BedSAT: Antarctica

Exploring what lies beneath using big data and modelling

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Impact Statement

Antarctica's bed topography data currently has local uncertainties of hundreds of metres in elevation due to sparse and unevenly distributed radar surveys, significantly limiting our ability to predict ice sheet behaviour and sea level rise contributions. Through the BedSAT project, I am developing a novel modelling approach that integrates remote sensing data and airborne-derived estimates, with mathematical and numerical ice flow models to substantially improve bed topography resolution and accuracy. I aim to derive a continent-wide bed topography dataset and conduct sensitivity analyses of dynamic ice loss to different realisations of topographic roughness through 2300CE. My work will quantify how bed topography uncertainties affect ice mass loss projections. This improved understanding can provide more reliable sea level rise predictions, and enable evidence-based policy decisions for climate adaptation strategies. This open-source approach and FAIR data principles will ensure these improvements benefit the broader scientific community and support more effective climate change mitigation planning.

Contents

Research problem

Bed topography is one of the most crucial boundary conditions that influences ice flow and loss from the Antarctic Ice Sheet (AIS) [1]. Bed topography datasets are typically generated from airborne radar surveys, which are sparse and unevenly distributed across the Antarctic continent. Interpolation schemes to "gap fill" these sparse datasets yield bed topography estimates that have high uncertainties (i.e. multiple hundreds of metres in elevation uncertainty; Morlighem et al. 2020) which propagate through simulations of AIS evolution under climate change [2]. Given the logistical challenges of accessing large parts of the Antarctic continent, there is a crucial need for alternative approaches that integrate diverse and possibly more spatially complete data streams – including satellite data.

1.1 Approaches to Bed Topography Reconstruction

An objective of my research is to understand the bed topography itself and how it influences ice dynamics. There are two ways to infer information about this relationship: Through forward modelling, with assumptions of the bed conditions; and through inverse modelling that relies on surface observations.

- **Forward models**
  The aim of forward models is to see how bed properties impact ice dynamics. A key example is using a large ensemble of bed topographies to investigate how bed uncertainties impact simulated ice mass loss. The generated bed topographies preserve elevation or texture:

  - **Geostatistics** statistical methods specialized for analyzing spatially correlated data. This approach is used to interpolate between sparse measurements and characterise spatial patterns in bed properties [3].

- **Inversion models**
  The aim of these models is to understand bed properties through knowledge of surface or other variables. A key example is the retrieval of bed topography or basal slipperiness from surface elevation and velocities.

  - **Control method inversion**: A variational approach that minimizes mismatches between observed and simulated fields through a cost function approach. Remote sensing data and theoretical ice flow models are used to obtain basal conditions [4]. Often needs regularization terms to prevent non-physical features or over-fitting [5].

- **4dvar**: Four-dimensional variational data assimilation - Similar to the control method inversion algorithm, but adds a time dimension. Used to optimize model parameters and initial conditions [5]. Can handle time-varying data and evolving glacier states, making it more suitable for dynamic systems unlike control methods. The trade-off for extra functionallity is increased computational cost [5].
- **Mass conservation**: Used to constrain inversion models and fill data gaps by employing physical conservation laws, particularly effective for reconstructing bed topography where direct measurements are sparse [1, 6]. Requires (contemporary) measurements of ice thickness at the inflow boundary to properly constrain the system [5].
- **Markov Chain Monte Carlo (MCMC)**: A probabilistic method that generates sample distributions to quantify uncertainties in ice sheet parameters and models [5]. While powerful for uncertainty quantification, these methods remain computationally intensive for continental-scale ice sheet models [5].
- **EnKF** Ensemble Kalman Filter. A sequential data assimilation method that uses an ensemble of model states to estimate uncertainty and update model parameters based on observations [5].

My research aims to develop an integrated method combining forward and inverse modeling to improve bed topography estimates by leveraging high-resolution satellite surface data in regions where radar data is sparse.

1.2 Theoretical Frameworks

Understanding how bed features manifest in surface observations requires a theoretical framework that connects these two domains.

1.2.1 Ice Flow Over Bedrock Perturbations - Budd 1970

The model by Budd [7] relates ice flow over bedrock perturbations to surface expressions. Budd's theory makes several key predictions that have been confirmed through spectral analysis of real ice cap profiles:

1. A basal disturbance wavelength of minimum damping occurs at approximately 3.3 times the ice thickness,

2. Surface undulations exhibit a $\pi/2$ phase lag relative to bedrock features with steepest surface slopes occurring over the highest bedrock points, and

