

Polynyas: Polar Physics Revealed through Visualization of the E3SM Global Climate Model

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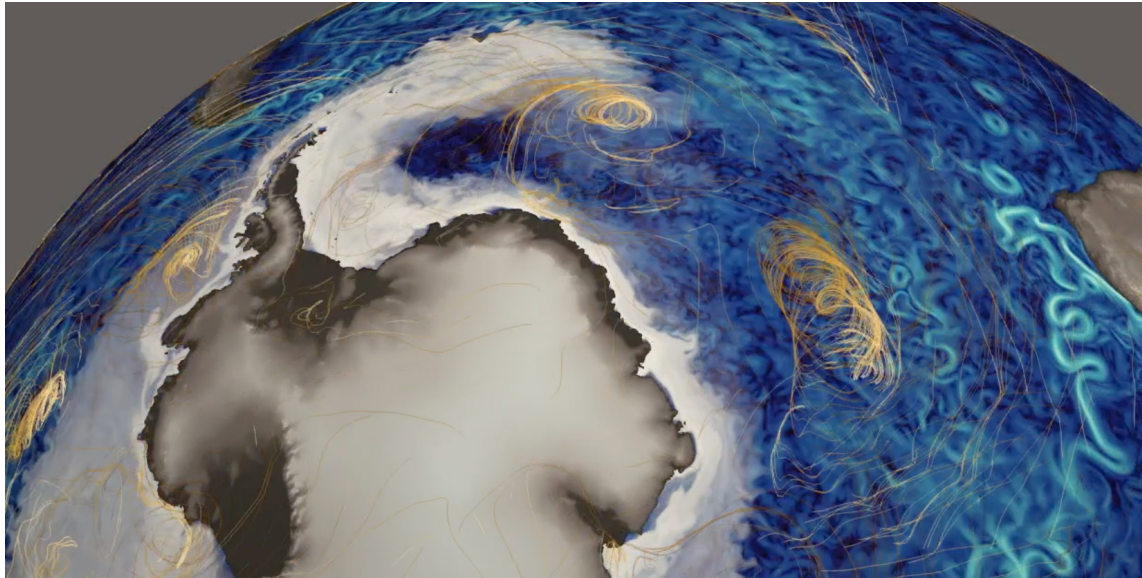


Fig. 1. Sea ice (white), ocean speed (blue), and streamlines of winds (yellow), around Antarctica in an E3SM simulation.

Abstract: Polynyas are openings within polar sea ice pack formed and sustained by atmospheric and oceanic processes. They occur in the Arctic ocean and the Southern ocean, lasting for many months, and act as a conduit for heat and water between the oceanic and atmospheric systems. Realistic coastal and open ocean polynyas in global climate models are a stringent test of the model's physical fidelity, as their formation depends on complex interactions between the sea ice, ocean, and atmosphere. In this video we highlight the role of polynyas in modulating earth's mesoscale processes using high-resolution simulations from the Energy Exascale Earth System Model (E3SM). A team of climate modelers, an artist, and a computer science specialist collaborated to generate animations that visualize these large data sets. The detailed overlay of variables, dense in time and space, provided climate scientists with new insights into their research — especially in regards to the dynamics of convective plumes driven by cold melt water near open ocean polynyas, and the katabatic winds that create coastal polynyas at the edge of Antarctica.

CCS Concepts: • **Applied computing** → **Physical sciences and engineering**.

Additional Key Words and Phrases: climate modelling, polar science, visualization

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1 INTRODUCTION

In the past 20 years, climate science and computational modeling have been thrust into the national spotlight as climate change has become a pressing global issue. The Sixth Assessment Report by the Intergovernmental Panel on Climate Change [5], released in August 2021, makes extensive use of climate models to predict the effects of future emissions scenarios. One of those models, the Energy Exascale Earth System Model (E3SM), is featured in this video (Fig. 1). The earth's climate is complex, with a large number of interacting processes. Climate models mirror this complexity, but allow researchers to analyze each variable at high resolution in space and time. Evaluation of these large data sets is important for climate science for verification, scientific understanding, and assessment of future emissions scenarios. Visualization is an integral part of this workflow. This video demonstrates the scientific value of big data visualization, highlighting atmosphere, ocean, and sea ice interactions through the formation and impact of polar polynyas.

