Scientific Visualization of Antarctica Ice Sheet and Southern Ocean Evolution

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***Abstract*—High-quality visualizations of climate simulations are a critical tool for providing scientific insight and for communication with stakeholders, policy makers, and the public. Here we present results from the cryosphere-ocean visualization project, which brings together experts in scientific visualization with domain scientists in climate, ocean, and land ice modeling. We study Antarctic ice sheet and Southern Ocean simulations with land ice and ocean model components of the U.S. Department of Energy's Energy Exascale Earth System Model (E3SM) in the context of ongoing development towards coupled Antarctic ice sheet simulations in E3SM. We primarily use ParaView and Python for data manipulation, visualization, and analysis. This document accompanies the similarly named Scientific Visualization and Data Analytics Showcase entry video for Supercomputing 2020.**

***Index Terms*—Visualization, Climate Modeling**

I. Introduction

The cryosphere is the part of the earth that is covered with or contains ice. Much of this ice is above sea level and when it melts it ends up in the ocean affecting the global sea level. In Antarctica, the ice is so voluminous that, if it completely melted, sea level could rise more than 60 meters. Ice in Antarctica forms glaciers that flow into the ocean, where it commonly remains attached and continues to flow as expansive sheets of floating ice called ice shelves. Ice shelves act as barriers and can "buttress" inland ice against additional glacial flow into the ocean; when the shelves are thinned or removed, the glaciers inland speed up. The ocean flows beneath and against the ice shelves and plays an important role at that interface in building, maintaining, or degrading them. The interaction between the shelves and the ocean, the responses of each of those systems, and how these processes ultimately affect society is the focus of this work. We bring together scientists from a range of disciplines to study results from large-scale computational models focused on understanding this unique interface between the ocean and the ice.

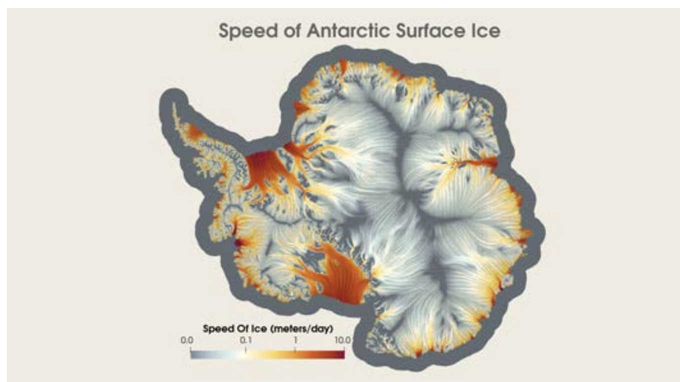

Fig. 1. Visualization of Antarctica with evenly seeded streamlines, colored by speed of the surface ice. Here, streamlines are useful for both defining individual catchment areas (or drainage basins) and for highlighting areas of fast flow.

The broad goals of the U.S. Department of Energy (DOE) Energy Exascale Earth System Model (E3SM) Cryosphere Science Campaign are to better understand the dynamics of Earth's changing polar regions and how changes in the cryosphere impact the broader climate system and, in turn, society [1], [2]. Of particular interest during the current phase of the E3SM project are the interactions between the Southern Ocean, Antarctic ice shelves, and the rest of the global climate system. Ice shelves form where Antarctica's ice sheet thins at its seaward margins and goes afloat by buoyancy. When relatively warm Southern Ocean waters circulate in cavities beneath the ice shelves (the two largest are each nearly the size of Texas), the base of the ice shelves can melt, thinning them from below. Because these ice shelves are still connected to the ice on land, they can exert a strong influence on the dynamics of the ice sheet, primarily by resisting the flow of ice from land into the ocean. In places where ice shelves thin and this resistance is diminished, more ice may be lost to the ocean than forms from new snow, contributing to global sea level rise. In addition, changes in freshwater entering the Southern Ocean through changes in ice shelf degradation may have significant impacts on global climate through changes in deep water formation and global ocean circulation.