3. The amplitude reduction depends systematically on ice speed, viscosity, thickness, and wavelength.

This theory demonstrates that energy dissipation and basal stress patterns are maximized for bedrock irregularities with wavelengths several times the ice thickness, while smaller-scale bedrock variations decay exponentially with distance into the ice and have minimal impact on overall ice motion. This selective filtering of bedrock signals provides crucial insights for understanding which scales of bed topography most significantly influence ice dynamics. A critical aspect of Budd's theoretical framework is understanding how ice rheology affects the bed-to-surface transfer relationships. Glen's flow law typically employs a stress exponent $n \approx 3$ for ice under most natural conditions, reflecting the strongly non-linear relationship between stress and strain rate. However, more recent research suggests that $n = 4$ may better represent ice flow in some locations [8]. Budd's analysis revealed that under certain low-stress conditions, ice deformation can behave more linearly ($n \approx 1$) than conventional wisdom suggests. This rheological distinction has profound implications for bed-to-surface transfer functions: because linear rheology ($n = 1$) may produce different amplitude dampening and phase relationships compared to nonlinear rheology ($n = 4$), particularly for wavelengths around the critical 3.3 times ice thickness scale. My current modelling work systematically explores this by generating forward models for multiple synthetic bedrock profiles across four scenarios combining rheological assumptions ($n = 1$ vs $n = 4$) with basal boundary conditions (no-slip vs sliding), enabling direct comparison of how these physical assumptions affect the detectability and reconstruction of bed features from surface observations. Understanding these differences is essential for developing robust inversion methods, as the choice of rheological model fundamentally determines the mathematical relationship between observable surface expressions and the underlying bed topography I seek to reconstruct. Crucially, Budd's work established the concept of frequency-dependent transfer functions that act as "filters" between bed and surface topography. This transfer function approach, expressed as $\psi(\omega) = \frac{\text{surface amplitude}}{\text{bed amplitude}}$ for wavelength $\lambda = 2\pi/\omega$, provides a direct mathematical framework for inversion. By inverting these transfer functions, one can theoretically reconstruct bed topography from surface observations, particularly for wavelengths where the damping factor is minimal and the signal-to-noise ratio is optimal.

1.2.2 Ice flow perturbation analysis - Ockenden 2023

Ockenden et al. (2023) use observed surface perturbations (in velocity and elevation) to invert for unknown basal perturbations. Ockenden et al. improve from their previous work in [9] by using full-Stokes transfer functions, which greatly improves their method when dealing with steep topography where the shallow-ice-stream approximation breaks down. They find this is crucial for better resolving the topographic features they are interested in. The core principle relies on the fact that variations in basal topography, slipperiness, and roughness cause measurable disturbances to the surface flow of the ice. Through linear perturbation analysis, they establish a systematic relationship between surface observations and bed conditions. The relationship is based on the forward model transfer function refined by Gudmundsson and Raymond in 2008 [10]. Ockenden et al apply this framework in reverse to infer the bedrock from modern, high-resolution satellite data estimates. A restrictive assumption in the modeling design by Ockenden et al might be their assumption of “constant viscosity”, this means that the strain rate is directly proportional to the stress. This is in contrast to the more commonly used non-linear Glen’s Flow Law, where n is typically around 3 or even 4.

1.3 Bridging Classical and Modern Approaches

Budd’s approach provides fundamental physical understanding of how specific wavelengths propagate through ice, establishing theoretical limits on what bed features can be detected from surface observations. Ockenden’s method extends this to practical applications using real satellite data but relies on linearised assumptions that may break down under certain conditions. By systematically exploring how different rheological models ($n = 1$ vs $n = 4$) and basal conditions affect the bed-to-surface transfer functions, my work aims to develop a robust inversion method that can better handle the nonlinear physics of ice flow. While simultaneously utilising the wealth of presently available satellite-derived surface data. My approach with BedSAT builds upon theoretical foundations and recent inversion methods to better understand how bed conditions—including slipperiness, roughness, and pinning points—affect both grounding line retreat rates and their surface expressions. BedSAT will connect surface observations with bed topography using more realistic rheological and geometric assumptions through an iterative process: Initially inverted bed topography integrated into forward models allowing for progressive improvement, ensuring the process is constrained and validated by independent established datasets like NASA’s ITS_LIVE and REMA (DEM).

1.4 Physics-Informed Machine Learning for Bed Topography Inversion

In the rheology and sliding study in section 3.1, I am establishing a “forward problem” investigation—how bed topography influences surface expression—under various physical assumptions. However, the goal of BedSAT is to solve the “inverse problem”: Inferring bed topography from surface observations. I plan to use Physics-Informed Machine Learning (Physics-ML), leveraging NVIDIA PhysicsNeMo which is designed to create high-fidelity, deep learning models, blending the governing physics of a system—Partial Differential Equations (PDEs)—with training data [11].

1. Forward model training: PhysicsNeMo can learn the relationship between ice sheet surface velocity and elevation to bed topography, basal sliding and ice rheology ($n = 1$ vs $n = 4$). The model can then generate vast amounts of synthetic training data—including variations with statistically realistic aeolian noise—orders of magnitude faster than a traditional ISSM solver.

2. Solving the Inverse Problem: PhysicsNeMo is explicitly designed to solve inverse problems by using observational data to infer unknown system parameters [11]. BedSAT will rely on the PhysicsNeMo data-driven architecture to learn the mapping from surface expression to bed topography, effectively creating a fast and accurate inverse solver.

By integrating PhysicsNeMo, BedSAT will develop into a model capable of near real-time inference, satisfying my project's third objective: Allowing for rapid sensitivity analyses of ice mass loss projections to different realisations of topographic roughness. This approach goes beyond traditional inversion methods, enhancing computational efficiency and physical realism of Antarctic bed topography reconstruction.

