BedSAT: Antarctica

Exploring what lies beneath using big data and modelling

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Contents

Preliminary Literature review

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—such as those used in Bedmap ice bed, surface and thickness gridded datasets (1,2,3) for Antarctica [2–4], or BedMachine [5]—to "gap fill" these sparse datasets yield bed topography estimates that have uncertanties of multiple hundreds of metres in elevation [1] which propagate through simulations of AIS evolution under climate change [6]. 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

To address the critical gap in understanding subglacial conditions, my research goal is to develop a method that combines forward and inverse modeling, leveraging high-resolution satellite surface data that significantly improve bed topography estimates in regions where direct radar measurements are sparse. Bed topography research is based on two primary modeling approaches to infer subglacial bed topography and its influence on ice dynamics: forward and inverse models. Forward models aim to understand how different bed properties affect ice flow by running simulations on large ensembles of statistically generated bed topographies. These methods, often using geostatistical techniques like kriging [7] or flexural modelling [8] and are valuable for investigating how uncertainties in the bed can impact outcomes like simulated ice mass loss. However, their fundamental limitation is that they rely on assumptions about the bed conditions rather than direct observation, exploring possibilities rather than determining the actual topography. While inverse models work by inferring bed properties, such as topography or basal slipperiness, from known surface observations like ice elevation and velocity. Techniques like control method inversion [9] and 4dvar assimilation minimise mismatches between observed and simulated data, on the other hand mass conservation approaches use physical laws to reconstruct the bed, especially where measurements are sparse [1,5]. Despite their power, these methods face significant challenges. Variational approaches often require regularisation to prevent non-physical results and over-fitting [10], and time-dependent methods like 4dvar are computationally expensive. Probabilistic methods such as Markov Chain Monte Carlo (MCMC) are powerful for quantifying uncertainty but remain too computationally intensive [10] for large-scale models. The core problem for all these methods is the difficulty of fully utilising abundant satellite surface data to overcome the primary challenge in glaciology: a limited understanding of subglacial conditions due to sparse direct measurements.

1.2 From Signal Transfer to Tractable Inversion

A robust theoretical framework is essential for connecting the observable surface features to the hidden subglacial bed topography underneath. The core principle is that the ice sheet acts as a physical filter, modifying the expression of bed features as they propagate to the surface. The work by Budd (1970) [11] established that ice preferentially dampens short-wavelength bed undulations while features with a wavelength approximately 3.3 times the ice thickness are most clearly expressed at the surface. This process also introduces a phase lag, and can be described mathematically using frequency-dependent "transfer functions". More recent studies have built directly on this foundation. For instance, Gudmundsson and Raymond (2008) [12] refined the transfer function concept for ice streams, and Ockenden et al. (2023) [13] applied it in reverse, using full-Stokes transfer functions to invert high-resolution satellite observations of surface elevation and velocity to infer bed properties. These studies collectively establish that the physical relationship between the bed and the surface provides a viable pathway for subglacial mapping.

Despite the success of these approaches, their practical application has been limited by simplifying assumptions about ice physics. A primary limitation is the reliance on a linear (Newtonian) ice rheology, where stress is directly proportional to the strain rate (i.e., a "constant viscosity"). This assumption is often utilised to make the inversion mathematically tractable, but it contrasts with the widely accepted non-linear Glen's Flow Law, where the stress exponent is typically $n \approx 3$ or even $n = 4$. As my preliminary modeling work shows in section [?], the choice of rheology is a critical control on the bed-to-surface signal transfer; a non-linear rheology ($n = 4$) produces significantly different surface expressions compared to a linear one ($n = 1$). By largely ignoring non-linear rheology and complex basal sliding conditions, past inversion methods have introduced uncertainties and may not be robustly applicable across all dynamic regimes of the ice sheet. This leaves a critical gap: the need for an inversion method that honours more realistic ice dynamics.

