# SubZero: a discrete element sea ice model that simulates floes as evolving concave polygons

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Summary

SubZero is a conceptually new discrete element sea ice model geared to explicitly simulate the life cycles of individual floes by using polygonal elements with time-evolving boundaries. This unique model uses parameterizations of floe-scale processes, such as collisions, rafting, ridging, fracturing, and welding, to simulate the behavior on sea ice floes subject to mechanical and thermodynamic forcing in confined or periodic domains. SubZero enables the exploration of a wide range of floe interaction rules and fracture criteria to further our understanding of sea ice mechanics, including distributions of floe sizes, thicknesses, and shapes. Figure 1 shows snapshots from a validation study where SubZero simulates floes moving through a channel. A complete model description and example process studies demonstrating its capabilities can be found in Manucharyan & Montemuro (2022). SubZero was developed using MATLAB (MATLAB, 2020), leveraging its built-in functions for polygonal operations. The model source code has been archived to Zenodo (Montemuro & Manucharyan, 2022).
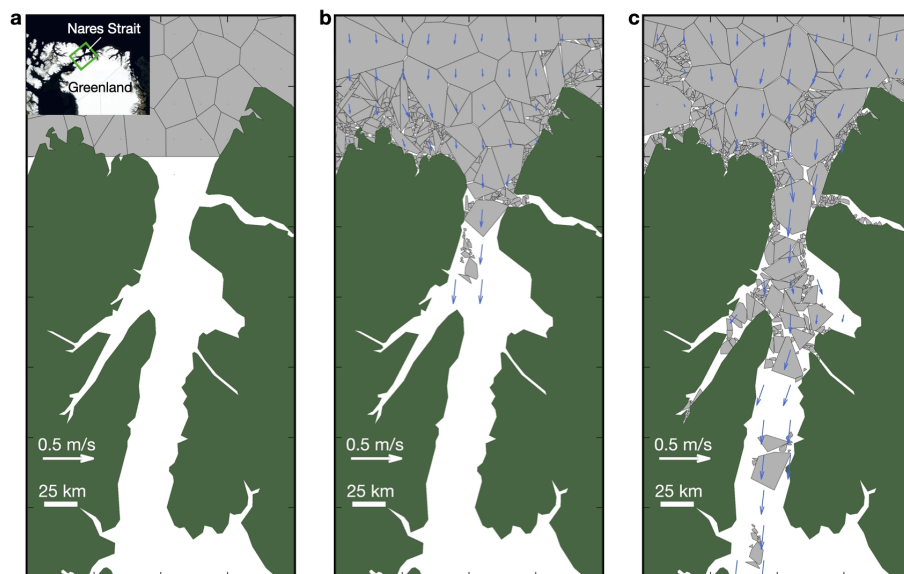
Figure 1: The evolution of sea ice floes as they pass through the Nares Strait (between Canada and Greenland), including (a) initial floe state with the inset showing the location of Nares Strait, (b) floes shortly after sea ice breakup that occurred after about three days, and (c) floe state after ten days when many floes have passed through the Nares Strait. The initial distribution of floes was generated using a Voronoi tessellation, and the subsequent evolution of floe shapes is only subject to floe fractures. In this simulation, the complex initial floe shapes near the land become simpler and more convex as they break up. The green box in panel (a) shows the modeled part of Nares Strait. The blue arrows represent sea ice velocity after averaging floe momentum on an Eulerian grid.

Statement of need

Sea ice dynamics span a wide range of scales. At length scales O(10–100) km and smaller (where O designates the order of magnitude), sea ice exhibits granular behavior as individual floes and fracture networks become evident (Rothrock & Thorndike, 1984; Stern et al., 2018; Zhang et al., 2015). Sea ice motion at relatively large scales, O(100 km), is commonly represented in climate models using continuous rheological models, like the viscous-plastic model (Hibler, 1979), which have not been formally derived from basic sea ice physics but have been postulated instead. The rheology defines a relationship between sea ice stress caused by floe-floe or floe-lead interactions, to the large scale deformation of ice cover, the material properties of sea ice, and the state of the ice cover. As such, the rheological models carry potentially large uncertainties in representing sea ice dynamics. They are also not designed to represent the scales of motion at which individual floes start to influence dynamics (Coon et al., 2007).

