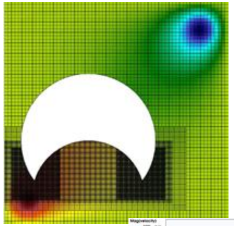




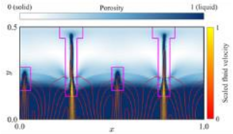


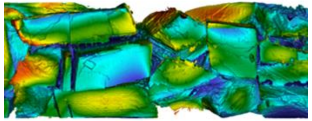
- **Adaptive Mesh Refinement (AMR)**
  - Block structured AMR dynamically focuses computational effort where needed to improve solution accuracy
  - Designed as a developers' toolbox for implementing scalable AMR applications
  - Implemented in C++/Fortran
  - Solvers for hyperbolic, parabolic, and elliptic systems of PDEs
- **Complex Geometries**
  - Embedded-boundary (EB) methods use a cut-cell approach to embed complex geometries in a regular Cartesian mesh
  - EB mesh generation is extremely efficient
  - Structured EB meshes make high performance easier to attain
- **Higher-order finite-volume**
  - Higher (4th)-order schemes reduce memory footprint and improve arithmetic intensity
  - Good fit for emerging architectures
  - Both EB and mapped-multiblock approaches to complex geometry

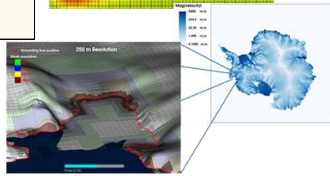




http://Chombo.lbl.gov





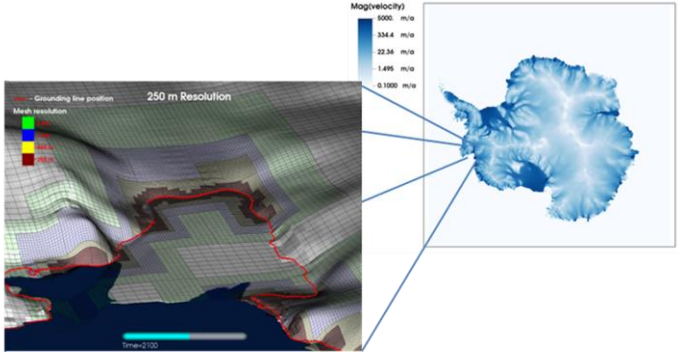


BISICLES for Ice Sheets

Model 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.**

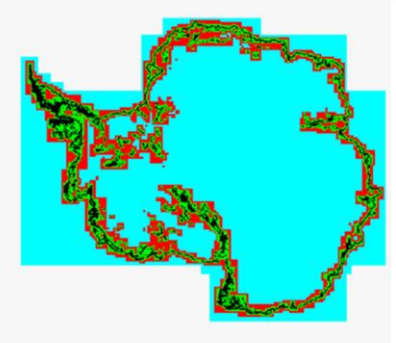
- **The West Antarctic Ice Sheet (WAIS) is a *marine ice sheet* - organized into fast-flowing ice streams flowing to the ocean, eventually crossing the *grounding line (GL)* (where the ice begins to float), and feeding into enormous floating ice shelves, which buttress and hold back the feeder streams.**



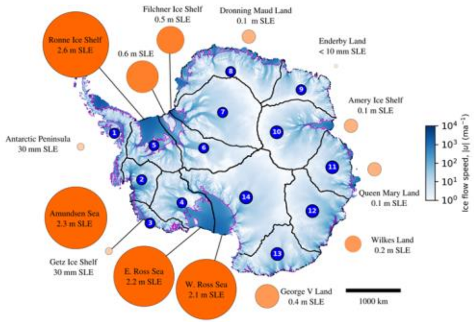
BISICLES-computed Antarctic ice velocity field. (inset) close-up of the Pine Island Glacier showing local mesh refinement near grounding line (red line).