The critical opportunity lies in the exploiting the vast wealth of underutilised high-resolution satellite surface observations including NASA's ITS_LIVE [14] velocities and REMA elevations [15]. My approach with BedSAT will harness these data streams by building upon established transfer function theory while addressing the fundamental limitation that has restricted past approaches: the mathematical intractability of non-linear ice physics. BedSAT will connect surface observations with bed topography using more realistic rheological assumptions ($n = 4$) and complex sliding conditions, rather than the simplified linear physics commonly used by traditional inversions. The key step to making this process tractable is Physics-Informed Machine Learning (Physics-ML), which solves the computational bottleneck that has forced previous methods to rely on unrealistic simplifications. By leveraging NVIDIA PhysicsNeMo—designed to blend governing physics (PDEs) with training data [16]—BedSAT can learn the non-linear mapping between surface expressions and bed topography without linearising the physics. This approach transforms what was previously computationally intractable into a fast, accurate inverse solver. My systematic forward modeling study (Section 5.1) directly informs this by establishing how different rheological and sliding assumptions alter bed-to-surface transfer functions, providing the physical constraints needed to train the Physics-ML model. Through an iterative process where initially inverted bed topography is integrated into forward models for progressive refinement, BedSAT will deliver physically consistent reconstructions validated against independent datasets. This represents a fundamental advance: where previous methods had to choose between physical realism and computational feasibility, Physics-ML enables both simultaneously.

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Aims

Antarctica's bed topography currently has local uncertainties of hundreds of metres in elevation due to sparse and unevenly distributed radar surveys. BedSAT will integrate remote sensing data and airborne-derived estimates, with ice flow models can improve bed topography resolution and accuracy. Quantifying how bed topography uncertainties affect ice mass loss projections via sensitivity analyses with different realisations of topographic roughness through 2300CE. Providing more reliable sea level rise predictions. Following open-source approach and FAIR data principles, these improvements benefit the broader scientific community and support more effective climate change mitigation planning.

2.1 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?

2.2 Objectives

- O1: Develop an ice sheet modelling approach to assimilate satellite remote sensing datasets to improve knowledge of the bed 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.

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Research Significance

The polar regions are losing ice, and their oceans are changing rapidly [17]. 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 [17]. 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 [18]. In addition, cold freshwater can dissolve larger amounts of CO_2 than regular ocean water creating corrosive conditions for marine life [17]. 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 [19]. 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 [19], 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 [20]. 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.

3.1 Writing Contributions

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 a case study on the Aurora Subglacial Basin and documents the most recent techniques used in the field. Framed the review as a comparison between different types of synthetic beds ("elevation-preserving" vs. "texture-preserving") underscoring how methodological choices in bed generation can significantly influence projections of future sea level contributions. 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. Setting the stage for introducing SMUG as a method designed to overcome specific challenges. This research effort, moves from a comprehensive assessment of existing tools to the justification and development of a next-generation approach for Antarctic bed mapping.

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Project Methodology

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).

4.1 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) [21] 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.

4.2 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 [22]). 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 [23]), 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 5 for detailed information on the progress of this work.

4.3 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.

4.4 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.

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Progress

5.1 Rheology and Sliding Study

Building upon the diagnostic ISMIP-HOM experiments in [24], 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) [25]. 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.