1.5 Research Significance

The polar regions are losing ice, and their oceans are changing rapidly [12]. The consequences of this extend to the whole planet and it is crucial for us to understand them to be able to evaluate the costs and benefits of potential mitigation strategies. Changes in different kinds of polar ice affect many connected systems. Of particular concern is the accelerating loss of continental ice sheets (glacial ice masses on land) in both Greenland and Antarctica, which has become a major contributor to global sea level rise [12]. Impacts extend beyond direct ice loss: as fresh water from melting ice sheets is added into the ocean, it increases ocean stratification disrupting global thermohaline circulation [13]. In addition, cold freshwater can dissolve larger amounts of CO_2 than regular ocean water creating corrosive conditions for marine life [12]. While there is high confidence in current ice loss and retreat observations in many areas, there is more uncertainty about the mechanisms driving these changes and their future progression [14]. Uncertainty increases in regions with variable bed conditions, where characteristics like bed slipperiness and roughness are difficult to verify via direct observations. Other problematic areas involve the ice sheet grounding line (GL): The zone that delineates ice grounded on bedrock from ice shelves floating over the ocean. The GL retreat rate depends crucially on topographical features like pinning points [14], which lead to increased buttressing by the ice shelf on the upstream ice sheet. Although this mechanism is established, major knowledge gaps persist in mapping bed topography across Antarctic ice sheet margins, with over half of all margin areas having insufficient data within 5 km of the grounding zone [15]. Addressing this data gap through both systematic mapping and improved interpolation —utilising auxiliary data streams with more complete coverage— would significantly improve both our understanding of current ice dynamics and the accuracy of ice-sheet models projecting future changes.

1.5.1 Writing Contributions: Bed Topography Estimation

I have helped evaluating existing methodologies to address the critical data gaps in Antarctic bed topography products by participating in writing two distinct works. In the manuscript titled"Synthetic bed topographies for Antarctica and their utility in ice sheet modelling". This review establishes the theoretical context for the paper's case study and documents the most recent techniques used in the field. A key outcome of this investigation was the identification of persistent limitations in widely-used interpolation techniques. Many established methods struggle to provide robust uncertainty estimates, avoid systematic biases, or realistically capture the spatial correlation of errors. In the manuscript **"Antarctic bed topography estimation using a Stochastic Meshless Uncertainty Gridding (SMUG) method". we establish the scientific rationale for SMUG. and articulate specific shortcomings of methods used in foundational datasets like Bedmap1, Bedmap2, and BedMachine. Setting the stage for introducing SMUG as a method designed to overcome these specific challenges. Together, these contributions represent a cohesive research effort, moving from a comprehensive assessment of existing tools to the justification and development of a next-generation approach for Antarctic bed mapping.

1.6 Aims

My research plan is structured around these three broad research questions:

1. How does the bed topography manifest on the ice surface?

2. To what extent do interpolation uncertainties in bed topography datasets affect the accuracy of Antarctic Ice Sheet evolution simulations under different climate change scenarios?

3. What is the impact of variable bed conditions and topography on the rate of grounding line (GL) retreat in continental ice sheets?

Underpinning these research questions are the following objectives (O):

- O1: Develop an ice sheet modelling approach to assimilate satellite remote sensing datasets to improve knowledge of the bed (BedSAT) informed by mathematical models of ice flow over topography;

- O2: Derive a new bed topography for Antarctica using BedSAT;

- O3: Evaluate the impact of the improved bed topography on projections of ice mass loss from Antarctica under climate warming through sensitivity analyses.

Methods

In order to achieve my objectives, each objective will be addressed in sequential phases. My primary focus is currently on O1: Deriving the BedSAT method. As the initial phase of O1, I am working on an investigation on the influence of different combinations of rheological and sliding law assumptions in ice sheet modeling. The goal of this investigation is to systematically understand the forward problem —how the bed affects the surface under different physical rules— to then use that knowledge to build a better inverse model (BedSAT).

2.1 Analysis of Bed-to-Surface Signal Transfer

The first critical step is to systematically quantify how fundamental physical assumptions influence the expression of subglacial topography at the ice surface. This directly addresses my first research question: "How does the bed topography manifest on the ice surface?". This work will leverage the Ice-sheet and Sea-level System Model (ISSM) [16] with a custom-built computational framework based on a synthetic bed topography database. ISSM is a state-of-the-art ice sheet model; It is well tested and supported by multiple developers, making it a robust choice for my project. This systematic study will verify and validate the necessary set of constraints on bed-to-surface transfer functions that account for realistic ice dynamics, taking into consideration different parameterisations, sliding laws and parameter values.

2.2 Development of the BedSAT Inversion Framework

By understanding how rheology and sliding conditions alter the surface expression of the bed, I can develop more physically robust transfer functions for the inversion process. The inversion model will be developed and tested using a regional catchment in Antarctica with extensive radar data, such as the Aurora Subglacial Basin (this data can be found in works such as [17]). The model will be constrained by available observations of surface velocity, thermal distribution, and ice thickness, this will allow for direct validation of the inversion results against known bed configurations. My methodology will include a pre-processing step to filter out high-frequency surface noise (e.g., aeolian features [18]), this process will be guided by consultation with experts in the field. Furthermore, the robustness of the model will be ensured through grid independence testing and a sensitivity analysis of model assumptions. See Chapter 3 for detailed information on the progress of this work.

2.3 Derive a new bed topography for Antarctica using BedSAT

I will apply the validated BedSAT methodology from O1 to the entire Antarctic continent, deriving a new continent-wide bed topography dataset. Using covariance properties from existing radar surveys, I will generate multiple realisations of the bed, each with unique and statistically-consistent topographic roughness.