II. Simulation Codes

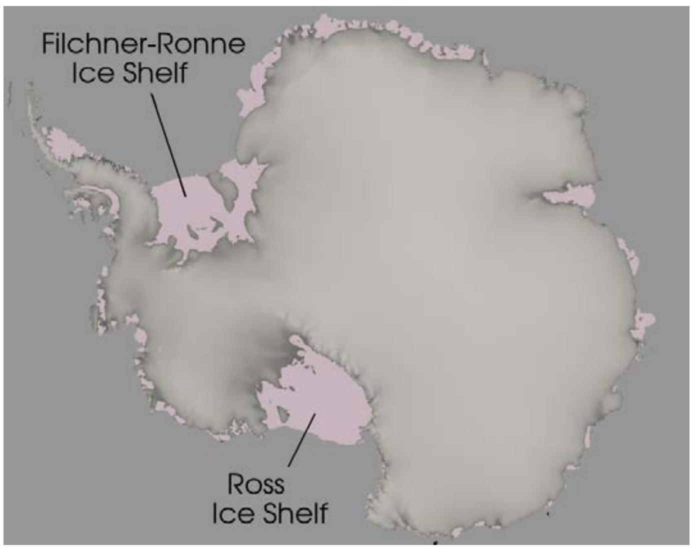

Fig. 2. Outline of Antarctica showing the location of the Ross and the Filchner-Ronne Ice Shelves, the two largest in the world and of importance to the cryosphere ocean project because they create a large area for interaction between the ocean and the ice.

This work studies output from two different simulation codes built on the The Model for Prediction Across Scales (MPAS) framework. MPAS [3] is a collaborative project for developing atmosphere, ocean, and other Earth-system model components on variable resolution, unstructured, global meshes for use in global climate and weather studies [4]–[6]. The primary development partners are the climate modeling group at Los Alamos National Laboratory (LANL) and the National Center for Atmospheric Research (NCAR). Both primary partners are responsible for the MPAS framework, operators, and tools common to the applications; LANL has primary responsibility for the ocean and sea ice models, NCAR has primary responsibility for the atmospheric model. The MPAS-Albany Land Ice Model (MALI) [7]–[9], which is built from the MPAS and Albany [10] software frameworks and the Trilinos solver libraries [11], is a joint collaboration between LANL and Sandia National Laboratories. These same individual component models make up the ocean, sea ice, and land ice components of E3SM.

The MPAS framework facilitates the rapid development and prototyping of models by providing much of the standard infrastructure typically required by model developers, including variable resolution mesh generation, high-level unstructured data types, parallel communications, and I/O routines [12]. By using MPAS, developers can leverage pre-existing code and focus development efforts on the unique domain-science aspects of their particular model.

A. MPAS-Albany Land Ice

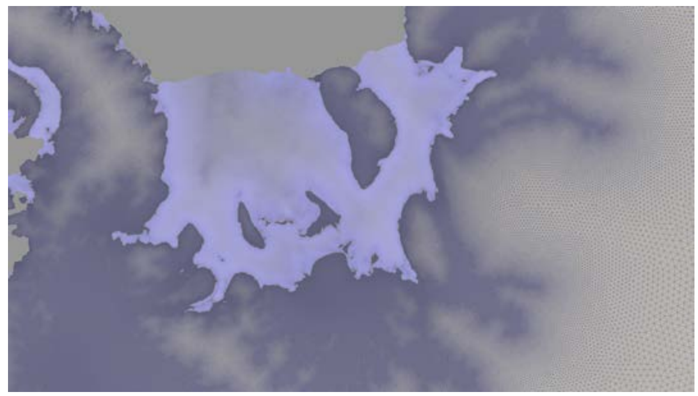

Fig. 3. Visualization of the Filchner-Ronne catchment area showing the variable and high density of the MPAS-Albany Land Ice model's computational grid. Light purple is ice shelf and grey is grounded ice sheet. Darker areas highlight areas of much higher grid resolution.

