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# GRANULAR ICE SIMULATION FOR BAY OF BOTHNIA

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**FOREWORD**

In this report no 117, the Winter Navigation Research Board presents the results of research project GRICE-BoB, Granular Ice Simulation for the Bay of Bothnia. A granular ice simulation in geophysical length scale was implemented in the Bay of Bothnia. This was done by adapting an existing solver for Baltic sea-ice and GPU acceleration in order to improve sea ice forecasting.

The Winter Navigation Research Board warmly thanks Jonni Lehtiranta for this report.

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# the Grice-BoB project

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## Summary

The Grice-BoB project aimed to introduce granular ice simulation in geophysical length scale and implement it in the Bay of Bothnia. This was done by adapting an existing solver for Baltic sea ice and GPU acceleration, to improve sea ice forecasting by improving the model resolution and introducing a granular approach that is more natural for sea ice that exists as a collection of separate ice floes.

A smoothed particle hydrodynamics (SPH) approach was chosen for this project along with the DualSPHysics solver. The tools for setting up and running these simulations were written and published online. Numerous tests were done to tune the system. However, the results remain inconsistent and more work needs to be done to properly simulate sea ice using this approach. In particular, the incompessible SPH (I-SPH) paradigm, under development, seems promising for sea ice simulation.


## 1 Introduction

Current operational sea ice models solve primitive equations on a regular grid. These models treat sea ice as a homogenous continuum. This assumption is unrealistic for sea ice, which consists of separate ice floes. The continuum assumption only works for length scales much larger than typical floe size, so the model resolution cannot be improved without weakening this assumption. Further, a regular grid doesn't allow high resolution near locations of special interest, such as harbors, shipping lanes and archipelagos.

In contrast, a particle-based granular approach works best at the length scales of ice floes. This approach also solves some problems like numerical diffusion automatically, and the improved resolution brings ice model closer to the ship scale. A Lagrangian, particle-based approach is not limited by a grid, and can easily handle complex coastlines and topography.

Several granular models have been developed (eg. by Mark Hopkins and Agnieszka Herman), but they are computationally expensive. Using modern Graphics Processing Units (GPUs) for acceleration techniques, discrete element simulation of sea ice is becoming possible, in high resolution, in the scale required for Baltic sea basins. The Grice-BoB project sought to bring a new computational approach to operational sea ice forecasting by adapting an existing solver package.

The project aimed at simulating only the sea ice dynamics, not taking thermodynamics into account. Ridging and rafting dynamics were also excluded. As is, the model predicts lead formation and forces in ice, but these also need extra work.

# 2 Choice of the solver

Many solvers exist for granular physics, both proprietary and open source. In this project, the choice was limited to open source solvers and modelling paradigms that have been used for sea ice before. Further, only gridless Lagrangian methods were considered. Two previously used approaches were identified, namely Discrete-Element Models (DEM) and Smoothed-Particle Hydrodynamics (SPH). DEMs are often used in small-scale simulations such as ice - structure interaction studies (Tuhkuri and Polojärvi, 2018), and have been used in Arctic-wide simulations (Hopkins and Thorndike, 2006). The DESIgn sea ice model is freely available, and was considered for this work. SPH models were originally developed for astrophysical simulations and are now primarily used for water, but this approach has been demonstrated for sea ice by several authors (Gutfraind and Savage, 1997; Lindsay and Stern, 2004; Staroszczyk, 2017). However, these models are not publicly available.

The requirements chosen are as follows:

- Solver is GPU accelerated (preferably multi-GPU)
- Solver supports 2-dimensional simulations
- Solver supports external forcing
- Solver supports non-Newtonian rheologies
- Solver allows setting separate properties for different ice classes
- Solver supports arbitrarily complex boundaries

## 2.1 The DESIgn sea ice model

DESIgn is a Discrete-Element bonded-particle Sea Ice model developed by Agnieszka Herman at the University of Gdansk. It is openly available particle-based sea ice model and was considered for this work. It has been used with success in small-scale sea ice simulations, but not in large scale. DESIgn itself is based on the LIGGGHTS discrete element solver, which in turn is based off LAMMPS, which is an atomic/molecular massively parallel simulator. The main atom in the LIGGGHTS for simulating granular materials is the sphere, and the dynamics for these particles is solved in 3D. It is possible to conduct simulations in only two dimensions, but unfortunately this does not mean a reduction in memory requirements or computational time. In DESIgn, disk-shaped particles are implemented. To represent sea ice, these include thickness, and if wave effects are to be taken into account, tilt.