2.4 Evaluate the impact of improved bed topography

The new bed topography datasets will be used to conduct a sensitivity analysis of ice sheet model projections to 2300 CE. This will investigate the impact of the improved topography and different roughness realisations on ice dynamics, subglacial hydrology, and overall ice mass loss from Antarctica, directly addressing the project's main research questions.
Note: Detailed methodological outlines for O2 and O3 will be developed following the completion and refinement of the BedSAT method in O1.

Progress

3.1 Rheology and Sliding Study

Building upon the diagnostic ISMIP-HOM experiments in [19], I extend the prognostic experiment F to systematically investigate the combined effects of rheology and basal sliding within this benchmark ice sheet model. The original experiment F included two scenarios: One with a frozen bed (no-slip) and another with linear sliding. My study expands upon these conditions by also incorporating non-linear rheology. This addition generates four distinct scenarios for comparison:

- **S1:** No-slip (frozen) bed + Linear rheology ($n = 1$).
- **S2:** No-slip (frozen) bed + Non-linear rheology ($n = 4$).
- **S3:** Linear sliding + Linear rheology ($n = 1$).
- **S4:** Linear sliding + Non-linear rheology ($n = 4$).

The method I follow to ensure that different model rheologies start from identical initial conditions is based on the re-scaling method by Getraer and Morlighem (2025) [8]. Their formula ensures that the initial ice viscosity—and therefore strain rates for a given stress—is identical between simulations with different rheologies. For the non-linear scenarios I am considering $n = 4$, since the assumption of $n = 3$ for ice deformation is not universally supported and values of $n > 3$ have been inferred from real-world glaciers.

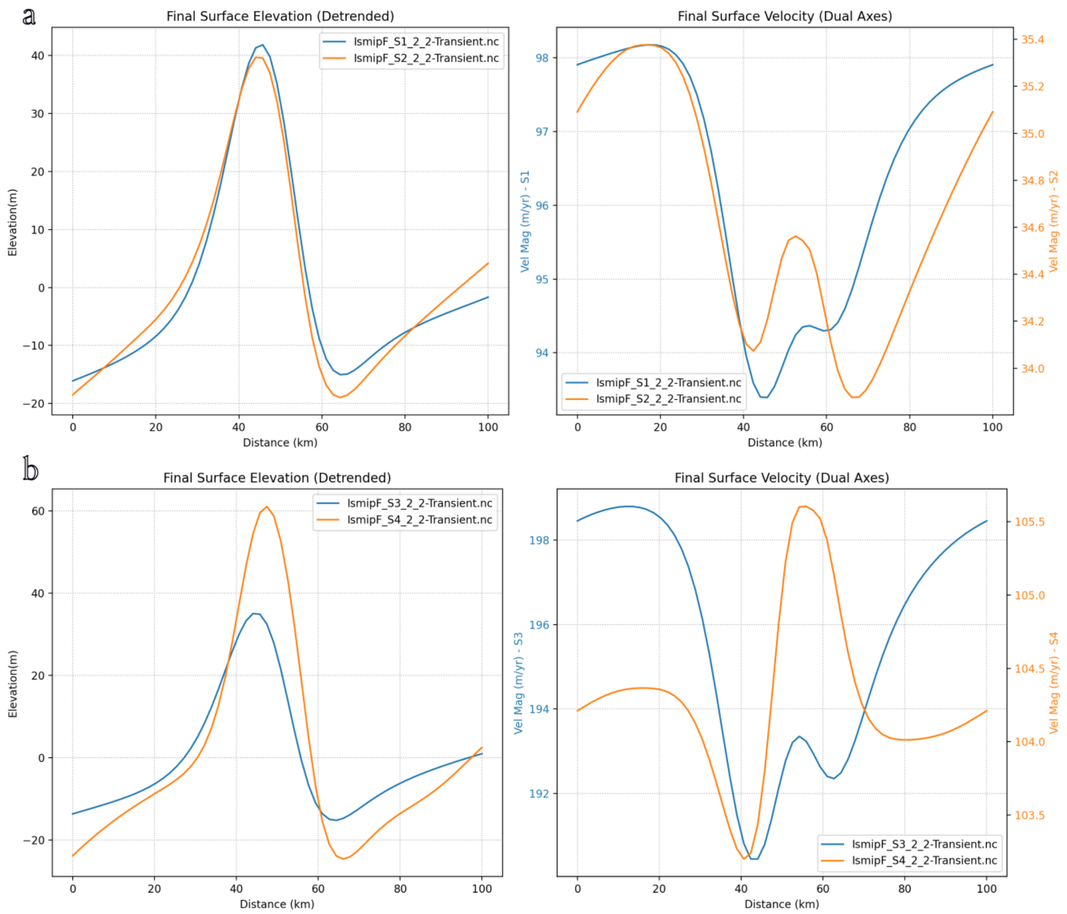


Figure 3.1: (a) Final surface elevations and velocities for the original frozen bed Experiment F (S1) and the corresponding transformed to non-linear rheology experiment (S2) (b) Final surface elevations and velocities for the original sliding bed Experiment F (S3) and the corresponding transformed to non-linear rheology experiment (S4).