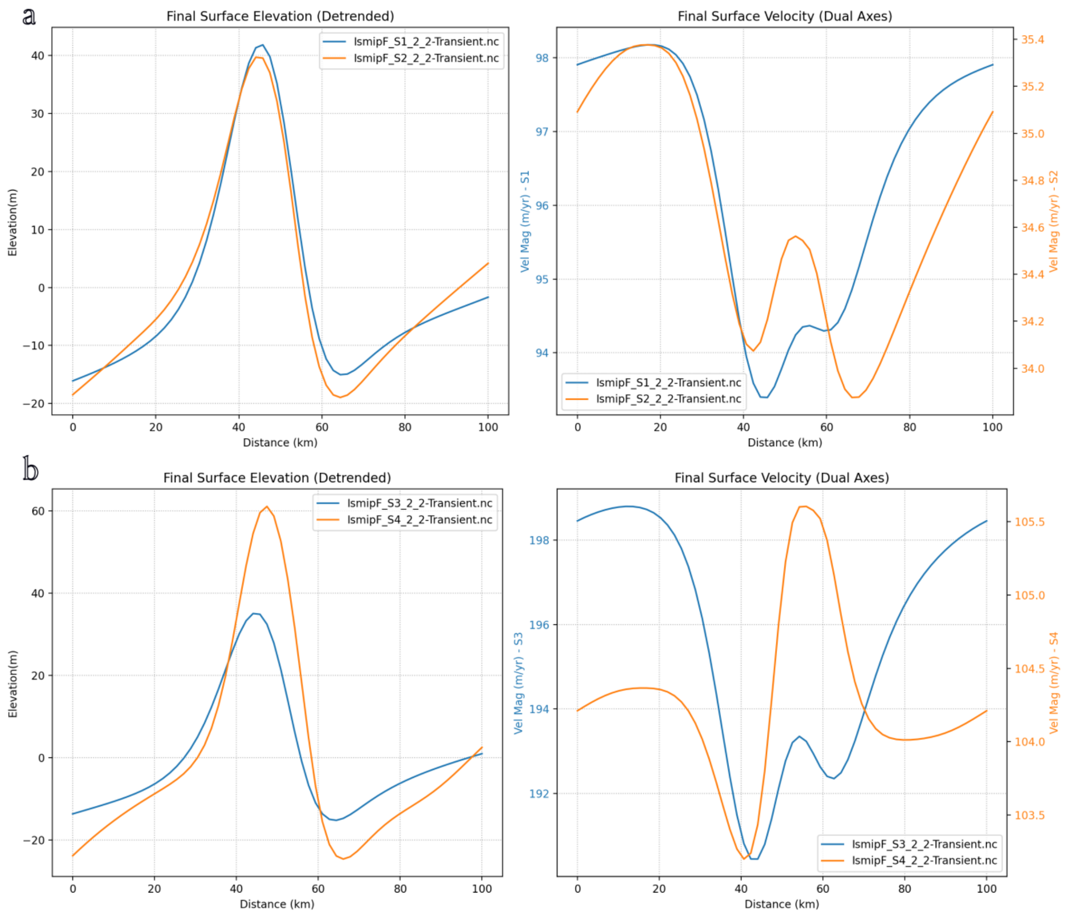

Figure 5.1: (a) Final surface elevations and velocities for the original frozen bed Experiment F (S1: linear rheology) and the corresponding transformed to non-linear rheology experiment (S2) (b) Final surface elevations and velocities for the original sliding bed Experiment F (S3: linear rheology) and the corresponding transformed to non-linear rheology experiment (S4).

The linear results depicted in blue in Figure 5.1 are consistent with the surface elevation and velocities found for Experiment F in [24]. 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.

5.2 Data Processing, Visualisation 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 [24] that can later be analysed in detail with other data processing tools.

