The Arctic Ocean in a Global Context Leading to E3SM V3

Andrew Roberts[1*], Nicole Jeffery[1], Jon Wolfe[1], Elizabeth Hunke[1], Erin Thomas[1], Alice Barthel[1], Jean-Christophe Golaz[2], Wuyin Lin[3], Xue Zheng[2], Xylar Asay-Davis[1]

1. Los Alamos National Laboratory | 2. Lawrence Livermore National Laboratory | 3. Brookhaven National Laboratory

*afroberts@lanl.gov | CAMAS Workshop February 14-16, 2024 | LA-UR-24-21393

Summary

A great many global interactions in an Earth System model are crucial for simulating the high northern marine environment. Many improvements needed to better model the physics and biogeochemistry of the Arctic Ocean can be informed by improvements in simulating the Southern Ocean. Here, we present simulations analyzed in the lead-up to the release of a new version of the global Energy Exascale Earth System Model (E3SM). This poster presents one sea ice improvement of many in our new model. The kind of incremental change reported here seldom feature in the literature, but remain important. In this case, a minuscule difference in a boundary condition used in sea ice dynamics and in the sea ice column physics impacted both Southern Ocean sea ice extent and shifted the location of the Beaufort Gyre in fully coupled simulations. This occurred without any loss of dynamic stability in the Elastic Viscous Plastic solution for sea ice, with more than 1600 years of integration stably completed in the pre-industrial spinup of E3SM V3 at the time this poster was produced. By unifying the minuscule cutoffs for which sea ice calculations are performed, unexpected changes occurred deep inside the pack including from coupled feedbacks, improving our ability to model waves in sea ice.