The linear results depicted in blue in Figure 3.1 are consistent with the surface elevation and velocities found for Experiment F in [19]. Meanwhile, the non-linear scenarios (S2 and S4) shown in orange represent the first key finding of this analysis. The marked differences in both final surface elevation and velocity compared to the linear counterparts (S1, S3) provide crucial evidence for my first research question ("How does the bed topography manifest on the ice surface?"). Using $n = 4$ leads to a strong non-linear relationship where a small increase in stress yields a much larger increase in deformation. The results demonstrate that the choice of rheology is an important control on the bed-to-surface signal transfer. Implying that a succesful inversion framework like BedSAT must account for non-linear effects.

3.2 Data Processing, Visualization and Analysis Tools

This study is supported by a suite of interconnected scripts and tools designed for generating conditions, running simulations, processing output, and performing scientific analysis. The core of this study is a time evolution flow simulation of fully grounded ice over 300 years with daily time steps. This simulation is designed to systematically investigate the relationship between basal geometry, ice rheology and flow response by running a series of ISMIP-HOM style experiments [19] that can later be analysed in detail with other data processing tools.

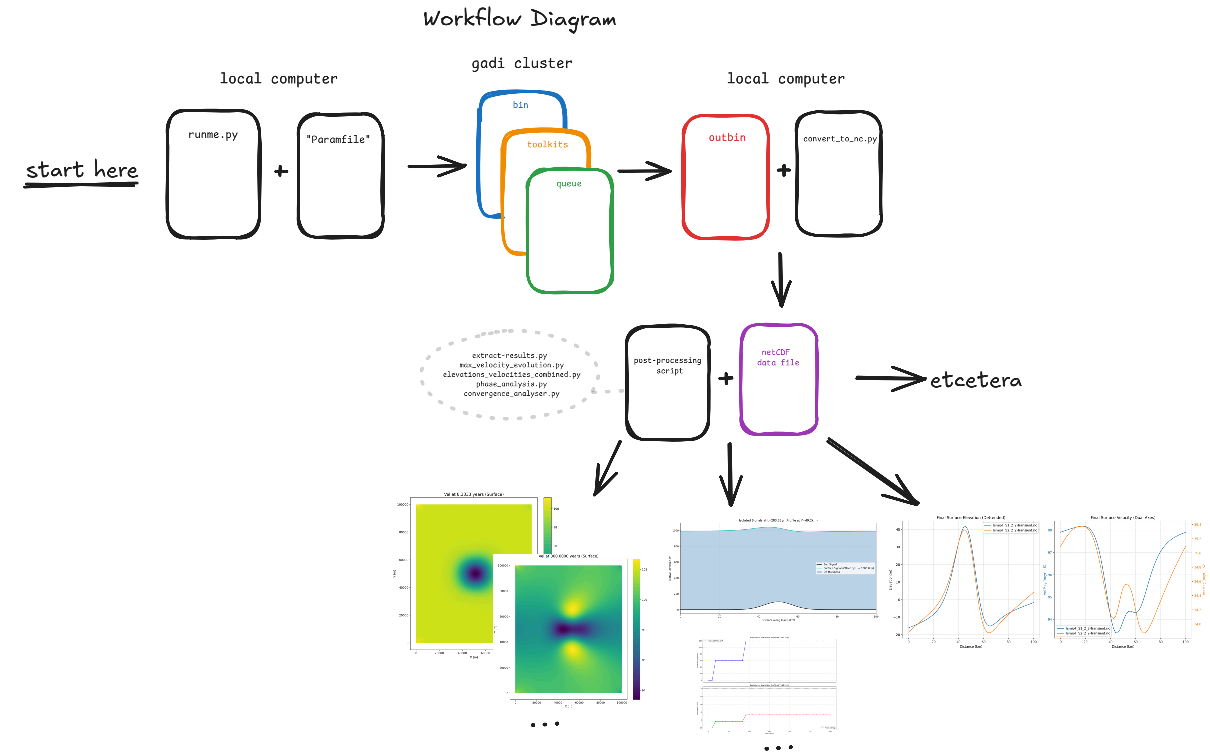


Figure 3.2: Diagrammatic representation of the current workflow using my ice simulation and analysis suite. For a particular simulation I will extract the results and visually inspect the output using all analysis scripts in the suite.

1. Binary to NetCDF Conversion: Converts ISSM `.outbin` files into the standard, portable NetCDF format.

2. Result Extraction and Visualization: Automatically finds and processes NetCDF files to generate visualisations of key fields like velocity and pressure.