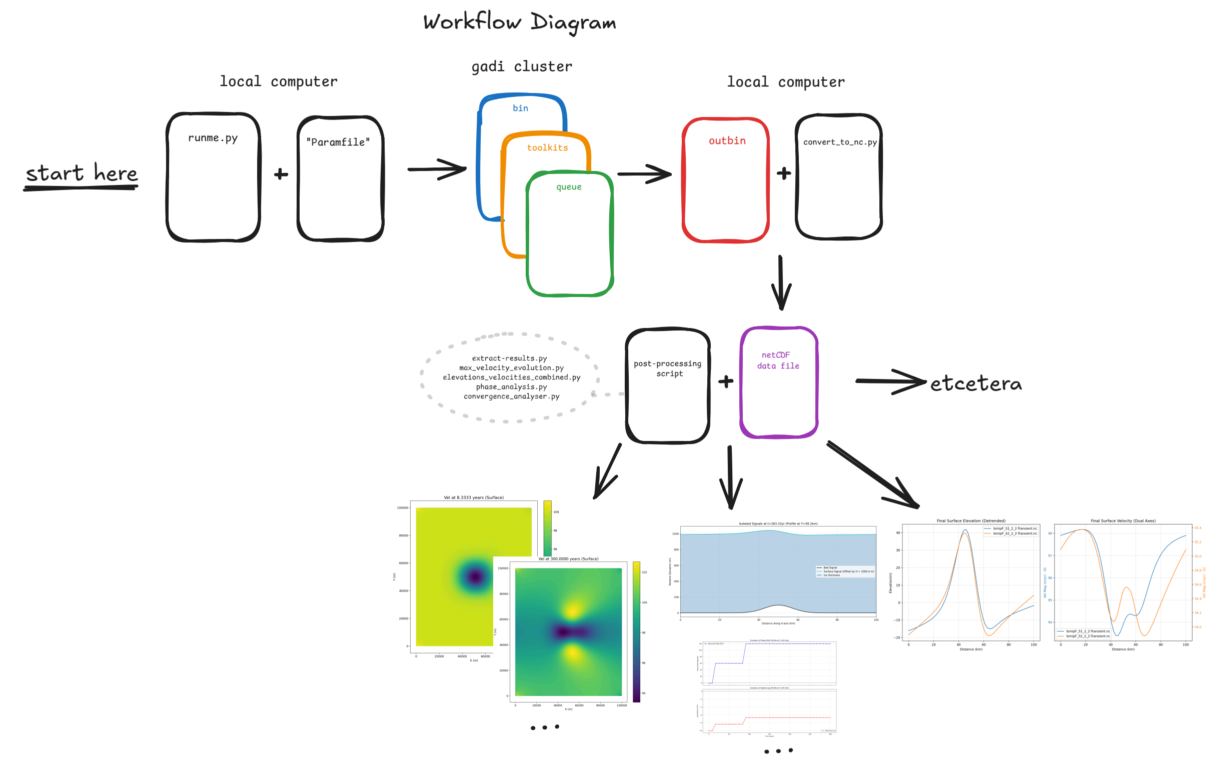

Figure 5.2: Diagrammatic representation of the current workflow using my ice simulation and analysis suite. For a particular simulation I will extract the results and visually inspect the output using all analysis scripts in the suite.

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

2. Result Extraction and Visualisation: 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.

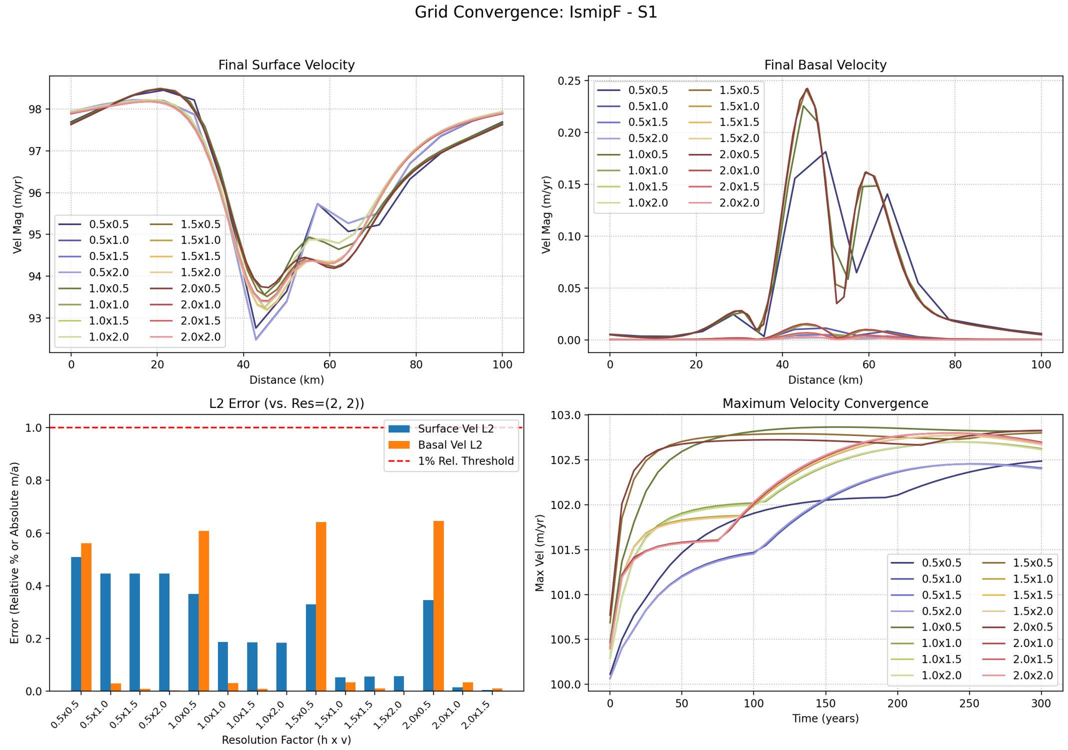

Figure 5.3: Grid convergence analysis for Scenario S1 (frozen bed, linear rheology, $n = 1$). The four panels show: (top-left) final surface velocity profiles and (top-right) final basal velocity profiles for 16 different mesh resolutions; (bottom-left) the L2 relative error of each simulation compared 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