Unfortunately, DESIgn is not available as a GPU-accelerated version. LAMMPS does have two rivalling GPU acceleration packages but both of these still rely on the CPU for some tasks, which implies difficulty in acceleration as moving data back and forth between the GPU and system RAM takes time. Further, LIGGGHTS does not seem to have any support for GPU acceleration. It was deemed possible to introduce GPU acceleration into DESIgn, but this would be complicated. As native GPU codes are rather different than conventional programming, best results are achieved when a solver is designed for GPU acceleration from the start.

DEM models are naturally suited for sea ice, but several unresolved issues remain before DEMs can be used for large-scale sea ice modeling. A considerable effort is needed to solve issues like floe evolution in a DEM framework. (Blockley et al., 2020)

## 2.2 Solvers for smoothed particle hydrodynamics

There are many GPU-accelerated SPH solvers available, and GpuSPH and DualSPHysics were judged to be the most popular and versatile options. They are both accelerated using the NVIDIA CUDA framework. GpuSPH was the first implementation of weakly compressible SPH to run entirely on GPU. It is highly optimized and can run on multiple GPUs. GpuSPH has been used for large-scale multiphase simulations including dam breaks in mountain valleys and lava flows. However, GpuSPH does not support 2D simulation without code modifications.

DualSPHysics builds on an older SPHysics code and has been modified to support GPU as well as CPU simulations. It supports configuration using a free CAD tool, and the documentation and source code are easy to understand and change. DualSPHysics was deemed to fit the set criteria best and was chosen to be used in this project. (Crespo et al., 2015)

The SPH modelling paradigm is granular in the sense that the ice is represented by moving particles, but it still makes use of the continuum hypothesis. Thus, existing continuum physics can be used in an SPH framework - however, a discretization error is made in the smoothing operation built into SPH. Several SPH solvers, including GpuSPH and DualSPHysics, support discrete elements within the SPH simulation. This is a very interesting possibility that, however, could not be pursued within this project.

# 3 The Grice-BoB toolbox

The toolbox built in this project includes the modified DualSPHysics source code, coastline and configurations for an operational setup, and a set of scripts that can be used to run simulations with minimum effort. However, the system could not be fully tuned to match the physical properties of sea ice during the project period. The toolbox is released in a GitHub repository.

## 3.1 Coastline and initial state

Both the coastline and initial model state are formed using icechart data in SIGRID-3 format. This is projected into a suitable transverse mercator format such that projection errors are minimized while running the model in a regular 2D domain. This ice chart data is read and made coarser to decrease the number of different ice categories in the simulation. Then the ice and coast polygons are saved as vector drawing instructions in a format understood by the DualSPHysics package. These drawing instructions are further processed into ice and boundary particles in the specified resolution by the solver. The initial interparticle distance used in tests was 500 meters, but this is configurable in the run scripts. Landfast ice is handled as a set of boundary particles and they remain stationary throughout the simulation.

## 3.2 Wind forcing

The atmospheric forcing used in the project is downloaded from the European Centre for Medium-Range Weather Forecasts (ECMWF). These are produced 4 times per day and come in GRIB format. These files are unpacked using GRIB tools and converted into CSV files to be loaded into the simulation. Currently wind is taken to be uniform across the Bay of Bothnia.

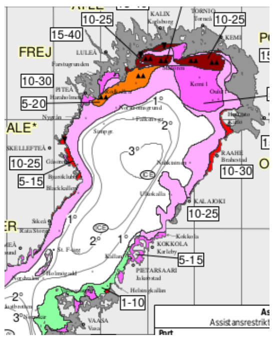
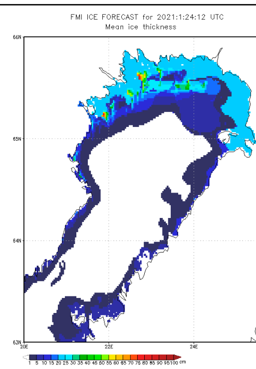
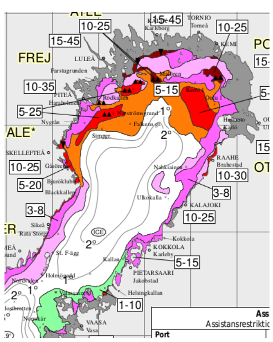
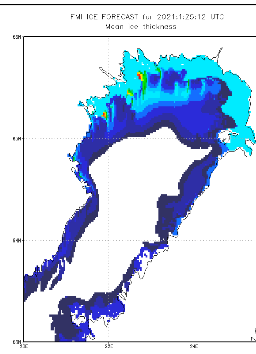
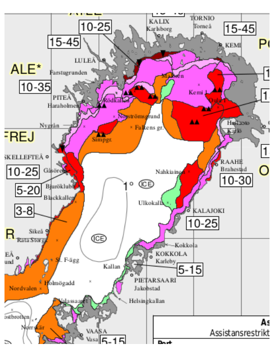
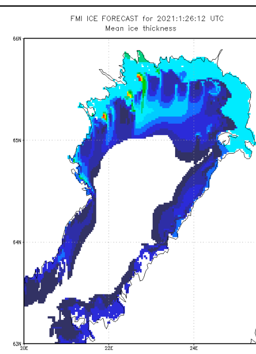
The external forcing code in DualSPHysics was modified to convert wind speeds into drag forces.

