

¹ ODINN.jl: Scientific machine learning glacier modelling

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¹² Summary

¹³ ODINN.jl is a glacier model leveraging scientific machine learning (SciML) methods to perform
¹⁴ forward and inverse simulations of large-scale glacier evolution. It can simulate both surface
¹⁵ mass balance and ice flow dynamics through a modular architecture which enables the user
¹⁶ to easily modify model components. For this, ODINN.jl is in fact an ecosystem composed of
¹⁷ multiple packages, each one handling a specific task:

- [Sleipnir.jl](#): Handles all the basic types, functions and datasets, common through the whole ecosystem, as well as data management tasks.
- [Muninn.jl](#): Handles surface mass balance processes, via different types of models.
- [Huginn.jl](#): Handles ice flow dynamics, by solving the ice flow partial differential equations (PDEs) using numerical methods. It can accommodate multiple types of ice flow models.
- [ODINN.jl](#): Acts as the interface to the whole ecosystem, and provides the necessary tools to differentiate and optimize any model component. It can be seen as the SciML layer, enabling different types of inverse methods, using hybrid models combining differential equations with data-driven models.

²⁷ Splitting large Julia ([Bezanson et al., 2017](#)) packages into smaller, focused subpackages is a good practice that enhances maintainability, usability, and collaboration. Modular design simplifies debugging, testing, and updates by isolating functionalities, while users benefit from faster precompilation and reduced memory overhead by loading only the subpackages they need. This approach also lowers the barrier for new contributors, fosters clearer dependency management, and ensures scalability as projects grow, ultimately creating a robust and adaptable software ecosystem. The ODINN ecosystem extends beyond this suite of Julia packages, by leveraging the data preprocessing tools of the Open Global Glacier Model (OGGM, [Maussion et al. \(2019\)](#)). We do so via an auxiliary Python library named Gungnir, which is responsible for generating all the necessary data to force and initialize the model, such as glacier outlines from the Randolph Glacier Inventory (RGI Consortium [\(2023\)](#), RGI), digital elevation models (DEMs), ice thickness observations from GlaThiDa ([Consortium, 2020](#)), ice surface velocities from different studies ([Millan et al., 2022](#)), and different sources of climate reanalyses and projections ([Eyring et al., 2016](#); [Lange, 2019](#)). This implies that ODINN.jl, like OGGM, is virtually capable of simulating any of the ~274,000 glaciers on Earth ([RGI Consortium, 2023](#)).