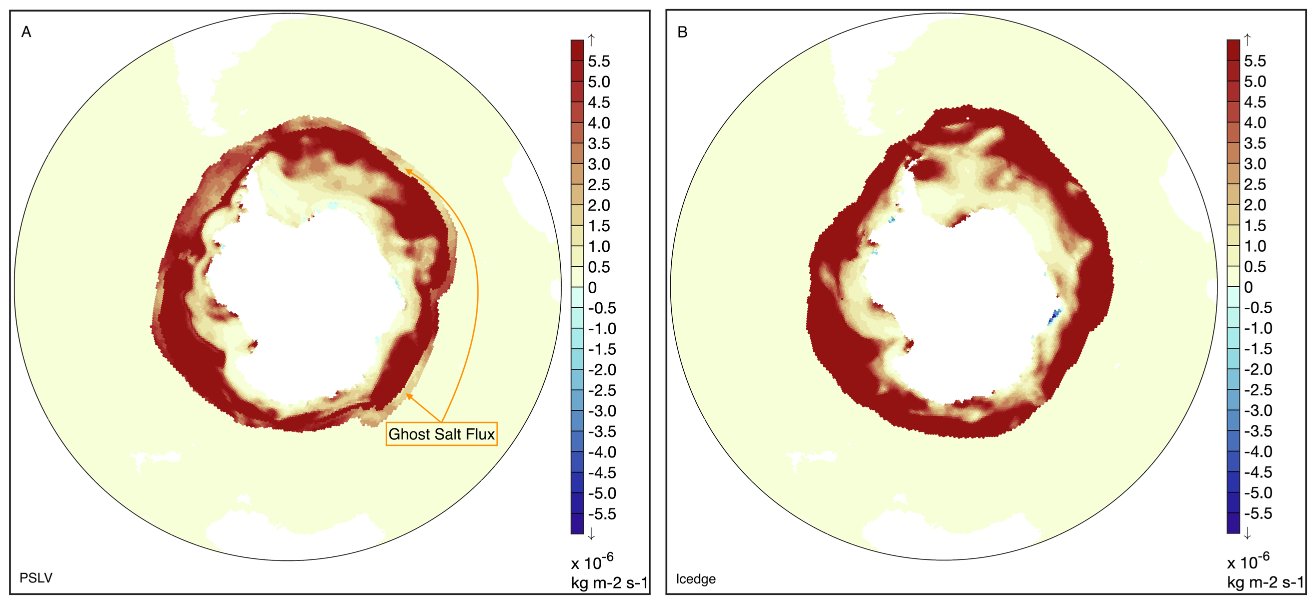

Figure 1: When a minimum concentration and mass boundary condition is provided to the sea ice dycore that is different from Icepack, a ghost field emerges in sea ice fluxes passed to the E3SM coupler, as indicated in panel A. These fluxes are inversely weighted by sea ice concentration so that the problem can be seen, here, for the salt flux passed to the ocean via the coupler from sea ice. This issue also exists for meltwater and heat passed to the ocean. The ghost fields disappear when the boundary conditions are aligned, surprisingly affecting the Arctic and Southern Ocean sea ice climate, and without loss of model stability. Instant fluxes are shown here on January 1, year 100 of a pre-industrial spinup. The problem is removed by unifying the cutoff (Panel B).

E3SM V3 Equal Area 30km Marine Mesh

Figure 2: The new unstructured 30km standard mesh for E3SM Version 3, including ice shelf cavities in the Antarctic and open shipping channels in the Arctic (orange).

Subtle but Important Consequences

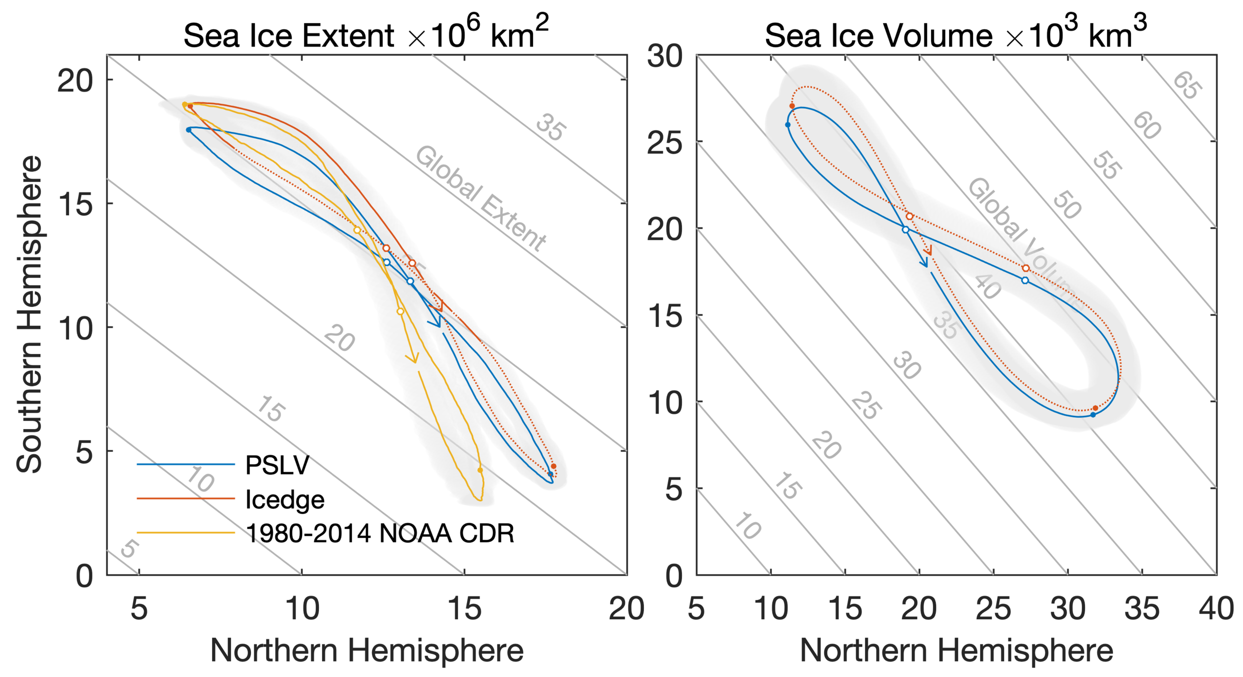

Figure 3: Daily sea ice lemnisc average (solid) and interquartile range (gray) illustrating the statistical difference of applying a seemingly inconsequential change in boundary conditions to Equation 1 for years 51-100 of a pre-industrial spinup of E3SM. Dotted red lines indicate the null hypothesis that the Icedge experiment is different from the PSLV control at 95% compatibility. Traces start on January 1, passing the northward equinox (●), northern solstice (○), southward equinox (●), and southern solstice (○) to the end of December (→). The NOAA Climate Data Record illustrates E3SM is most biased in the winter Arctic due to excessive sea ice cover in the Labrador Sea. Significant global extent differences from the control occur September to December.