BISICLES for Ice Sheets

- 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*** **) is also essential.**



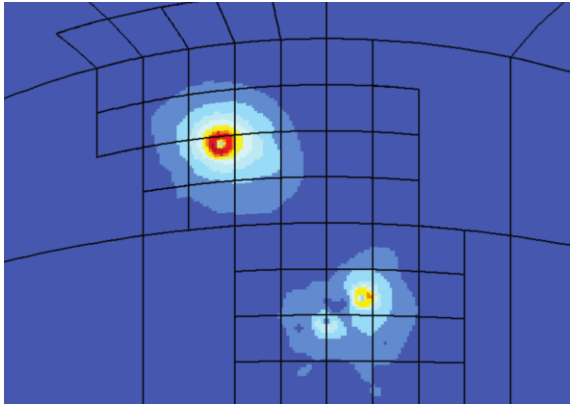
(above) Mesh resolution for BISICLES Antarctic simulations
(below) BISICLES-computed millennial-scale vulnerability to ice shelf collapse



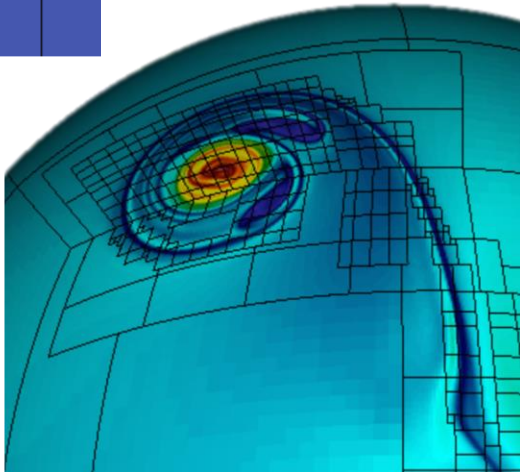
Chombo Atmospheric Dycore

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
- 4^{th}-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
- Implementation in Chombo



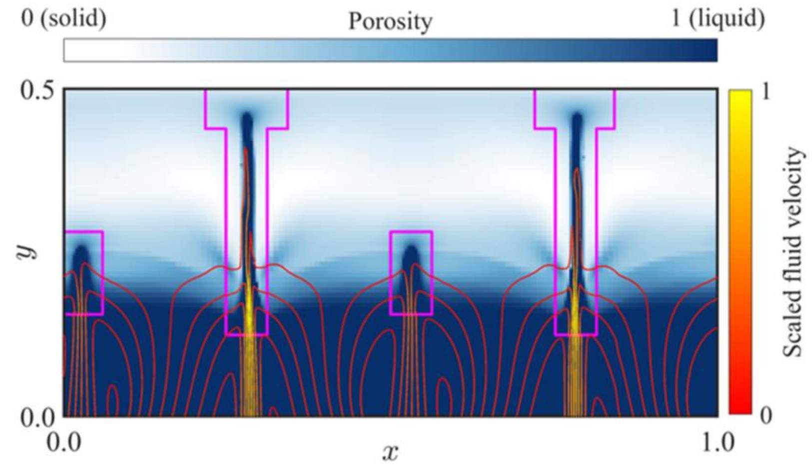
Left: *AMR-based simulations can greatly improve resolution of an idealized tropical cyclone, with only 1 level of refinement. With 3 levels of refinement, a resolution of 2.5km can be achieved with 1000x fewer points than a uniform mesh.*