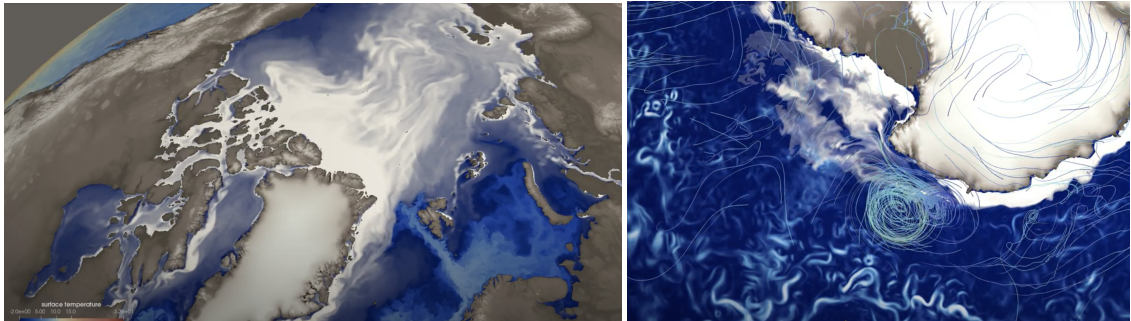
2 THE SCIENCE

Fig. 2. Sea ice cover with ocean temperature over the Arctic (left); sea ice with ocean speed and winds in the Antarctic (right).

Sea ice—ice that freezes atop the ocean and floats on the surface—plays an important role in both regional polar climate and global climate processes (Fig. 2). During the fall and winter months, sea ice grows and expands in the Arctic ocean and in the Southern Ocean, then shrinks and melts in the spring and summer. These annual cycles alter the salinity and temperature of the polar oceans' surface.

Polynyas are openings in the sea ice that strongly influence air-sea exchanges. Observational evidence [3] can be found in satellite observations [8] and in high-resolution climate simulations [7]. There are two types: coastal polynyas and open ocean polynyas [9].

Coastal polynyas are created when strong off-shore winds push sea ice away from the coast, and occur in both the Arctic and Antarctic [9]. This exposes open water below, which quickly freezes when it contacts the frigid polar air. This cycle of freezing and sea ice displacement is a major source of new sea ice formation. The brine rejected from the freezing sea ice creates dense, salty water below the coastal polynyas, which then sinks and is a major source of bottom water that is transported throughout the world's oceans via thermohaline circulation.

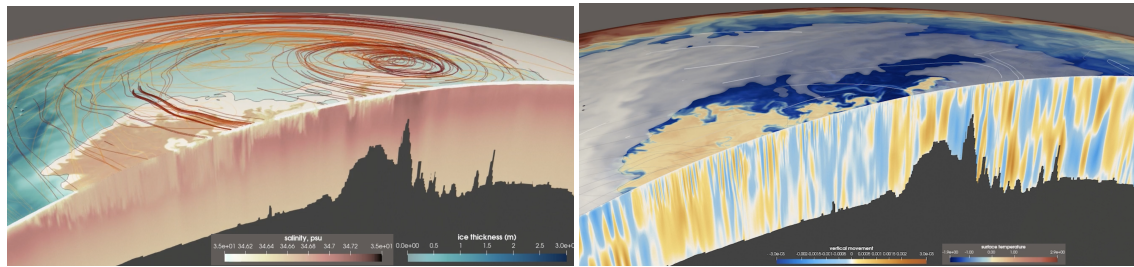


Fig. 3. Cross-sections through an open-ocean polynya in the Weddell Sea region showing salinity (left) and surface temperature and vertical velocity (right) overlaid by sea ice thickness and winds. Convective plumes induce upwelling of saline waters.

Open-ocean polynyas in the Southern Ocean form in preconditioned regions, where warm ocean water up-wells to the surface, melting the sea ice [7]. The occurrences of the Weddell Sea open ocean polynyas are closely tied to the strengthening of the Weddell Gyre, which in turn are tied to strong negative wind stress curl anomalies in the Weddell Sea [7]. Figs. 3 and 4 shows an open-ocean polynya the size of Colorado forming in the Weddell Sea Region. Realistic polynyas in global climate models are indicative of the model's physical fidelity, as polynya formation is sensitive to the complex interactions between ocean, sea ice, and atmosphere. This particular polynya closely approximates real world observations: the Weddell Sea Polynya appeared in this same region from 1974 to 1976, and then again in 2016 and 2017 [6].

The process of open-ocean polynya formation in the winter and spring months begins when salty warm, deep equatorial waters circulate to the Southern Ocean. Frigid air causes the surface of the ocean to freeze, forming sea ice. As the warm and salty equatorial waters circulate and up-well to the surface, they come into contact with the sea ice, melting it from below and preventing further ice formation. When this melting thins the sea ice enough to break through, it forms an open-ocean polynya. When the sea ice freezes, it rejects the ocean brine, resulting in ice pack composed primarily of fresh water. When this ice later melts, it produces a layer of fresh water (white layer in Fig. 3, top). As the subsurface warm, salty water ascends, the fresh icemelt sinks in plumes due to its relatively higher density, creating a continuous cycle of vertical mixing. This process is visible in (Fig. 3, bottom) as alternating columns of vertical velocity.