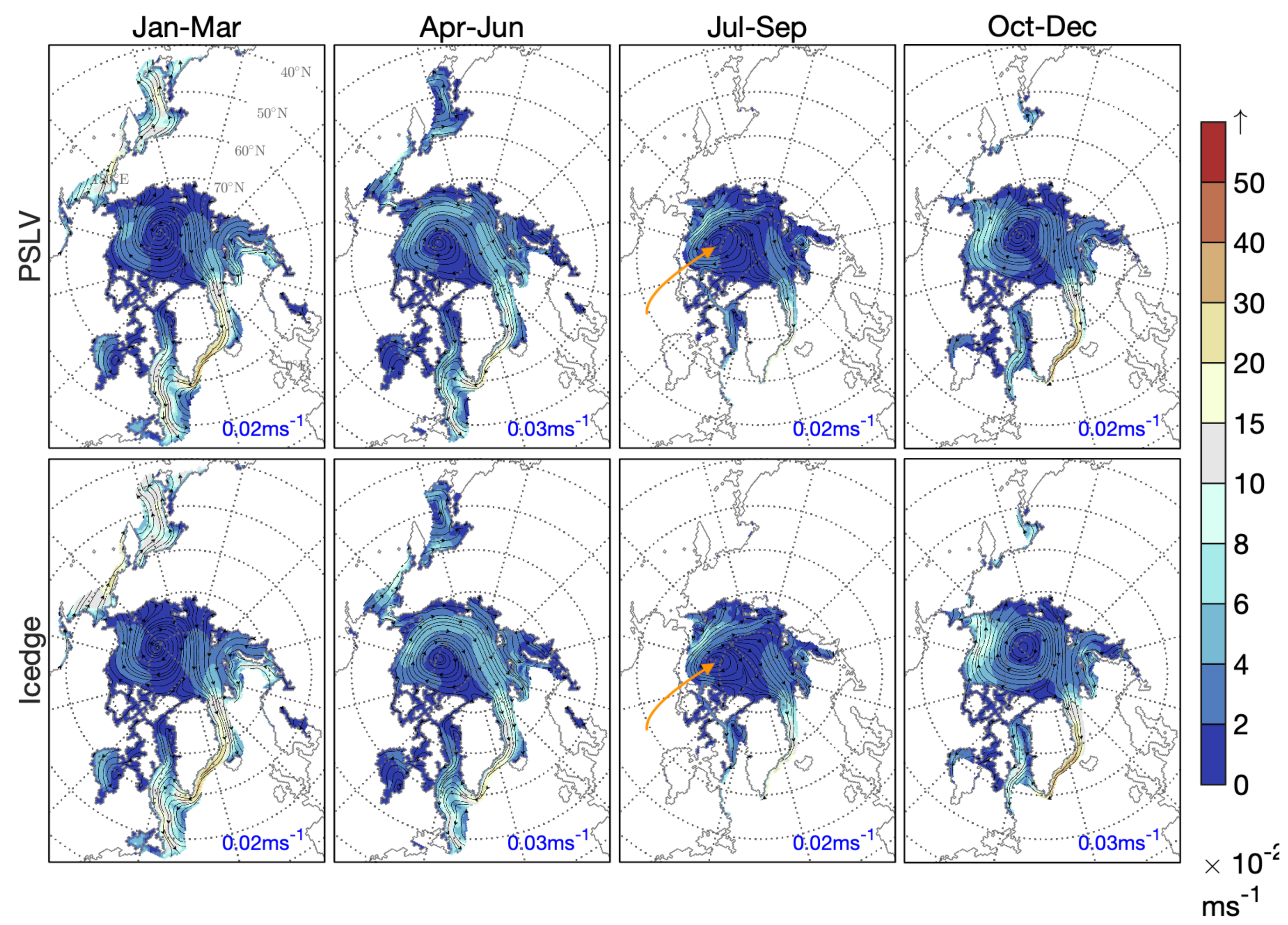

Figure 4: 50-year pre-industrial average northern seasonal sea ice drift (streamlines) and speed (shaded), with mean hemispheric speed (blue digits). The top row represents the PSLV control, bottom row the Icedge experiment. With the change in boundary conditions, there is a subtle but important shift in the location of the Beaufort Gyre.