Developed initially in the context of granular assembles and rock dynamics (Cundall & Strack, 1979; Potyondy & Cundall, 2004), Discrete Element Models (DEMs) are an alternative to continuous rheology models. DEMs can be computationally demanding because they represent media as a collection of many colliding bonded elements with specified shapes and contact laws. DEMs resort to setting the interaction laws between their elements and strive to calibrate them using micro-scale observations because the continuous equations of motion are often unknown. Existing floe-scale sea ice DEMs use bonded elements of simple preset shapes like disks (Chen et al., 2021; Damsgaard et al., 2018; Herman, 2013), polygons (Kulchitsky et al., 2017), or tetrahedra (Liu & Ji, 2018) to represent complex floe geometries. However, floe-scale modeling remains challenging due to difficulties reconciling discrete elements' idealized nature with complex floe-scale observations. Observations indicate that ice floes vary dramatically in size and shape and change over time due to various processes like fractures, rafting/ridging,

lateral growth/melt, welding, etc. Therefore, using prescribed element shapes creates ambiguity about what elements and bonds between them represent. It is difficult to search for direct correspondence between the state variables of existing sea ice DEMs and real observations without a clear understanding of what an individual DEM element represents.

SubZero was designed as an alternative to continuous rheology models and existing sea ice DEMs to improve the realism of sea ice simulations at floe scales. Floes undergo many processes that affect their shapes, including fracturing, ridging/rafting, and welding, making them concave. In contrast with existing sea ice models that use elements of pre-defined simple shapes, SubZero uses concave polygonal elements that are free to evolve in complexity in response to these parameterized floe-scale processes. The model's capability of developing floe shapes naturally might bring us closer to direct model validation using floe-scale observations and advance our understanding of sea ice physics through idealized process studies.

Acknowledgements

References

Chen, N., Fu, S., & Manucharyan, G. (2021). Lagrangian data assimilation and parameter estimation of an idealized sea ice discrete element model. *Journal of Advances in Modeling Earth Systems*, *13*(10), e2021MS002513. https://doi.org/10.1029/2021MS002513

Coon, M., Kwok, R., Levy, G., Pruis, M., Schreyer, H., & Sulsky, D. (2007). Arctic ice dynamics joint experiment (AIDJEX) assumptions revisited and found inadequate. *Journal of Geophysical Research: Oceans*, *112*(C11). https://doi.org/10.1029/2005JC003393

Cundall, P. A., & Strack, O. D. (1979). A discrete numerical model for granular assemblies. *Geotechnique*, *29*(1), 47–65. https://doi.org/10.1680/geot.1979.29.1.47

Damsgaard, A., Adcroft, A., & Sergienko, O. (2018). Application of discrete element methods to approximate sea ice dynamics. *Journal of Advances in Modeling Earth Systems*, *10*(9), 2228–2244. https://doi.org/10.1029/2018MS001299

Herman, A. (2013). Numerical modeling of force and contact networks in fragmented sea ice. *Annals of Glaciology*, *54*(62), 114–120. https://doi.org/10.3189/2013AoG62A055

Hibler, W. D. (1979). A dynamic thermodynamic sea ice model. *Journal of Physical Oceanography*, *9*(4), 815–846. https://doi.org/10.1175/1520-0485(1979)009%3C0815:ADTSIM%3E2.0.CO;2

Kulchitsky, A., Hutchings, J., Johnson, J., & Lewis, B. (2017). *Siku sea ice discrete element method model*. University of Alaska Fairbanks; Oregon State University. https://www.boem.gov/sites/default/files/boem-newsroom/Library/Publications/2017/BOEM2017-043_CMI_IceModel.pdf

Liu, L., & Ji, S. (2018). Ice load on floating structure simulated with dilated polyhedral discrete element method in broken ice field. *Applied Ocean Research*, *75*, 53–65. https://doi.org/10.1016/j.apor.2018.02.022

Manucharyan, G. E., & Montemuro, B. P. (2022). SubZero: A sea ice model with an explicit representation of the floe life cycle. *Journal of Advances in Modeling Earth Systems*, *14*(12), e2022MS003247. https://doi.org/10.1029/2022MS003247

MATLAB. (2020). *Version 9.8.0 (R2020a)*. The MathWorks Inc.

Montemuro, B., & Manucharyan, G. (2022). *SubZero v1.0.2* (Version v1.0.2). Zenodo. https://doi.org/10.5281/zenodo.7335901

Potyondy, D. O., & Cundall, P. (2004). A bonded-particle model for rock. *International Journal of Rock Mechanics and Mining Sciences*, *41*(8), 1329–1364. https://doi.org/10.1016/j.ijrmms.2004.09.011

Rothrock, D., & Thorndike, A. (1984). Measuring the sea ice floe size distribution. *Journal of Geophysical Research: Oceans*, *89*(C4), 6477–6486. https://doi.org/10.1029/JC089iC04p06477

Stern, H. L., Schweiger, A. J., Zhang, J., & Steele, M. (2018). On reconciling disparate studies of the sea-ice floe size distribution. *Elementa: Science of the Anthropocene*, *6*. https://doi.org/10.1525/elementa.304

Zhang, J., Schweiger, A., Steele, M., & Stern, H. (2015). Sea ice floe size distribution in the marginal ice zone: Theory and numerical experiments. *Journal of Geophysical Research: Oceans*, *120*(5), 3484–3498. https://doi.org/10.1002/2015JC010770