3 THE ENERGY EXASCALE EARTH SYSTEM MODEL (E3SM)

E3SM is a fully coupled Earth system model made up of ocean, atmosphere, land, river, and sea ice components [4, 10]. Coupled models allow us to study the entire earth system and how the components interact, rather than only simulating one aspect at a time. All E3SM components are based on variable-resolution unstructured meshes. The ocean component, the Model for Prediction Across Scales (MPAS)-Ocean, is a hydrostatic, incompressible, Boussinesq ocean model on a C-grid, with near-hexagonal grid cells [11, 12]. The sea ice component, MPAS-Sea Ice, lies on the same grid, facilitating the study of ocean-sea ice interactions. The atmosphere component E3SM Atmosphere Model (EAM) is computed on a separate grid. For this study, the full model was run for three years on a standard CPU cluster, at a speed of 6 months per wall clock day on 4096 cores. Output was saved at extremely high frequency—six-hourly frames—to produce smooth animations.

This simulation is one of the highest-resolution climate models ever run, with 6 km resolution for sea ice and ocean in polar regions [2] and 25km resolution for the atmosphere. A great advantage of running the ocean and sea ice

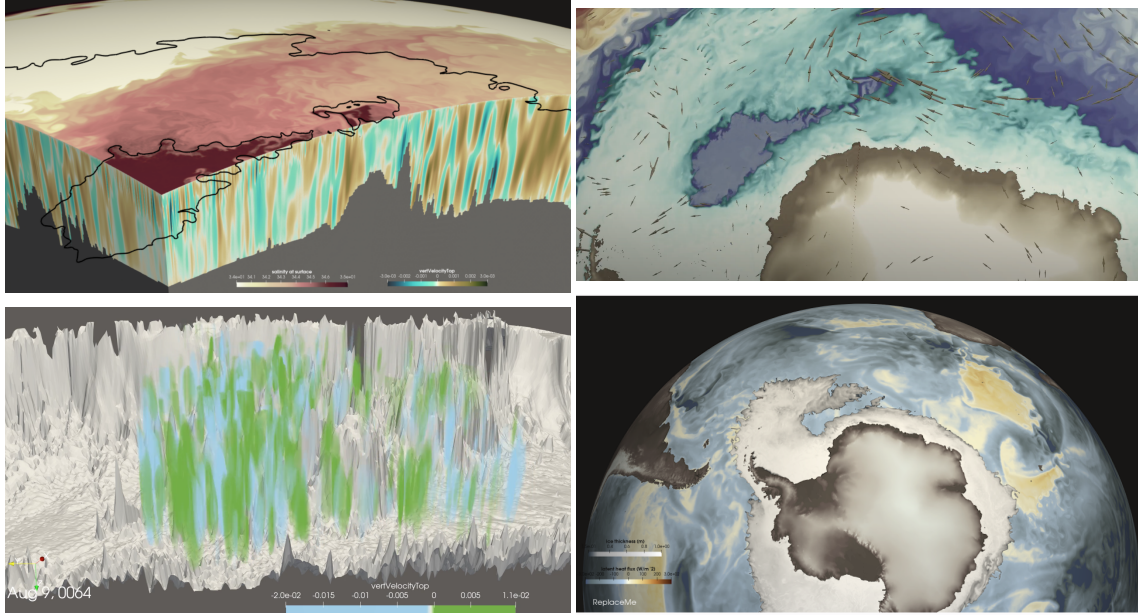


Fig. 4. Assortment of images produced during a working session between scientists and visualization specialists, including: surface salinity, section of vertical velocity, contour of sea ice (upper left); wind vectors, sea ice thickness, ocean temperature (upper right); volume rendering of vertical velocity (lower left); surface heat flux and sea ice cover (lower right).

components at this high resolutions is that the largest eddies are explicitly resolved, so horizontal sub-grid scale eddy parameterizations may be avoided. At 6km resolution, the raw data for the ocean model consists of 3.69M surface cells with 80 irregular vertical layers and mostly cell-centered variables. Each year of daily timesteps is 576GB. The sea-ice model is on the same grid with a single layer; a year of dailies is 13.2GB. Finally, the atmosphere data consists of 0.7M points, with 80 vertical layers, for 130GB per year. The original simulation ran for 160 years of model time.

4 VISUALIZATION

The goal in this project is to enable domain scientists to study how processes in several domains interact to produce conditions giving rise to polynyas, and how the polynyas themselves affect conditions in the ocean. All visualizations in this work were done using Paraview [1]. Data processing was done using VTK [13] and custom tools developed in-house.

