BedSAT: Antarctica

Exploring what lies beneath using big data and modelling

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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 for Antarctica [2–4], or BedMachine [5]—to "gap fill" these sparse datasets yield bed topography estimates that have uncertainties 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 Antarctica, 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, significantly improve bed topography estimates in regions where direct radar measurements are sparse. The generation of gridded bed topographies in Antarctica is based on two primary modeling approaches to infer subglacial bed topography and its influence on ice dynamics, these are classified as forward and inverse models.

Forward models aim to understand how different bed properties influence ice flow. These often generate interpolated gridded topography using geostatistical techniques like kriging [7] and are valuable for investigating how uncertainties in the bed can impact outcomes like simulated ice mass loss. Forward models can generally be classed as elevation-preserving or texture-preserving (the bed's geostatical properties are mantained), 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.

Inverse models involve methods that assimilate other data sources and work by inferring bed properties, such as topography or basal slipperiness, from surface observations like ice elevation and velocity. Techniques like control method inversion [8] 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 [9], 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 [9] for large-scale models.

Ultimately, the limitations of these methods reveal a core challenge in modern glaciology: the need to develop a new approach that can fully leverage rich satellite surface data to overcome the scarcity of direct subglacial measurements.

1.2 From Signal Transfer to Tractable Inversion

This project aims to develop a framework to connect observable surface features to subglacial bed below, ensuring that the governing physics of ice sheet flow are respected. To do this, my work focuses in utilising surface-bed transfer functions.

The core principle behind a transfer function 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) 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 [10]. 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) refined the transfer function concept for ice streams [11], and Ockenden et al. (2023) applied it in reverse, using full-Stokes transfer functions to invert high-resolution satellite observations of surface elevation and velocity to infer bed properties [12]. 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 (Section 5.1), 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 [13] velocities and REMA elevations [14]. 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 [15]—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.

1.3 Knowledge Gaps

Several knowledge gaps currently limit the accuracy of AIS models. My research is designed to address the following gaps:

1. **Incomplete Understanding of Bed-to-Surface Signal Transfer**:
   While transfer functions provide a theoretical basis for connecting surface observations to subglacial topography, practical application has been limited by simplifying assumptions, such as a linear ice rheology. Understanding how signal transfer operates under the more realistic, non-linear conditions that govern actual ice flow, which directly motivates the research question:
   How does bed topography manifest on the ice surface?

2. **Impact of Interpolation Uncertainty on Projections**:
   Existing bed topography datasets rely on interpolation schemes that fill vast data gaps, resulting in high uncertainty estimates. While it is known that these uncertainties propagate through ice sheet models, specific impact on the accuracy and reliability of long-term simulations remains poorly quantified. This leads to the second research question:
   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. **Poorly Constrained Topography at Critical Ice Sheet Margins**:
   Major knowledge gaps persist in mapping the bed topography at the grounding line (GL). Since GL retreat is highly sensitive to local topographic features, the lack of high-resolution data in these areas is a primary obstacle to producing reliable models of ice sheet instability, raising the third question:
   What is the impact of variable bed conditions and topography on the rate of GL retreat in continental ice sheets?

Aims

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 BedSAT, I aim to develop 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. One of my goals is to derive a continent-wide bed topography dataset. I plan to use this dataset to 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. The resulting open-source dataset and model will provide more reliable sea-level rise predictions, benefiting the broader scientific community and informing climate change mitigation strategies.

2.1 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.

Research Significance

The polar regions are losing ice, and their oceans are changing rapidly [16]. The consequences of this extend to the whole planet and it is crucial for us to understand them to be able to evaluate the timing and magnitude of potential mitigation strategies. The accelerating loss of continental ice sheets in both Greenland and Antarctica are major contributors to global sea level rise [16]. 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 [17]. In addition, cold freshwater can dissolve larger amounts of CO_2 than regular ocean water creating corrosive conditions for marine life [16]. 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 [18]. 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 where the ice sheet is grounded on bedrock. The GL retreat rate depends crucially on topographical features like pinning points [18], which lead to increased retardation of upstream flow. 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 [19]. 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 critical data gaps in Antarctic bed topography products.

The review titled “Synthetic bed topographies for Antarctica and their utility in ice sheet modelling” establishes the theoretical context for a case study on the Aurora Subglacial Basin. This manuscript is framed 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: an algorithm to generate robust estimates of the bed topography using Taylor series expansions with robust uncertainty estimates. The paper sets stage for introducing SMUG as a method designed to overcome specific challenges faced by commonly used interpolation methods. 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.

Project Methodology

4.1 Analysis of Bed-to-Surface Signal Transfer

The first 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 well-tested and robust Ice-sheet and Sea-level System Model (ISSM) [20]. ISSM is a state-of-the-art ice sheet model that is well tested and supported by multiple developers, making it a robust choice for my project. I have developed tools that quantify the the bed-to-surface phase signal transfer by tracking the evolution of the surface with respect to the base using cross-correlations to calculate the spatial lag and phase shift between signals for each time step. This verifies and validates the necessary set of constraints for realistic ice dynamics, taking into consideration different parameterisations, sliding laws and parameter values.

4.2 Development of the BedSAT Inversion Framework

BedSAT is a model that comprises physically informed transfer function, leveraging an improved understanding of how ice rheology and basal sliding conditions affect the surface expression of subglacial topography. The framework encompases the following stages.