# 4 Tests and results

Sea ice simulations have been run for several days in the years 2019 - 2021 and using interparticle distances varying from 500 m to 1600 m. These simulations produce realistic ice velocities in some cases, but also occasional instability and problems caused by the simplifications made in the scope of this project. In the current configuration the model does not melt ice or form new ice by freezing. Further, ice compaction and processes such as ridging and rafting are not taken into account. As expected, this causes clear errors in situations where these phenomena are important. For these reasons, verification is not conducted using statistical data gathered from a large number of simulations.

It is seen in the tests that when wind blows from the coast, a coastal lead always form at the fast ice edge. One such situation is presented below.

## 4.1 Coastal lead formation in january 2021

| | Ice chart | Helmi forecast | Grice-BoB |
|---|---|---|---|
| 24.1. |  |  |  |
| 25.1. |  |  |  |
| 26.1. |  |  |  |

One case when the Grice-BoB simulation works is the period between 24. January and 26. January 2021. Winds were mostly northerly and blowing at 5 - 8 m/s. In the ice charts, a patch of consolidated ice (dark red) is easily visible on the 24th day. The consolidated ice moves southwards and is replaced by thin ice (light purple). In the Helmi forecast, similar southward movement of thicker ice (light blue) is also evident. The Grice-BoB simulation produces a similar outcome. It should be noted that the physical meaning of the colors are different in each case. The ice chart shows different ice types as determined by ice service personnel, the Helmi forecast is showing mean ice thickness, and the Grice-BoB output is only showing fast ice and drift ice separately.

These three views on the sea ice development match, but they also reveal differences. Neither of the numerical models produce the correct shape of ice edge or the change in landfast ice region. Further, the Grice-BoB model erroneously interprets some of the consolidated ice as landfast ice and doesn't melt ice even when needed.

# 5 Discussion

Challenges resulting from SPH numerics remain. Current established SPH solvers employ a weakly compressible formulation. This causes internal oscillations in the pressure field. The easiest way to alleviate the problem is to apply spatial filtering to the density field. Other solutions exist, but some rely on an external body force, such as gravity, acting on the particles in the simulation. The method also tends to create unphysical gaps between ice particles and boundaries.

One possibility to alleviate these issues is to include discrete ice elements into the simulation. This is supported by the DualSPHysics solver, but could not be done within this project. Large ice floes, perhaps consisting of consolidated deformed ice, could be modelled as discrete polygonal elements interacting with more broken ice simulated as a continuum of smoothed particles. It would be challenging, however, to initialize these discrete inclusions, and a selection should be made to only include ice floes that can be assumed to keep their shape.

Another possibility to solve these issues could be using newer SPH schemes, such as Incompressible SPH (I-SPH). While conventional SPH simulations employ explicit time stepping and assume weak compressibility. I-SPH employs implicit time stepping and no numerical compressibility. This necessitates an iterative solver which comes with a computational cost, but allows far longer time steps to be taken. The result is the complete disappearance of internal oscillations caused by weak compressibility. I-SPH implementations exist, but the DualSPHysics package doesn't come with an incompressible SPH solver yet.

# 6 Summary

The DualSPHysics solver has been augmented to simulate sea ice on the Bay of Bothnia. Codes have been written to run a short-term forecast for current or past dates based on ice charts and wind forecasts as produced by FMI and ECMWF respectively. However, issues affecting the stability and accuracy of the forecast remain to be solved in the future. These issues will be addressed in the author's Ph.D work.

The work demonstrates the Smoothed Particle Hydrodynamics approach for sea ice in the geophysical scale and its applicability for high-resolution simulations in complex coastal regions. Problems stemming from weakly compressible SPH formulation remain. Many of them have recent solutions in literature, but these are currently not available yet in solver codes.

Many different approaches are under research for the future of sea ice modelling. The question of rheology has seen recent developments, coastal ocean models are adopting unstructured grids, and the neXtSIM sea ice model employs a dynamically changing computational grid. Gridless methods such as DEM and SPH remain promising modelling paradigms, but more work needs to be done before these could challenge the established sea ice forecast models.

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