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

Sea Ice Formation – Brine Rejection Channels

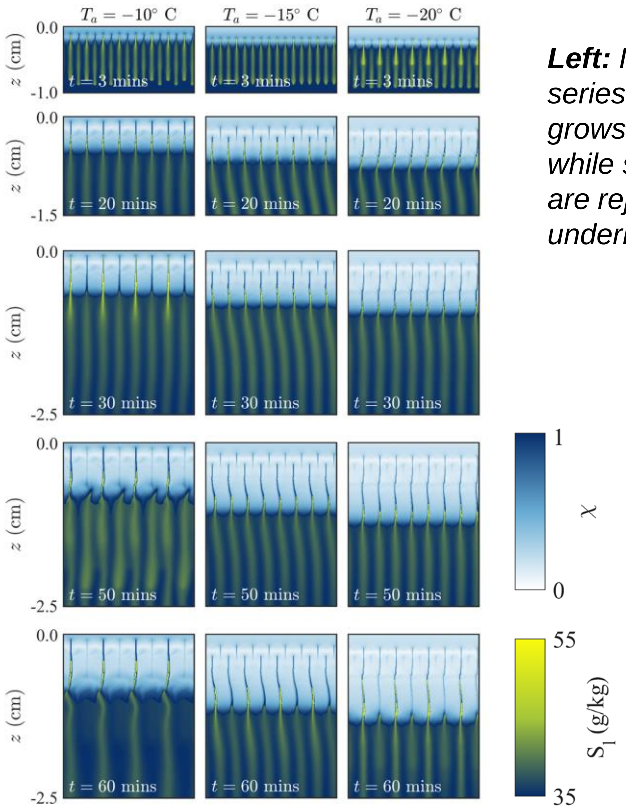
- **Sea ice forms in a mushy layer of ice crystals and brine. Dense and supercooled brine is drained away during ice formation via relatively narrow brine channels**
- **Very fine resolution is required locally to sufficiently resolve brine channels.**
- **Brine channels are formed dynamically as a part of the ice formation process; their locations are not known a priori, making dynamic adaptivity essential.**
- **We are collaborating with researchers at the University of Oxford in the UK to develop a Chombo-based AMR model to simulate these processes.**



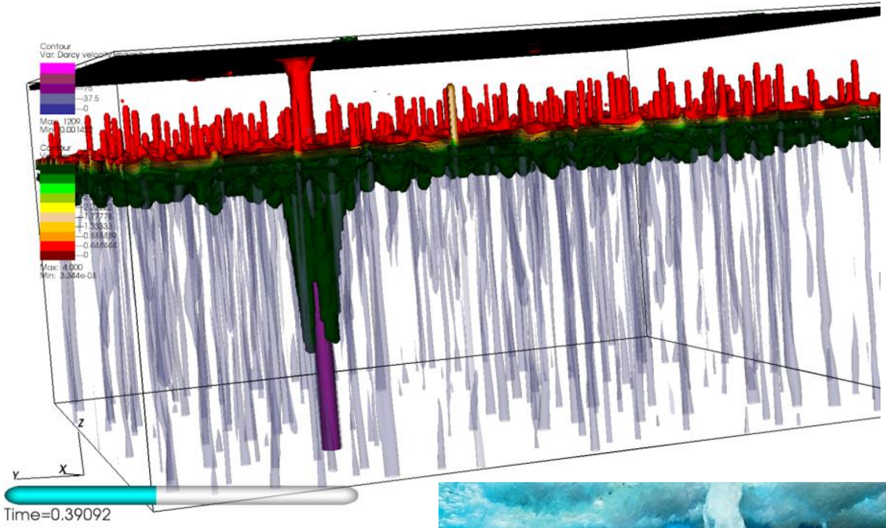
ABOVE: AMR mushy-layer calculation showing adaptive refinement around brine channels.

Ref: Parkinson, Martin, Wells, and Katz, “Modelling binary alloy solidification with Adaptive Mesh Refinement”, *JCP (2020).*

Brine Rejection Channels (cont)



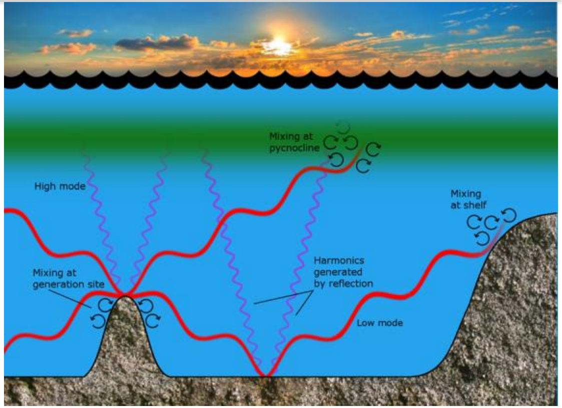
Left: *Ice formation time series. Porous ice (white) grows from the top boundary while salty plumes (yellow) are rejected into the underlying liquid.*