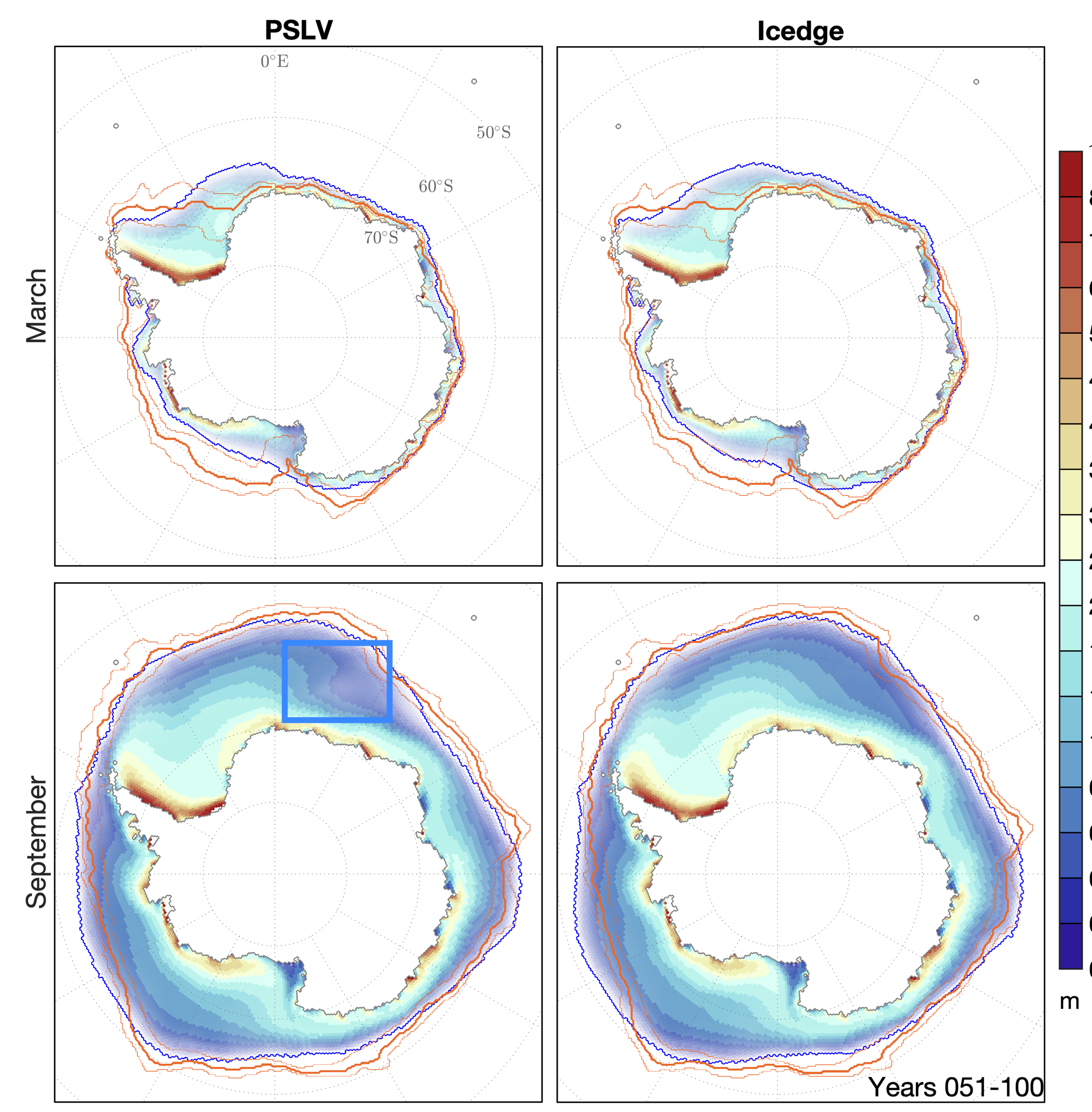

Figure 5: Antarctic mean cell sea ice thickness for years 51-100 of a pre-industrial spinup of the PSLV control and Icedge experiment. The blue contour is model extent, orange contours are 1979-1999 NOAA CDR extent $\pm\sigma$ as an observed metric comparison. Color transparency is weighted by concentration. The blue box indicates an erroneous low concentration melt area in E3SM fixed in the Icedge experiment.