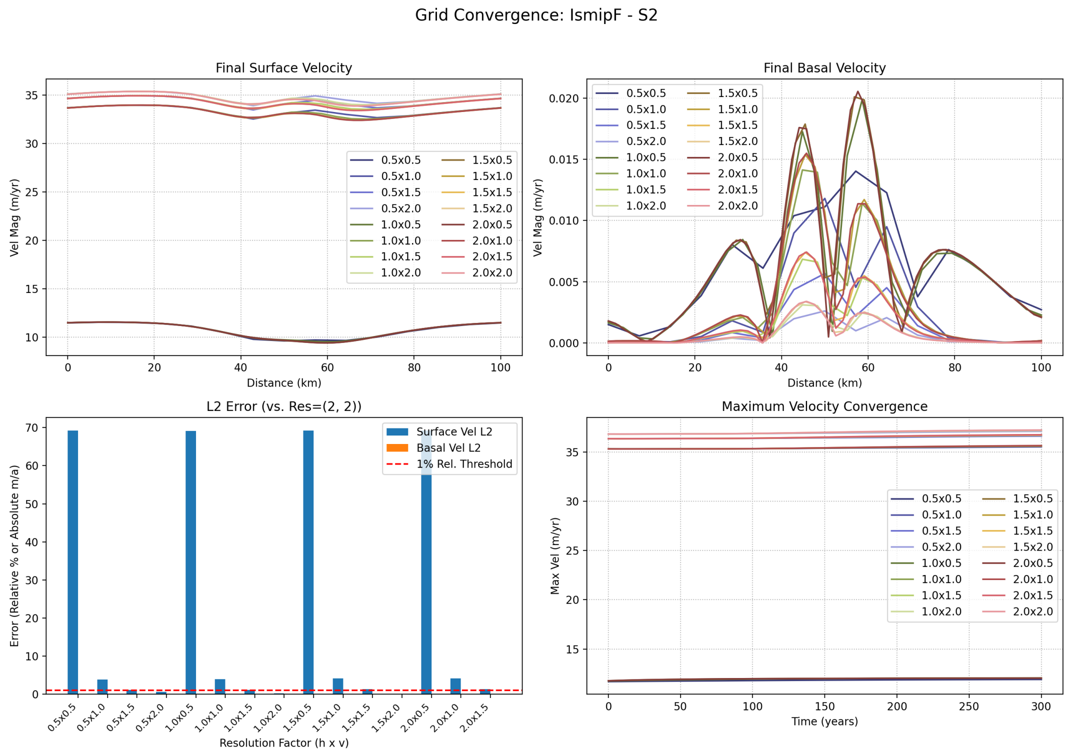

Figure 5.4: Grid convergence analysis for Scenario S2 (frozen bed, non-linear rheology, $n = 4$). An extension of ISMIP-HOM Experiment F. The panels display the same metrics as Figure 5.3. This scenario exhibits high sensitivity to vertical resolution refinement, with low-resolution simulations showing the highest errors and converging to a much slower flow state ($\approx$ 11 m/a) compared to high-resolution runs ($\approx$ 37 m/a).