MPAS-Albany Land Ice [8], [13] is designed for large-scale, high-resolution simulations of ice sheet dynamics, using Finite Element and Finite Volume Methods on variable resolution meshes [14]. MALI uses a three-dimensional, higher-order approximation to the equations of ice motion (nonlinear Stokes flow). The model is initialized using a partial-differential-equation-constrained optimization problem that allows for spatially variable basal sliding in order to best match present day observed surface velocities for the Antarctic ice sheet.

The MPAS–Albany Land Ice (MALI) model simulates the dynamics of the Antarctic Ice Sheet, which is up to 4000 meters thick in its interior and covers the entire continent. Ice flows slowly from these high, central regions but speeds up to several kilometers per year as it nears the coast and converges into narrow (several to tens of km wide) outlet glaciers and ice streams. These feed into vast, floating ice shelves that can be up to 2000 meters thick where they initially go afloat. Ultimately, the shelves thin to several hundreds of meters at their lateral margins, due to ice flow (i.e., stretching) and sub-ice shelf melting. Icebergs eventually break off of the shelf edge through the process of "calving". Ice in the shelves has already displaced ocean water. The melting of ice shelves does not directly contribute to sea level rise, the ice shelves play a key role in restraining the grounded ice behind them, as discussed above.

B. *MPAS-Ocean*

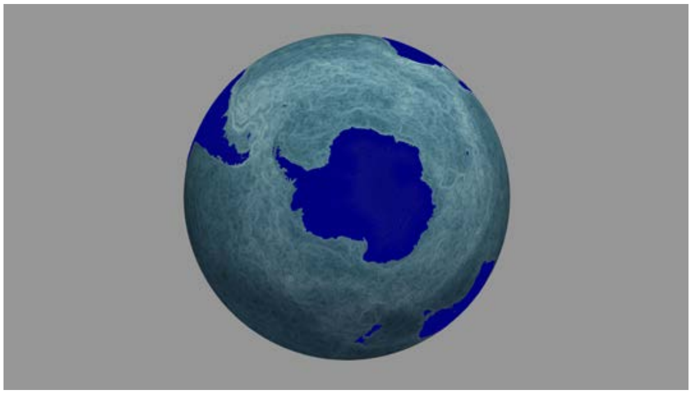

Fig. 4. Antarctica placed on the globe back-dropped by a global ocean model from MPAS-Ocean colored by surface speed.

MPAS-Ocean [4] is designed for the simulation of the ocean system from time scales of months to millennia and spatial scales from sub 1 km to global circulations [15]. MPAS-Ocean simulates the dynamics of the global ocean and, critically for the cryosphere campaign, the ocean circulation within the cavities beneath the ice shelves. This is necessary for capturing the exchange of heat and freshwater between the ice shelf and ocean that impacts the dynamics of both the ice sheet and the Southern Ocean. The rate of ice-shelf melting is a function of the ocean temperature, salinity, the pressure of the water at the ice shelf base, and the speed of the ocean currents, all of which change on a wide range of timescales and in response to a wide range of forcings, including anthropogenic climate change. MPAS-Ocean and MALI are currently run separately and are forced by historically observed changes in climate and initialized with the observed ice sheet and ice shelf geometry. Ongoing work is focused on proper coupling of these two components within E3SM so that changes to the ocean, ice shelves, and ice sheet interact dynamically and feed back on one another as they do in the real world.

III. Datasets

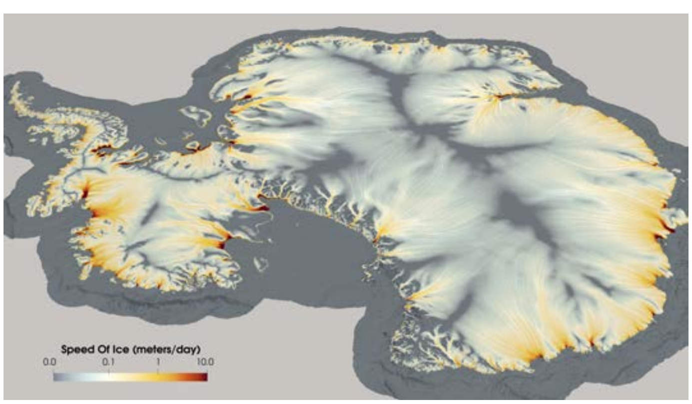

Fig. 5. ABUMIP's first time step with all floating ice removed. The flow rate of the ice on the boundary with the ocean is dramatically increased.