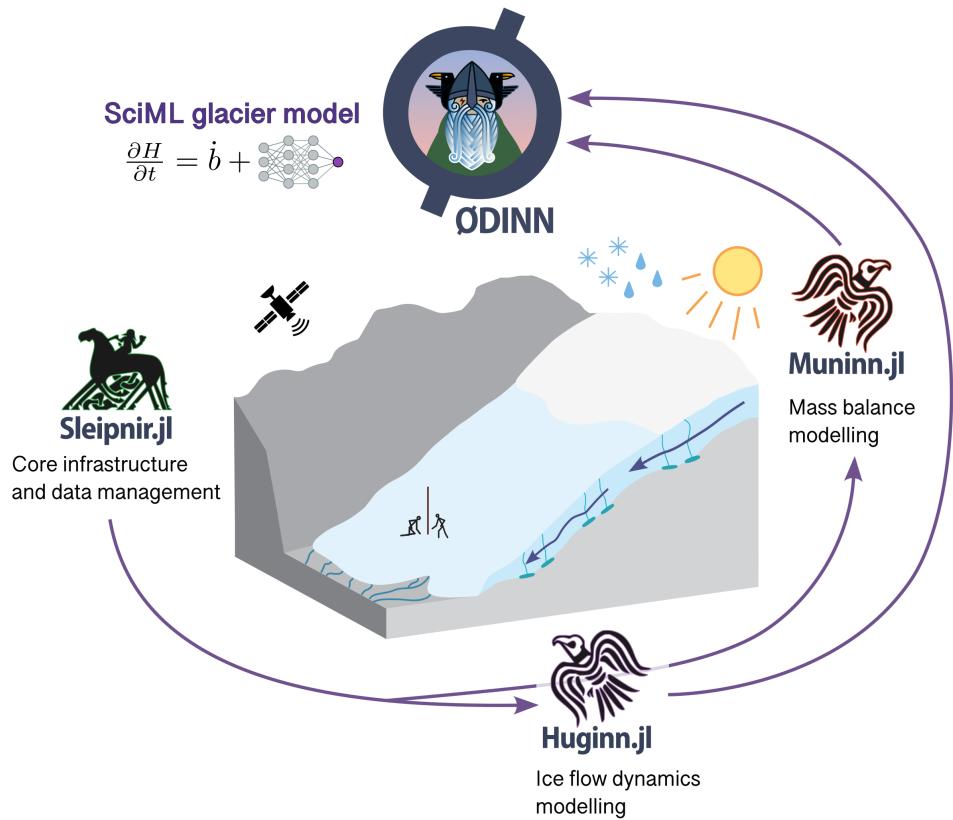


Figure 1: Overview of the ODINN.jl ecosystem.

43 ODINN.jl provides a high-level user-friendly interface, enabling the user to swap and replace
 44 most elements of a glacier simulation in a very modular fashion. The main elements of a
 45 simulation, such as the Parameters, a Model and a Simulation (i.e. a Prediction or an
 46 Inversion), are all objects that can be easily modified and combined. In a few lines of
 47 code, the user can automatically retrieve all necessary information for most glaciers on Earth,
 48 compose a Model based on a specific combination of surface mass balance and ice flow models,
 49 and incorporate data-driven models (e.g. a neural network) to parametrize specific physical
 50 processes of any of these components. Both forward and inverse simulations run in parallel
 51 using multiprocessing, leveraging Julia's speed and performance. Graphics Processing Unit
 52 (GPU) compatibility is still not ready, due to the difficulties of making GPU architectures
 53 compatible with automatic differentiation (AD). Nonetheless, it is planned for future versions.

54 The most unique aspect of ODINN.jl is its differentiability and capabilities of performing
 55 all sorts of different hybrid modelling. Since the whole ecosystem is differentiable (where
 56 differentiable means the ability to compute model derivatives with respect to parameters
 57 (Shen et al., 2023)), we can optimize almost any model component, providing an extremely
 58 powerful framework to tackle many scientific problems (Bolibar et al., 2023). ODINN.jl can
 59 optimize, separately or together, in a steady-state (time-independent simulation) or transient
 60 (time-dependent simulation) way the following model parameters:

- 61 ▪ The initial or intermediate state of glaciers (i.e. their ice thickness) or the equivalent ice
 62 surface velocities.
- 63 ▪ Model parameters (e.g. the Glen coefficient A related to ice viscosity in a 2D Shallow
 64 Ice Approximation (Hutter, 1983)), in a gridded or scalar format. This can be done for
 65 multiple time steps where observations (e.g. ice surface velocities) are available.