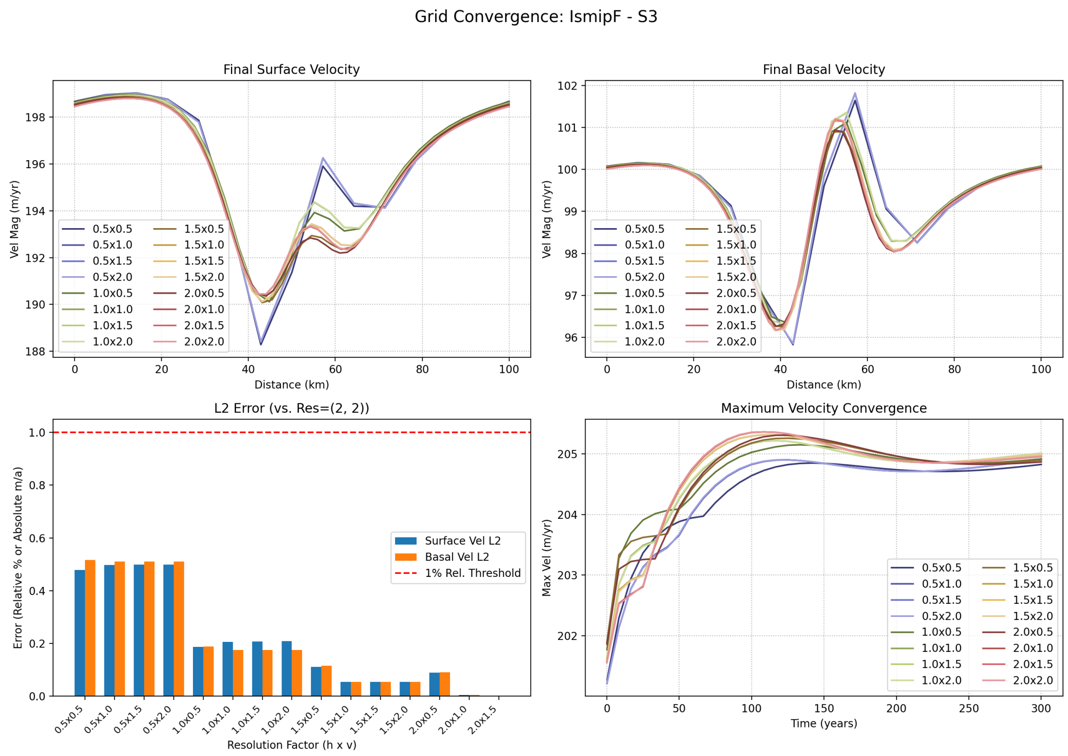

Figure 5.5: Grid convergence analysis for Scenario S3 (linear sliding, linear rheology, $n = 1$). The four panels show: (top-left) final surface velocity profiles and (top-right) final basal velocity profiles for 16 different mesh resolutions; (bottom-left) the L2 relative error of each simulation compared 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

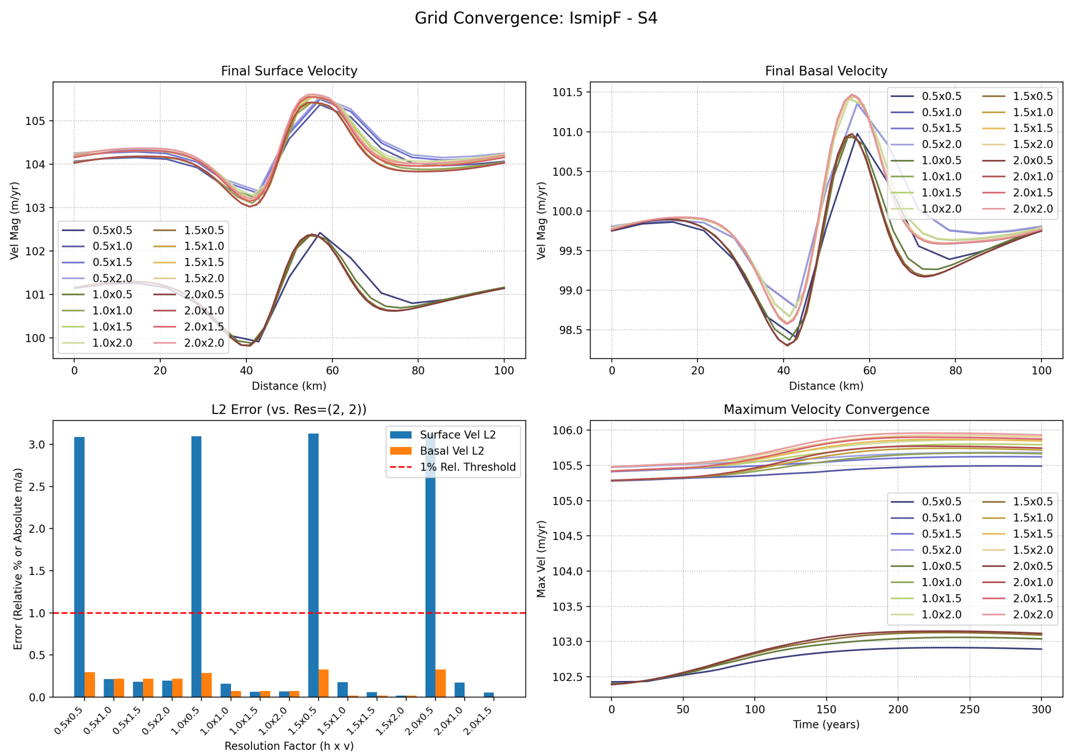

Figure 5.6: Grid convergence analysis for Scenario S4 (linear sliding, non-linear rheology, $n = 4$). Another extension of ISMIP-HOM Experiment F, similarly to the other non-linear case (S2) in Figure 5.4, this scenario is highly sensitive to vertical resolution. The convergence analysis shows that the 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 5.4 and 5.6, 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. This high sensitivity underscores the necessity of using converged, high-resolution simulations to generate the training data for BedSAT, ensuring the machine learning model is not learning artefacts from unresolved model physics. 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.