Land ice modeling datasets include 3 simulations from the CMIP6 Ice Sheet Model Intercomparison Project (ISMIP6) [16]: InitMIP-Antarctica [17], LARMIP [18], and ABUMIP [19]. From InitMIP-Antarctica, we use a control run where the present day climate of the ice-sheet is held steady for 200 years. From the LARMIP set of experiments, we use a sensitivity simulation where ice-shelf basal melt rates beneath the Filchner-Ronne Ice Shelf are instantaneously increased by 8 m/yr and then held steady for 200 years to represent a large perturbation to the ice shelf system. ABUMIP investigates an extreme scenario where all ice shelves around Antarctica are removed instantaneously and prevented from reforming over a period of 500 years. While the LARMIP perturbation experiment has a potential real-world analog (currently seen in a number of climate model simulations, e.g. [20]), the ABUMIP experiment is climatologically unrealistic. However, it provides an estimate for the upper-bound response of the Antarctic ice sheet to the loss of its ice shelves. For the simulations presented here, MALI uses a mesh with 2 km resolution in dynamically important areas near the coast and coarsens to 30 km resolution in the slow moving ice sheet interior, with a total of 1.8 million grid cells in the horizontal. The mesh uses ten vertical layers preferentially concentrated near the ice sheet base, where vertical shearing tends to be greatest. The simulations discussed here were run on approximately 6000 processors on the Edison and Cori supercomputers at the National Energy Research Scientific Computing Center (NERSC).

Ocean datasets are taken from global E3SM simulations that include active ocean and sea ice, while atmospheric, land, and run-off fields are provided by historical data, as described in [1]. A static Antarctic ice sheet configuration allows for ocean circulation within ice shelf cavities [21], and includes the exchange of heat and freshwater fluxes between the ocean and overlying ice shelves. The resolution of the ocean and sea ice components near the Antarctic ice shelves is around 10 km. This configuration is a step towards fully dynamic ice shelves that may change their extent due to basal melting and calving at the margins.

IV. Cryosphere Ocean

The goals of the Cryosphere–Ocean Visualization Project are to study these data sets and provide visualizations that are of interest to the cryosphere ocean domain scientists and their communities, including stakeholders and policymakers, the broader scientific community, and the general public. The visualizations should be reproducible using open-source tools. They should be accessible and reproducible by the stakeholders. Overall, our goal is to create a video that is consumable by a broad audience of non-specialists, that tells the story of ocean and land ice interactions, climate change, and sea level rise, as understood through climate simulations conducted on some of the world's largest supercomputers. That narrative can be understood according to the following ordered list of cause-and-effect processes:

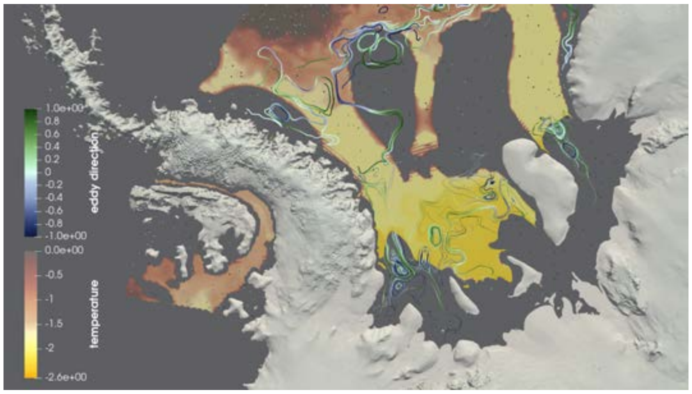

Fig. 6. Streamlines of ocean currents beneath the Filchner-Ronne Ice Shelf backed by an isosurface of constant depth showing ocean temperature.