Our first task was to convert the raw simulation data (the mostly-cell centered hexagonal surface grid) to a form amenable for visualization. We converted to triangles by connecting the cell centers of adjacent hex cells, leaving 7.3M surface triangles. For volumetric data (e.g. the ocean beneath the polynyas) we connected the layers of triangles creating space-filling triangular wedges, which we then converted to tetrahedra.

Given this voluminous data, we first surveyed 12 years to find periods containing interesting polynyas. We found a classic Weddell Sea polynya in simulation year 64, and so narrowed our focus to a 30 month period. To enable our scientists to investigate the Arctic and Antarctic regions interactively, we then clipped the overall grid first to high-latitude bands ($> 50^\circ$), reducing the surface-triangle count to 2M the south and 1.3M in the north (489M and

324M tetrahedra, respectively). We later clipped to smaller regions around polynyas that our science colleagues found interesting.

As we began visualizing the data, we discovered that, while daily timesteps were sufficient for slow-moving features—particularly in the ocean—they were not sufficient for fast-changing features like wind and sea-ice coverage. For the wind, we tested both Eulerian and Lagrangian techniques (e.g. arrow glyphs at pre-specified points and particle traces integrating the instantaneous flow over time). Both jump distractingly from timestep to timestep and provide poor understanding of the continuous underlying physics. In order to capture detail in these features we determined that a 6-hourly timestep was sufficient. We therefore reran the simulation models, using checkpoint/restart files, in the (relatively) narrow time intervals of interest.

The visualization challenge is to develop visualizations that combine multiple variables, some from each model component, together in a manner that allows the viewer to understand them in context. For example, to understand the effect of the polynya on the ocean surface and sub-surface salinity, we need to see both the sea ice data, to show the polynya's extent, as well as salinity on the ocean data's surface. To see the ocean surface *inside* the polynya, we can clip the sea ice data using the **seaIceVolume** variable, which indicates the normalized depth of ice on the surface. By clipping the sea-ice data at a very low value of **seaIceVolume** (0.01) we remove the part with no sea ice, revealing the ocean data underneath - for example, as seen in Fig. 3, left. However, this masks the ocean surface *under* the ice, hiding how the ocean's surface properties differ across the ice boundary. We can reveal this by using a *contour* of the **seaIceVolume** variable of the sea ice data, revealing the ocean surface with an indicator of the polynya boundary (Fig. 4, top left).

More problematic are properties of the volumetric ocean data beneath the surface. Domain scientists would like to understand the relationship between vertical motion in the ocean and polynyas on the surface. Fig. 3, right, shows one approach; here we slice the volumetric ocean data in the zonal direction and use a divergent color map on the vertical component of the flow vector. This method is effective for revealing the vertical flow over long ranges. Alternatively, volume rendering (Fig. 4 bottom left) shows the three-dimensional structure of the convective plumes; this technique proves useful on smaller regions (with respect to feature size) of the data.

An important feature of coupled climate interaction is the effect of storms in the atmosphere on the ocean. Since these are effects *over time*, instantaneous representations of wind direction and magnitudes such as glyphs and streamlines *within* timesteps fail to capture this effect; they jump distractingly from timestep to timestep and provide poor understanding of the continuous underlying physics. This led us to implement *pathlines* - the track of massless particles through wind over time, giving a view of the wind over a period of time. By laying pathlines over the ocean, which changes much more slowly than the wind, we were able to visualize the lasting effects of storms on the speed of the ocean surface (Figures 1, also video).

5 CONCLUSIONS

Intuitive visualizations and graphics of ocean, atmosphere, and sea ice data are powerful tools for analysis, interpretation, and discovery in the climate sciences. Comprehensive, multifarious visualizations can also increase efficacy in public climate communication. Generating these kinds of visualizations requires not only iteratively working with scientists to understand what they need from their data and simulations, but also drawing from the arts in order to produce coherent imagery that speaks to a wider audience.

The addition of these specialized, artistic visualization techniques and the compilation of all three models (ice, ocean, and atmosphere) enabled us to observe new and intriguing interactions between variables in the data, such as the katabatic winds blowing sea ice away from the coast and exposing the ocean below.

The three-dimensional visualizations take these capabilities a step further. Ocean data, most often visualized in horizontal slices, is much more complex than a simple layer cake of processes. Rather than analyzing this data one depth at a time, we were able to view the convection occurring beneath the polar polynyas using 3D visualization techniques. In fig. 3 we can see both the height of the convective plumes and their spatial extent. The details of how the plumes varied from ice-covered to open ocean, portrayed with many variables in tandem, were a new and exciting discovery for the scientists. This led to several interactive sessions with the visualization experts, further improvements, and ultimately, the insightful collection of climate visualizations presented in this video.

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