Sea Ice Model Boundary Conditions

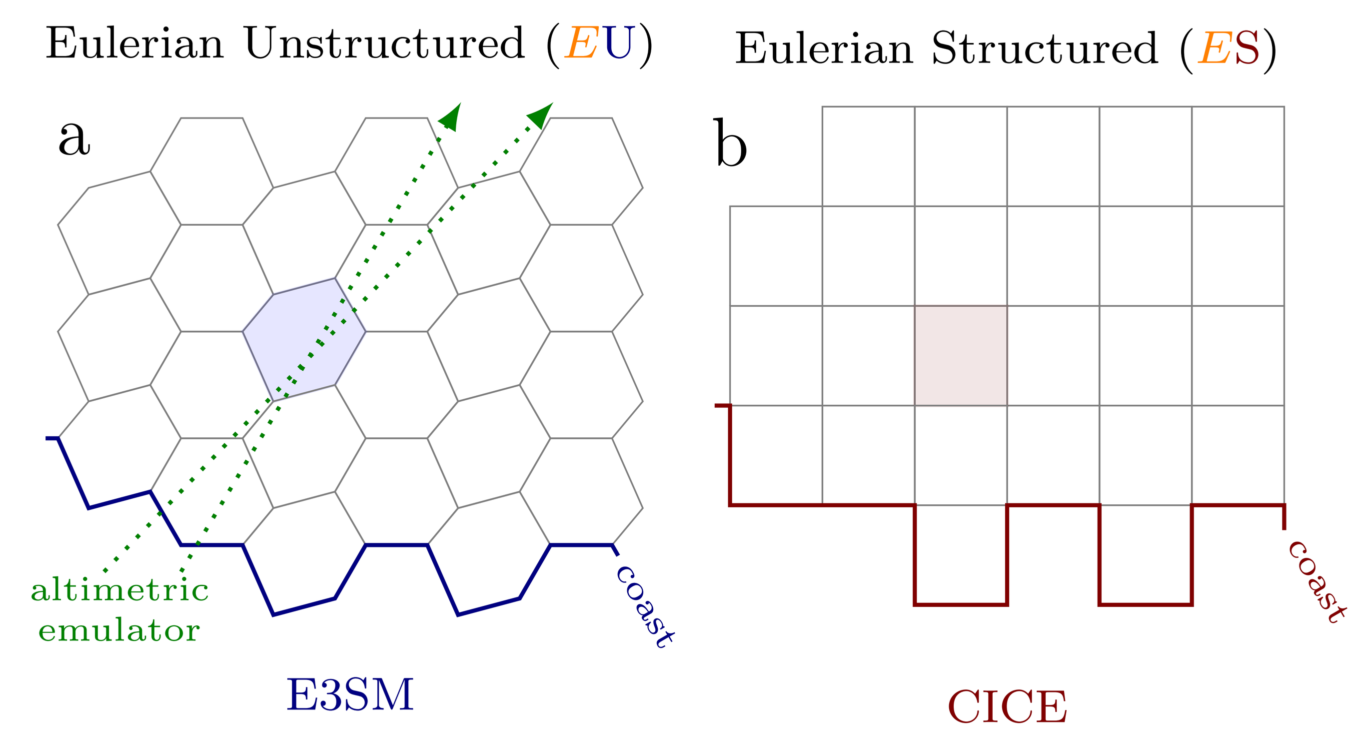

Figure 6: Schematic of mesh types comparing the E3SM dynamical core to CICE. Sub-grid scale sea ice physics and biogeochemistry in Figure 7 are represented statistically within elements or cells (blue and red shading, respectively) for (a) E3SM and (b) CICE. Green tracks in (a) represent satellite ground passes as one example of an observational emulator capability being installed in E3SM.

