Ultra-Realistic Modeling and Simulation of Arctic Sea Ice

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PROJECT SUMMARY

Overview:

A central issue in advancing the science of the changing Arctic marine environment, and climate modeling more broadly, is to improve our ability to model, simulate, and visualize the dynamic and thermodynamic behavior of sea ice. The multiscale nature of sea ice as a porous polycrystalline composite of pure ice with brine and air inclusions presents formidable challenges, as does the sea ice cover itself, which has a multiscale composite structure of snow-covered ice floes, with sizes ranging over many orders of magnitude, in an oceanic host. Much of sea ice modeling has been geared toward parameterization in large scale, coarse grained climate models. Here we focus on developing the mathematics and computations needed for ultra–realistic modeling and simulation of key intermediate scale processes, such as the formation of ridges and leads, the evolution of melt ponds, and the interaction of sea ice with ocean surface waves. A recently developed framework offers the potential to transform sea ice simulation and visualization, with its capability of accurately handling rheologies ranging from fluid to solid. Based on the Material Point Method (MPM), it has been applied to simulating the beautiful yet varied dynamics of snow, yielding a new level of insight and predictability into the complex mechanics of avalanches and wet sand. What particularly distinguishes this approach, beyond rigid adherence to the physics, is the significant advance in visual realism, as evidenced by the MPM-produced snow scenes in the animated Disney film Frozen.

Here we propose to build an MPM framework for sea ice to bring this new level of realism, resolution, and physical accuracy to modeling important processes in the Arctic sea ice cover. We focus on building blocks of sea ice dynamics, such as floe collision and break-up, and the response of sea ice to waves and other forcings. As phase change and thermo-mechanical processes fall within MPM capabilities, we will consider the freezing and melting of sea ice, such as pancake formation in a wave field and the evolution of surface ponding and floe break-up. We will develop an MPM framework and related mathematics designed to efficiently treat the wide range of material parameters, rheologies, fracture, phase transitions and topological changes arising in complex sea ice scenes. Our framework will capture the essential physics and produce ultra-realistic visual representations of processes controlling ice pack morphology and properties.

Intellectual Merit:

Our approach will drive major advances in mathematical and computational modeling of sea ice and other complex multiscale materials with a broad range of rheological and phase change characteristics (e.g., land ice, biomaterials, concrete, tectonic plates). It will provide researchers in sea ice dynamics and thermodynamics with a powerful new class of modeling techniques with unprecedented realism and fidelity to the physics, with the capability to produce stunning visual renderings. Extensive algorithm and software development will be essential to building a realistic MPM framework for sea ice. However, there are other critical components which must be addressed, such as determining the constitutive equations describing the rheological behavior of sea ice over a range of length and time scales, by incorporating the results of field studies into the numerical simulations. We will bring to bear advanced methods of mathematical homogenization to determining the effective rheological properties of sea ice and their dependence on the characteristics of the brine and polycrystalline microstructures, which are key inputs in the proposed sea ice MPM. Moreover, our project features close connections to major field campaigns on Arctic sea ice, with access to extensive data on the scenarios we are simulating. MPM is particularly well suited to the efficient assimilation of these data into the models to achieve desired realism and accuracy.

Broader Impacts:

The investigators are active in outreach involving young people at many levels. We expect that the very high level of visual realism that we will achieve in our simulations will attract students, and the broader public, to the story of sea ice and its role in our changing climate. Participants in the project will be immersed in a highly interdisciplinary melding of cutting edge computational physics and mathematics of homogenization for multiscale composites, as well as the science of Arctic sea ice and the broader marine environment.