3. Targeted Scientific Plotting: Additional scripts are used to create specific scientific plots.

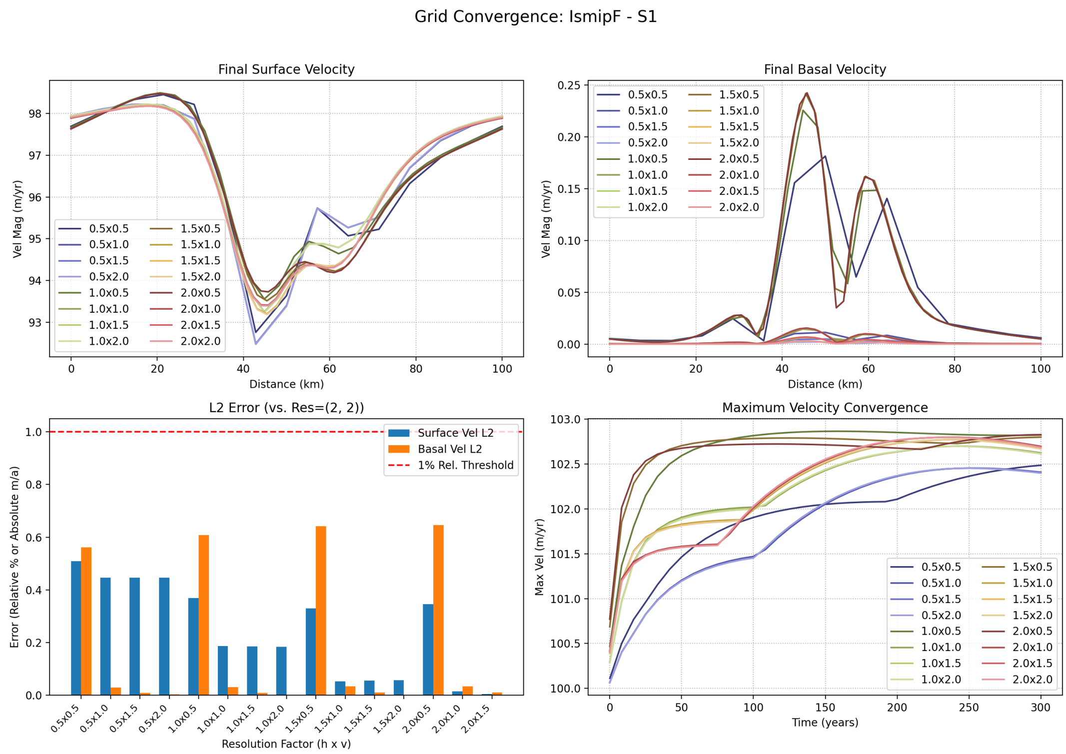


Figure 3.3: Grid convergence analysis for Scenario S1 (frozen bed, linear rheology, $n = 1$). The four panels show: (top-left) final surface velocity profiles and (top-right) final basal velocity profiles for 16 different mesh resolutions; (bottom-left) the L2 relative error of each simulation compared to the highest-resolution mesh (2.0×2.0), with a 1% relative error threshold indicated by the dashed line; and (bottom-right) the evolution of the maximum velocity over the 300-year simulation period

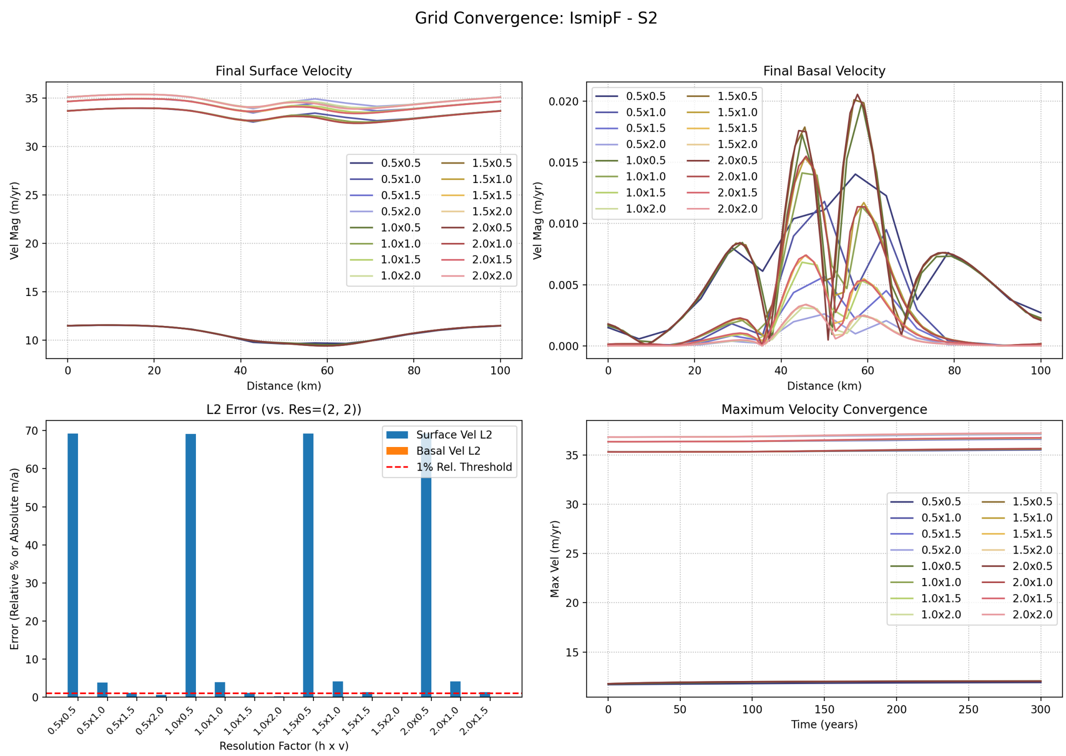


Figure 3.4: Grid convergence analysis for Scenario S2 (frozen bed, non-linear rheology, $n = 4$). An extension of ISMIP-HOM Experiment F. The panels display the same metrics as Figure 3.3. This scenario exhibits high sensitivity to vertical resolution refinement, with low-resolution simulations showing the highest errors and converging to a much slower flow state ($\approx$ 11 m/a) compared to high-resolution runs ($\approx$ 37 m/a).

