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WAVI.jl: Ice Sheet Modelling in Julia

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Software

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Summary

Ice sheet models are used to improve our understanding of the past, present, and future evolution of ice sheets. To do so, they solve the equations describing the flow of ice when forced by other climate elements, particularly the atmosphere and oceans. We present `WAVI.jl`, an ice sheet model written in Julia. `WAVI.jl` is designed to lower the bar to ice sheet modelling, whilst including sufficient detail to be used for addressing cutting-edge research questions.

Statement of Need

Ice sheet models allow us to simulate the behaviour and evolution of ice sheets, which are large masses of glacial land and marine ice. There are two main uses of ice sheet models: firstly, prognostic use, which involves making predictions about the future of ice sheets. Prognostic predictions often relate to sea level rise contributions: the world's two largest ice sheets, located in Antarctica and Greenland, hold enough ice to raise sea levels by approximately 58 and 7 meters, respectively (Bamber et al., 2018); prognostic modelling of these ice sheets enables us to make predictions on (for example) how much of this ice will be lost (Edwards et al., 2021), to investigate the possibility of runaway ice loss (DeConto et al., 2021), and analyze whether or not such instabilities have already been initiated (Favier et al., 2014). Secondly, ice sheet models are also used diagnostically, which involves using a model to investigate processes controlling the behaviour of an ice sheet, such as how loss of ice shelves – the floating extensions of ice sheets – influences ice flow speed (Joughin et al., 2021), how different bed conditions affect ice sliding (De Rydt et al., 2021), and probing the conditions under which so-called 'tipping-points' might be passed (Schoof, 2007).

On the long [O(1000s km)] lengthscales that are relevant to ice sheets, ice behaves approximately as a highly viscous fluid with a shear-thinning rheology (meaning that as the ice deforms, it becomes thinner and flows more easily). `WAVI.jl` (Wavelet-based Adaptive-grid Vertically-integrated Ice-sheet-model) is a Julia package for the numerical solution of an accurate approximation to the Stokes equations, which describe conservation of mass and momentum in such a fluid. This approximation, which is appropriate for fluid flows with a high aspect ratio (as is the case for the vast majority of ice sheets), treats longitudinal and lateral stresses as depth independent, but accounts for vertical velocity gradients in the nonlinear viscosity and in the treatment of basal stress (Goldberg, 2011).

Physically, ice sheets do not stand alone, but are forced by other parts of the climate system. For example, the rapid changes that have occurred in the West Antarctic Ice Sheet in the previous decades are understood to have been driven by an increase in oceanic heat content reaching the floating ice shelves which fringe this region(Pritchard et al., 2012). For basal melting in particular, `WAVI.jl` includes a broad range of community melt rate parametrizations (Asay-Davis et al., 2017), as well as a developmental coupling with the ocean general circulation model MITgcm (Marshall et al., 1997). More generally, `WAVI.jl` leverages Julia's multiple dispatch paradigm to create a simple, user-friendly interface for embedding models of other physical processes, such as accumulation, ice damage, ice shelf calving, and solid earth effects, into `WAVI.jl`.

`WAVI.jl` is designed to be usable by anyone interested in ice sheet modelling, from students with no programming experience to expert researchers in the field, and everyone in between. To facilitate detailed research, including simulations at high spatial and temporal resolution, `WAVI.jl` employs a number of tools to improve computational speed, including multithreading capabilities, an adaptive numerical grid and a wavelet-based preconditioner (Arthern & Williams, 2017). To facilitate accessibility, `WAVI.jl` includes a simple, user friendly API, which is aided by Julia's convenient syntax. In addition, the GitHub repository in which the code is stored includes a number of well-documented examples, which demonstrate the software's capabilities in a wide variety of situations.

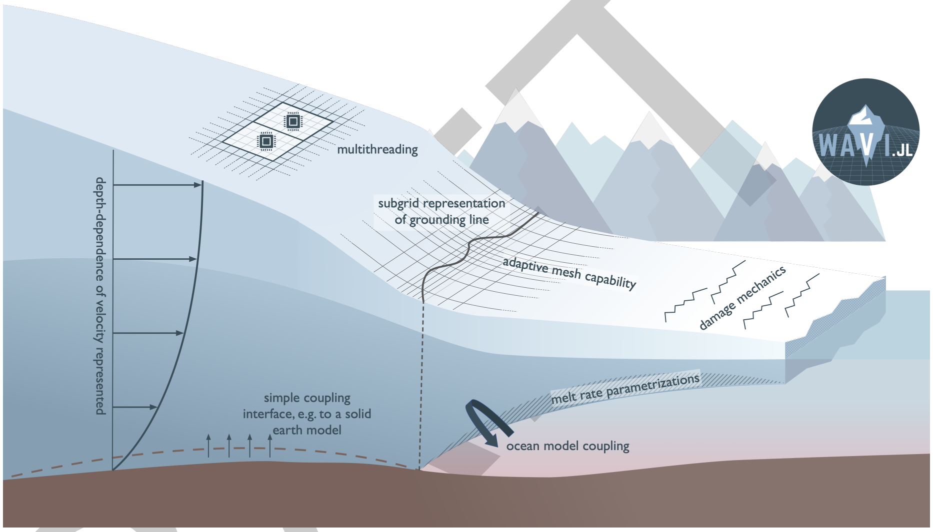

Figure 1: Schematic diagram of a marine ice sheet-shelf system, whose flow may be simulated using WAVI.jl. Labels and text indicate features of the software.

`WAVI.jl` is the successor to a similar code, written in the proprietary programming language MATLAB, which was never publicly released. This previous code has been used extensively as research software [e.g. (Arthern & Williams, 2017), (Arthern et al., 2015)], as well as having participated in the most recent ice sheet model intercomparison exercise (Cornford et al., 2020), which acts as a benchmark for ice-flow models. The new version, `WAVI.jl`, has also been verified independently against these benchmark experiments.

There exists a wide variety of ice sheet models with varying levels of complexity. Examples include (but are certainly not limited to) the Ice Sheet System Model (Larour et al., 2012), the Parallel Ice Sheet Model (Bueler & Brown, 2009), BISICLES (Cornford et al., 2013), Elmer/Ice (Gagliardini et al., 2013), and Úa (Gudmundsson, 2019). Every ice sheet model makes approximations in order to facilitate the numerical solution of the appropriate governing equations; since these equations have no analytic solutions, the *intercomparison* between ice sheet models is of paramount importance when assessing the trustworthiness of models; `WAVI.jl` contributes to this community of ice sheet models. `WAVI.jl` is also, to our knowledge, the first ice sheet model written entirely in Julia and, alongside other accessible ice sheet models such as IcePack (Shapero et al., 2020), helps to lower the barrier to entering ice sheet modelling.

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