- 66 ▪ The parameters of a statistical regressor (e.g. a neural network), used to parametrize a
67 subpart or one or more coefficients of an ice flow or surface mass balance mechanistic
68 model. This enables the exploration of empirical laws describing physical processes of
69 glaciers, leveraging Universal Differential Equations (UDEs, Christopher Rackauckas et
70 al. (2021)).
- 71 For this, it is necessary to differentiate (that is, computing gradients or derivatives) through
72 complex code, including numerical solvers, which is a non-trivial task (Sapienza et al., 2024).
73 We use reverse differentiation based on the adjoint method to achieve this. We have two
74 strategies for computing both the adjoint and the required vector-jacobian products (VJPs):
75 (1) manual adjoints, which have been implemented using AD via Enzyme.jl (Moses et al.,
76 2021), as well as fully manual implementations of the spatially discrete and spatially continuous
77 VJPs; and (2) automatic adjoints using SciMLSensitivity.jl (Chris Rackauckas et al., 2019),
78 available with different AD back-ends for the VJPs computation. These two approaches are
79 complementary, with the manual adjoints being ideal for high-performance tasks by providing
80 more control on the implementation, and serving as a ground truth for benchmarking and
81 testing automatic adjoint methods from SciMLSensitivity.jl.
- 82 Beyond all these inverse modelling capabilities, ODINN.jl can also act as a more conventional
83 forward glacier model, simulating glaciers in parallel, and easily customizing different model
84 parametrizations and choices within the simulation. Its high modularity, combined with the easy
85 access to a vast array of datasets coming from OGGM, makes it very easy to run simulations,
86 even with a simple laptop. Huginn.jl is responsible for the ice flow dynamics models, with
87 an architecture capable of integrating and easily swapping various models. Models based on
88 partial differential equations (PDEs) are solved using DifferentialEquations.jl (Christopher
89 Rackauckas & Nie, 2017), which provides access to a huge amount of numerical solvers. For
90 now, we have implemented a 2D Shallow Ice Approximation (SIA, Hutter (1983)), but in the
91 future we plan to incorporate other models, such as the Shallow Shelf Approximation (SSA, Weis
92 et al. (1999)). Validation of numerical forward simulations are evaluated in the test suite based
93 on exact analytical solutions of the SIA equation (Bueler et al., 2005). Muninn.jl incorporates
94 surface mass balance models based on simple temperature-index models. Nonetheless, the
95 main addition of the upcoming version will be the machine learning-based models from the
96 MassBalanceMachine (Sjursen et al., 2025), which will provide further mass balance models.

97 Statement of need

98 ODINN.jl addresses the need for a glacier model that combines the physical interpretability of
99 mechanistic approaches with the flexibility and data-assimilation capabilities of data-driven
100 methods (Bolibar et al., 2023). By integrating both paradigms, it enables targeted inverse
101 methods to learn parametrizations of glacier processes, capturing unknown physics while
102 preserving the physically grounded structure of glacier dynamics through differential equations.
103 While purely mechanistic and purely data-driven glacier models already exist (e.g. Gagliardini
104 et al. (2013), Maussion et al. (2019), Rounce et al. (2023), Bolibar et al. (2022)), they
105 often lack the flexibility needed to fully exploit the growing wealth of glacier observations, such
106 as ice surface velocities, ice thickness, surface topography, surface mass balance or climate
107 reanalyses. Existing empirical laws do not always link directly to these observables, making
108 their calibration challenging. Approaches based on differentiable programming and functional
109 inversions offer a path forward, allowing the derivation of new empirical relationships from
110 carefully chosen proxies and providing a framework to test hypotheses about poorly understood
111 physical processes such as basal sliding, creep, or calving.
112 Improving the representation of these complex processes is crucial for accurate projections of
113 glacier evolution and their impacts on freshwater availability and sea-level rise (IPCC, 2021).
114 To this end, ODINN.jl provides a unified modelling ecosystem that supports both advanced
115 inverse methods for model calibration and efficient, modular forward simulations for large-scale

¹¹⁶ glacier studies.

¹¹⁷ Developing such a framework places demanding requirements on scientific software. Inefficient
¹¹⁸ codes and irreproducible implementations can severely restrict progress, emphasizing the
¹¹⁹ importance of open-source, community-driven tools that follow modern research software
¹²⁰ engineering (RSE) practices (Combemale et al., 2023). For this end, software should support
¹²¹ modular and adaptable design patterns that enable prototyping and augmentation of existing
¹²² pipelines (Nyenah et al., 2024). The Julia programming language provides two key advantages in
¹²³ this context: it solves the two-language problem by offering Python-like high-level expressiveness
¹²⁴ with C-level performance (Bezanson et al., 2017), and it enables source-code differentiability,
¹²⁵ essential for modular gradient-based optimization in inverse modelling and setting the foundation
¹²⁶ for a strong ecosystem where hybrid modelling, and particularly UDEs, can thrive. With
¹²⁷ ODINN.jl, our goal is to provide a robust and future-proof modelling framework that bridges
¹²⁸ the gap between physical understanding and data-driven discovery. Its modular architecture,
¹²⁹ thorough testing, and continuous integration (CI) ensure reproducibility and reliability, while its
¹³⁰ open design invites collaborations and both methodological and applied advancements across
¹³¹ the glaciological and Earth system modelling communities.

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