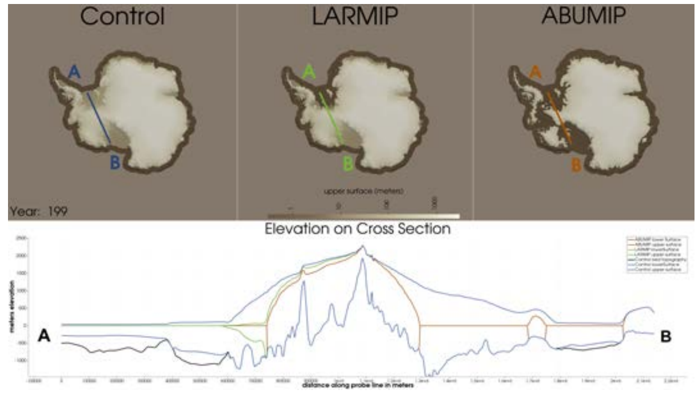

Fig. 7. Contol, LARMIP, and ABUMIP simulations at 199 years of evolution with a cross section plot showing the upper and lower ice surface for each. Due to the loss of ice following ice shelf thinning or removal, the grounded ice sheet elevation is lower for the LARMIP (green) and ABUMIP (orange) simulations relative to the control (blue) simulation.

1) Ocean circulation beneath Antarctica's floating ice shelves influences their melt rates; increased melting leads to increased ice shelf thinning. The visualization in Figure 6 shows ocean dynamics beneath the Filchner-Ronne Ice Shelf that could lead to ice shelf thinning.
2) Increased ice shelf thinning reduces the ice shelves' ability to restrain ("buttress") the flow of ice farther up-stream, increasing the flux of ice from the continent into the ocean. The ABUMIP data shows an extreme case of this, completely removing the floating ice obviates the restraining power of the shelf as seen in Figure 5.
3) Increased flux from the continent and into the ocean is expressed by an overall "thinnning" of the ice sheet, seen in Figure 7.
4) Antarctica's ice sheets store many tens of meters of sea level equivalent; thinning of the ice sheet translates directly to increased rates of sea level rise. Figure 8 demonstrates the amount of sea level rise above the control for LARMIP and ABUMIP.
5) Coastal population centers around the world are at significant risk of future sea level rise. According to the 2017 UN Ocean Conference Fact Sheet [22], over 600 million people, making up 10% of the world's population, live less than 10 meters above sea level. Even minor increases in sea level can have devastating impacts during extreme events like storms. Research also suggests that the economic impacts of sea level rise are non linear compared to the sea level rise itself [23].

A. ParaView

ParaView [24] is a parallel, distributed memory, general-purpose visualization tool that has had substantial funding for its development from the DOE for the purpose of handling extremely large data sets efficiently. It has a variety of filters that allow transformations of input data sets into visualizations. Where more custom transformations are required, there is a mechanism for easily integrating a "Python programmable filter" that allows arbitrary Python code to be executed on the data in the pipeline. This capability was used to visually align the MPAS-Ocean and the MALI data sets. It was used to present the Antarctic data on the globe.

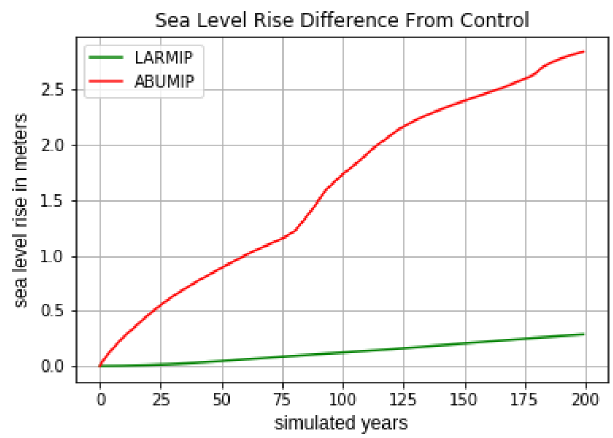

Fig. 8. Sea level rise greater than control over time from LARMIP and ABUMIP simulations. Note the amount of ice sheet thinning is directly responsible for the rise.