Upper Right: *3D Mushy-layer simulation showing formation of a mega channel draining the upper layer along with an array of smaller brine channels draining the lower part of the mushy layer.*

Lower Right: *Brine mega-channel in nature ("Icy Fingers of Death")* http://www.bbc.com/earth/story/20161219-brinicle-finger-of-death

SOMAR for Ocean Modeling

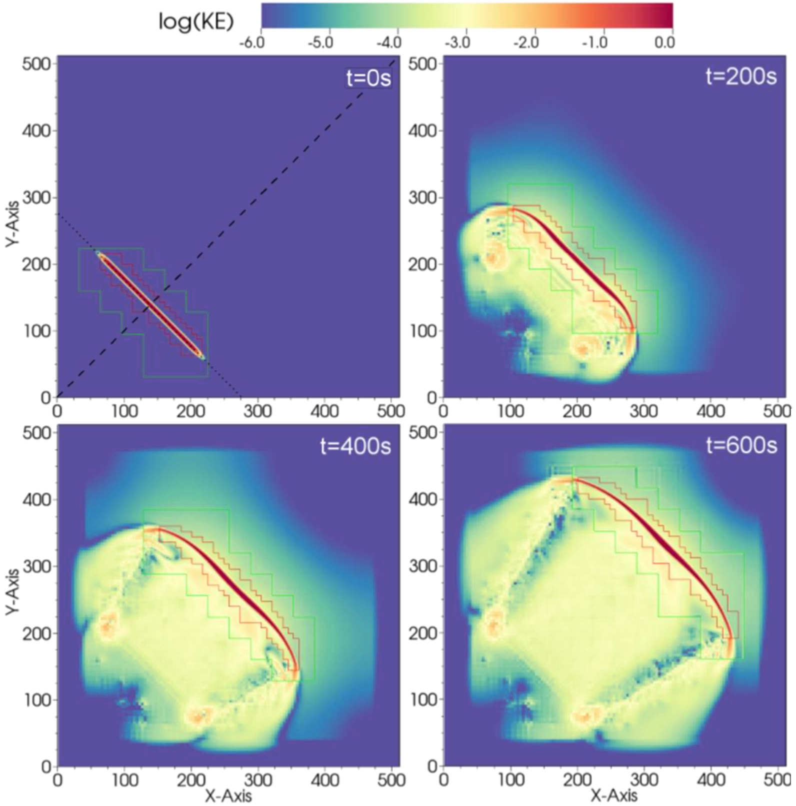


Illustrates the problem SOMAR-LES was designed to model. The coarse level provides the large scale (tidal) forcing, while the fine level LES is used at the mixing locations.

Regional Ocean Modeling

- **Coastal and regional ocean processes span a range of scales from hundreds of kilometers to tens of meters.**
- **The Chombo-based Stratified Ocean Model with Adaptive Refinement (SOMAR) has been developed to apply dynamic mesh adaptivity to ocean modeling, solving the non-hydrostatic, baroclinic flows encountered in regional and coastal ocean simulations.**
- **SOMAR employs a combination of mapped-grid meshes and fully anisotropic adaptive mesh refinement (AMR) to accurately resolve circulation in coastal regions with complex geometries.**
- **SOMAR refines in time as well as space for efficiency.**
- **SOMAR's discretization uses an elliptic solver that is optimized for high-aspect ratio domains *(Santilli and Scotti, 2011)***

SOMAR for Ocean Modeling (cont)



LEFT: *Demonstration of SOMAR's non-hydrostatic capabilities. Initial condition is solution to the 2D Dubreil-Jacotin-Long (DJL) equation placed in a 3D domain (along the dotted line in the first image), extruded, and tapered off at the ends, forming a localized solitary wave along the line y=x. SOMAR solutions illustrate how the wave stays coherent and travels at the correct speed (which is not the advection speed).*

Below: *Internal waves formed by tidal sloshing over a submarine ridge, showing a large overturn and the associated turbulent kinetic energy.*