The E3SM sea ice dycore solves for momentum using the Elastic Viscous Plastic (EVP) method adapted to the unstructured mesh:

$$m\frac{\partial \mathbf{u}}{\partial t} = mf\mathbf{k}\times\mathbf{u}_i + \tau_a + \tau_w - mg\nabla H + \nabla\cdot\sigma \qquad (1)$$

where $\mathbf{u}$ is sea ice velocity at time t for ice mass density m. $\nabla\cdot\sigma$ is the internal ice force, τ_a and τ_a are the surface wind and ocean stress, respectively, g is acceleration due to gravity and f is the Coriolis parameter. Sea surface height, H, is coupled from the ocean. For many years, a boundary condition of $|\mathbf{u}| = 0$ has been applied in CICE, and replicated in E3SM, for cell concentration $< 10^{-3}$ or $m < 10^{-2}$ (**PSLV control**), which has differed from the cutoff of cell concentration $< 10^{-11}$ applied to column physics in Icepack (Figure 7). The higher concentration was applied to Equation 1 for dynamic stability, a seemingly innocuous difference. However, we have found there is no need for this inconsistent stability criteria, and cutoffs in cell concentration $< 10^{-11}$ or $m < 10^{-10}$ (**Icedge experiment**) may be applied consistently, hardly affecting sea ice kinetic energy (Figure 8).