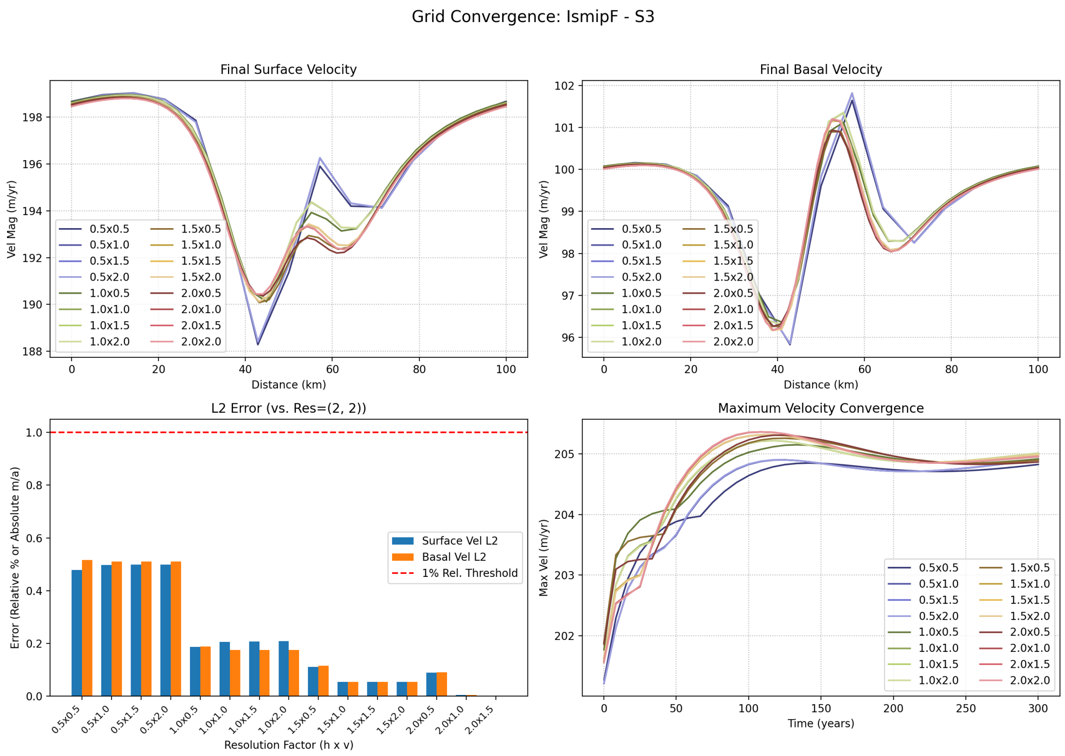


Figure 3.5: Grid convergence analysis for Scenario S3 (linear sliding, linear rheology, $n = 1$). The four panels show: (top-left) final surface velocity profiles and (top-right) final basal velocity profiles for 16 different mesh resolutions; (bottom-left) the L2 relative error of each simulation compared to the highest-resolution mesh (2.0×2.0), with a 1% relative error threshold indicated by the dashed line; and (bottom-right) the evolution of the maximum velocity over the 300-year simulation period