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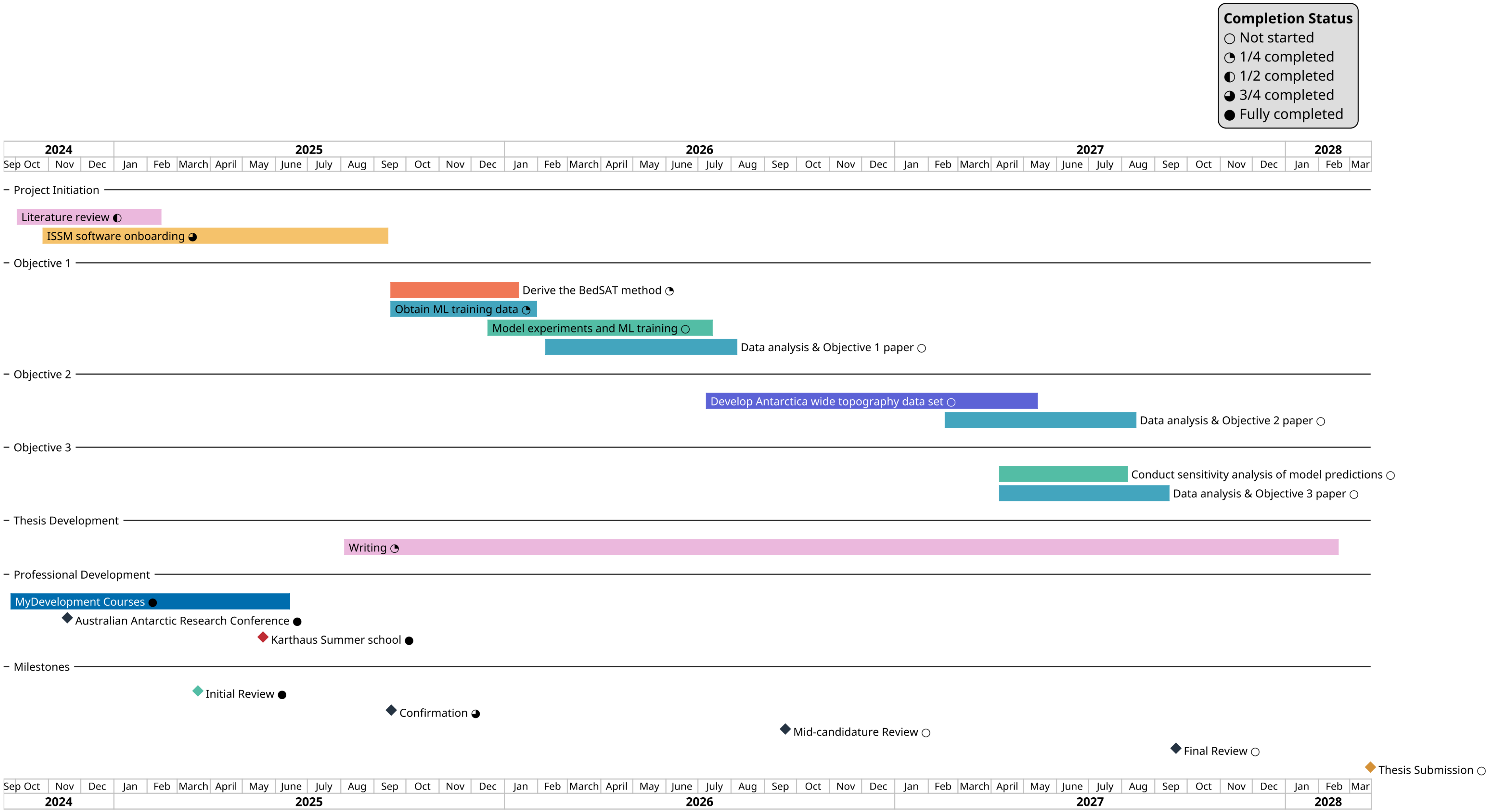
Project timeline



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