V. Animation

ParaView provides the functionality required to generate high-quality animations. Scenes showing the temporal evolution of the simulation data were simple to create using the default TimeKeeper animation. Flyover scenes were created using the Camera—Interpolate Camera Locations animation. Camera locations and orientations must be carefully chosen to result in a smooth camera track while moving the view to interesting locations in the data. Fades of the ice sheets were accomplished by animating over the opacity value of a ParaView pipeline element that contained the surface. Python and Matplotlib were used for generating the overlayed plots.

VI. Visualization Techniques

The primary visualization techniques used for this work are isosurfaces, streamlines, and surface warping by scalar fields.

ParaView makes these available as filters that can be applied to data before extracting geometry for rendering. All available scalar fields that intersect the new geometry are retained and can be used for coloring the visualizations.

Isosurfaces or contours are a common visualization technique that calculate a surface of constant value through a volume. It is analogous to an isoline or contour line, which shows a line of constant value in a 2-dimensional space, such as contours of constant elevation on a topographic map. Figure 1 uses an isosurface of constant depth that is colored by temperature to create a visual backdrop for the streamlines, explained later, showing ocean flow. The goal of Figure 6 is to develop an intuition in the viewer that there is a dynamic ocean beneath the ice shelves and interacting with the ice shelves.

Streamlines are a visualization technique for vector fields, such as those describing fluids. They are lines that are produced by "seeding" a starting point in a vector field, then propagating a line from that starting point that is tangential to the vector field at all times, showing a path in which the water is flowing. For the ocean in Figure 6, this develops an intuition that there are currents and eddies. The streamlines are colored using a divergent colormap so that both the degree (values between 0 and 1, Fig. 2) and direction of curvature (positive or negative, Fig. 2) are evident. This allows ocean scientists to discriminate between green (positive) cyclonic or counterclockwise and blue (negative) anticyclonic or clockwise eddies in the flow field. For the ice in Figure1 the seeding and streamlines develop an intuition of the direction of the flow, topography, and the catchment areas. The streamlines are colored by velocity so they are also indicating where the ice flows slowly and quickly. Streamlines can be calculated both forward and backward from a seed point. The streamlines for the ice are calculated forward only. The streamlines for the ocean are calculated both forward and backward.

Warping by a scalar allows a 2-dimensional surface to be extruded in a third dimension. This is mostly seen here in surface topography. Most of our imagery of the Antarctic surface has been warped to create a visual sense of elevation, a sense that the 2-dimensional map of the surface is embedded in a 3-dimensional space. This warping, necessary to show the extreme elevations in Antarctica at this scale, is problematic. As the warping is increased, the perception of the size of the continent seems to decrease.

VII. Collaborative Scientific Visualization Development

Our vision for this project was to produce a large quantity of analysis products: images, videos, and plots. We needed to track, modify, and improve the quality of visualizations and keep them organized, searchable, and allow for comments associated with each one. We expected that we could have regular meetings that would allow the multi-disciplinary group to quickly review the visualization products produced during the previous week, make comments for further work, and organize them for future use and accessibility by a variety of stakeholders.

We introduced innovations to the ParaView workflow. Inspired by the Cinema [25] project, we developed a mechanism in ParaView that allows the saving of a ParaView state file and a screenshot simultaneously with a single button click. In addition, a text file is generated that supports plain text for notes that can be easily searched for keywords or other metadata. This code, released as a plugin, is in versions of ParaView starting with 5.8.1.

VIII. Results

We produced the video presented here. We also created a large number of visualizations and 2-D plots that provide an assortment of analysis products that can be drawn upon by the climate scientists. Most of the visualizations and analyses are not presented here but are available to the cryosphere ocean team and funding sponsors for further review and use. The new snapshot mechanism in ParaView proved invaluable and allowed the visualization scientists to easily create many reproducible images by transparently saving the associated states for each. In addition the associated state files supported our ability to iteratively improve visualizations.

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