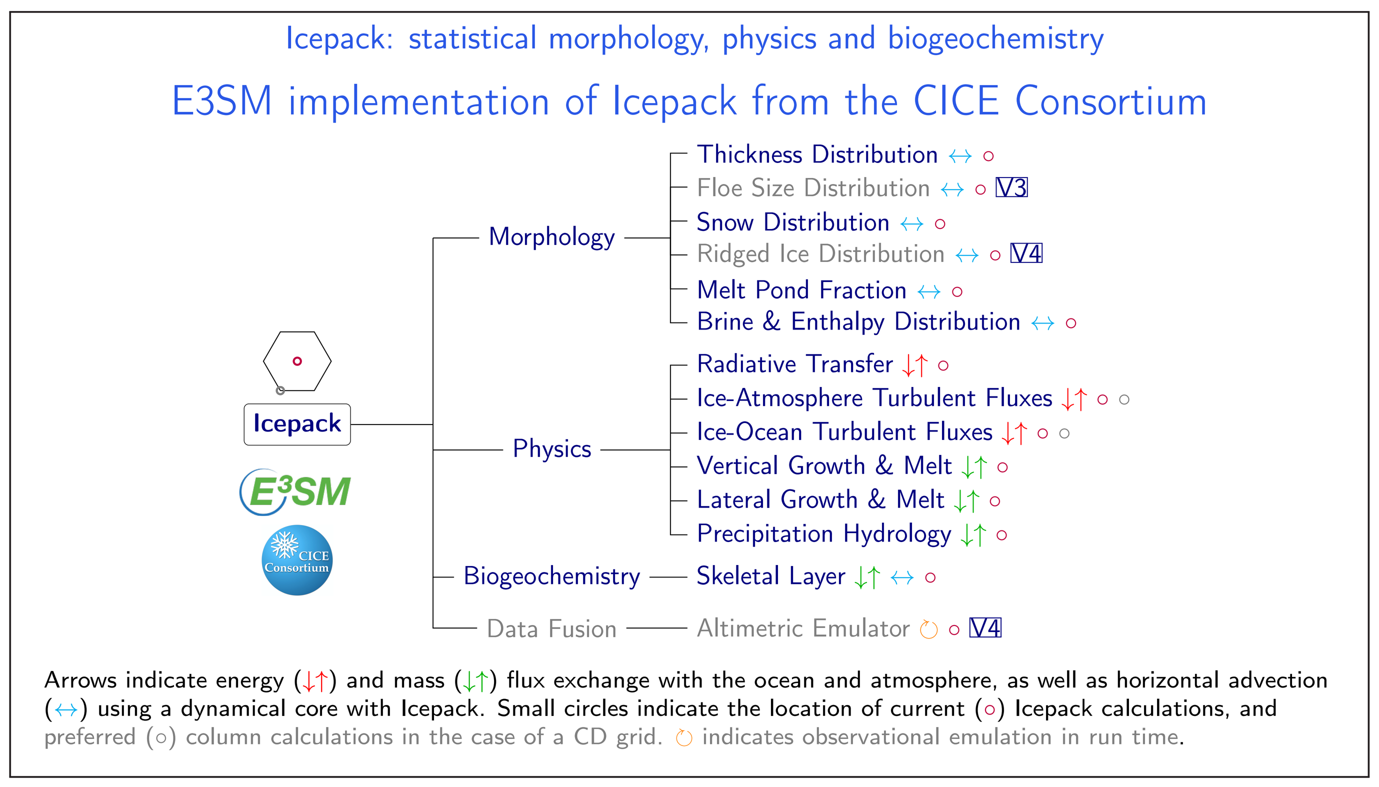

Figure 7: Schematic of Icepack as it is represented in E3SM, where gray indicates features being tested or introduced in Versions 3 or 4 of E3SM.

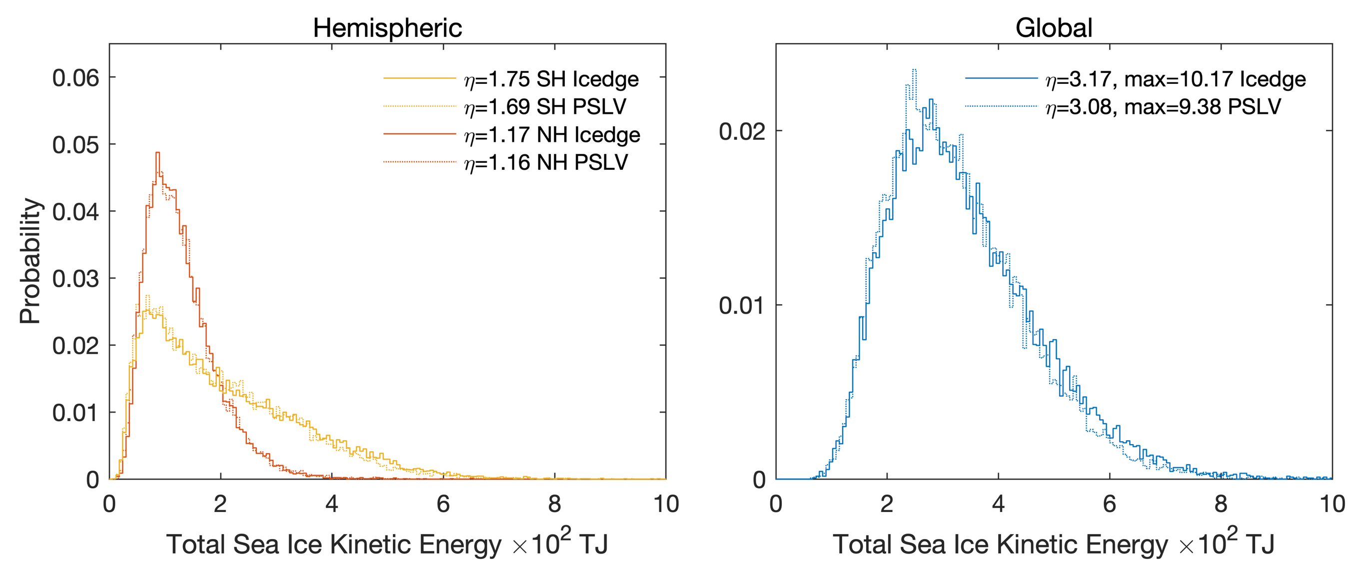

Figure 8: Sea ice kinetic energy distribution comparing 50 years' integration of the PSLV control with the Icedge experiment (η is the median value).