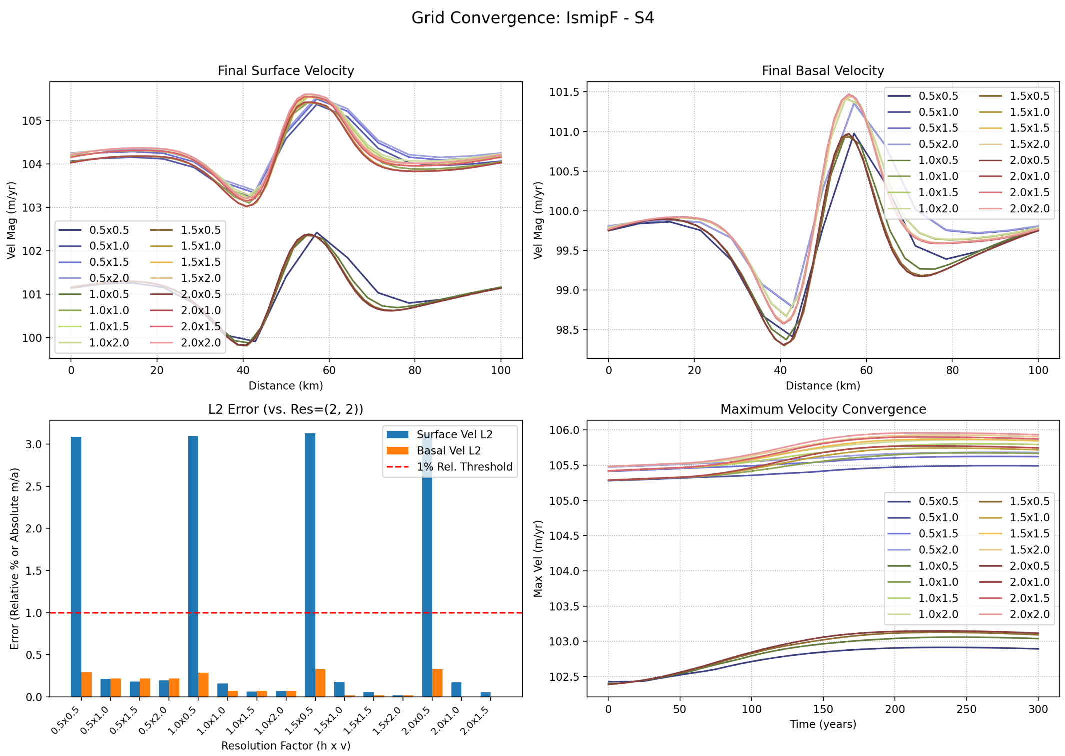
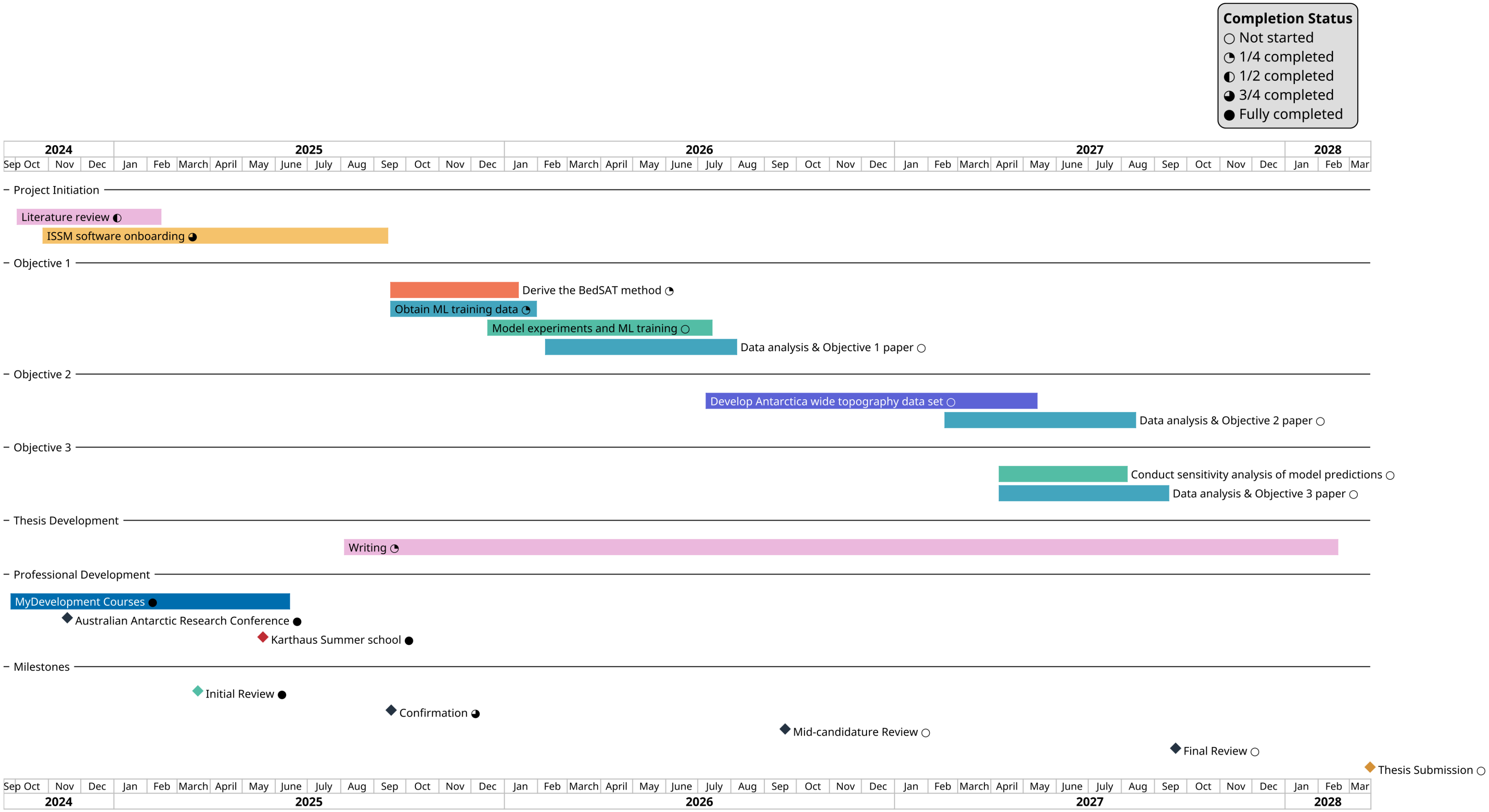


Figure 3.6: Grid convergence analysis for Scenario S4 (linear sliding, non-linear rheology, $n = 4$). Another extension of ISMIP-HOM Experiment F, similarly to the other non-linear case (S2) in Figure 3.4, this scenario is highly sensitive to vertical resolution. The convergence analysis shows that the 1% relative error threshold is only achieved for simulations using the highest vertical resolution factor (2.0)

Convergence analyses show the simulations as most sensitive to vertical resolution. Particularly, non-linear rheology scenarios in Figures 3.4 and 3.6, where refining vertical resolution produces qualitatively different results. The convergence threshold of 1% is only achieved for both S2 and S4 with the finest resolution. The next phase of my research involves a suite of realistic synthetic bedrock topographies—closely mimicking the conditions found in Antarctica—in order to further inform the development of BedSAT.

Project timeline



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