1. **Training the Machine-Learning model**: The BedSAT framework will be trained and validated using a synthetic bedrock database and a data-rich region, such as the Aurora Subglacial Basin, where extensive ice-penetrating radar data of the bed is available for direct comparison.
   Forward Ice Flow Model: The forward model of ice dynamics will be configured for the chosen study site, including key model assumptions, such as the choice of ice flow equations and the parameters governing ice rheology. The robustness of the numerical configuration will be confirmed through grid independence testing to ensure that the results are not an artifact of the model's spatial resolution.
   Inversion Pre-processing: The primary observational inputs for the model will be satellite-derived surface velocity, surface elevation [13, 14] and ice thickness [21, 22]. A critical pre-processing step will involve filtering high-frequency noise (e.g., aeolian features) from the surface data to ensure that the glaciological signal from the underlying bed is isolated, this step will require assesment from experts in the field.

2. **Inverse Modelling to Estimate Bed Topography**: The core of the BedSAT framework is the inversion. BedSAT will iteratively adjust an initial estimate of the bed topography, aiming to minimize the mismatch between the forward model's simulated surface velocities and the satellite-observed velocities.

3. **Validation and Sensitivity Analysis**: The framework's performance will be rigorously evaluated. First, the inverted bed topography will be directly validated against the "ground-truth" radar-derived bed maps for the study region. Second, a series of sensitivity analyses will be conducted to quantify the model's robustness. These tests will systematically alter key assumptions, such as the rheological parameters for different regions, to determine their impact on the final inverted topography and to establish the uncertainty bounds of the framework's results.

4.3 BedSAT: Antarctica - Derive a new bed topography

I will apply the validated BedSAT methodology from Objective 1 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 new bed topography

The new bed topography datasets will be used to conduct a sensitivity analysis of ice sheet model projections to 2300CE. 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.

Progress

5.1 Rheology and Sliding Study

Building upon the diagnostic ISMIP-HOM experiments in [23], 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 ($n = 4$).

To utilise non-linear rheology and still have consistent simulations, I ensure that different model rheologies start from identical initial conditions. The method I follow is based on the re-scaling method by Getraer and Morlighem (2025) [24]. Their formula ensures that the initial ice viscosity—and therefore strain rates for a given stress—is identical between simulations with different rheologies. The fundamental model for the deformation of glacial ice and the equations which govern ice flow is Glen's flow law.

$$\dot{\varepsilon} = A_n \tau^n, \tag{5.1}$$

here the $\dot{\varepsilon}$ is the strain rate, A_n is the rate factor and τ^n is the stress deviator. 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.

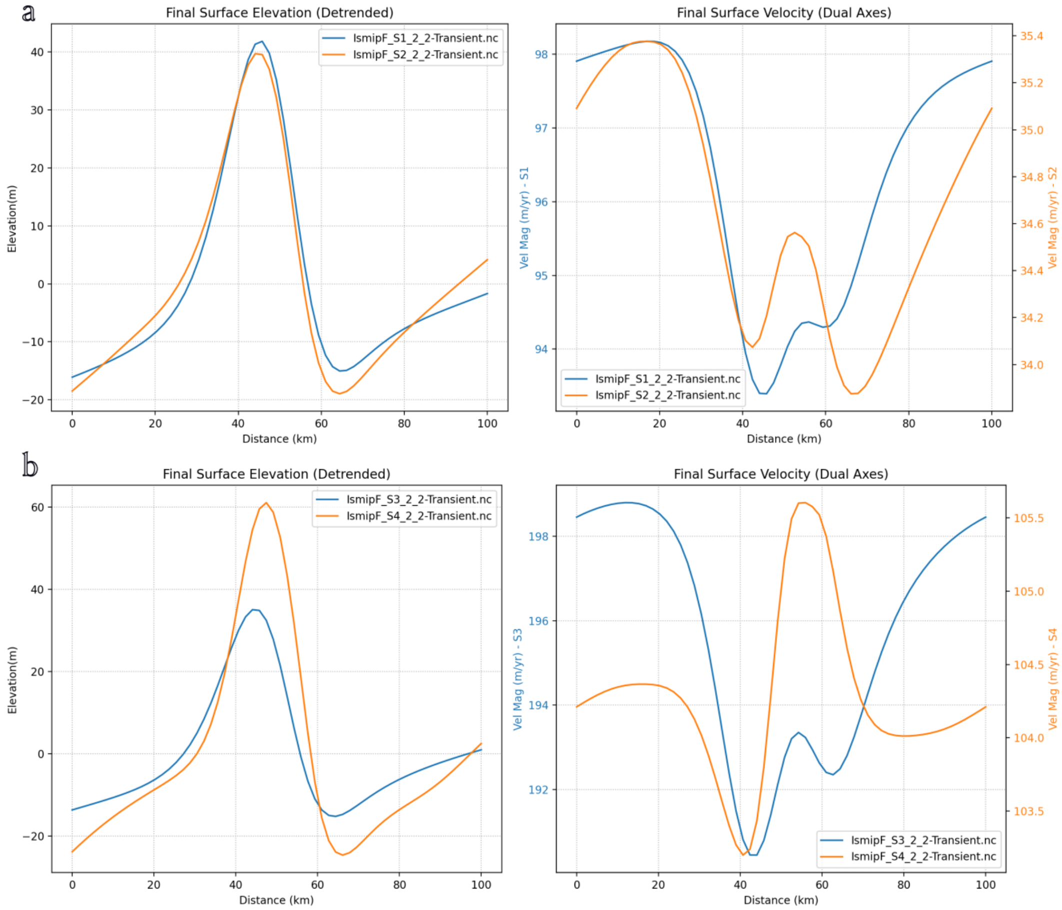


Figure 5.1: (a) Final surface elevations and velocities for the original frozen bed Experiment F (S1: linear rheology) and the corresponding transformed to non-linear rheology experiment (S2) (b) Final surface elevations and velocities for the original sliding bed Experiment F (S3: linear rheology) and 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 [23]. 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. These grid independence 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

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 [23] that can later be analysed in detail with other data processing tools.

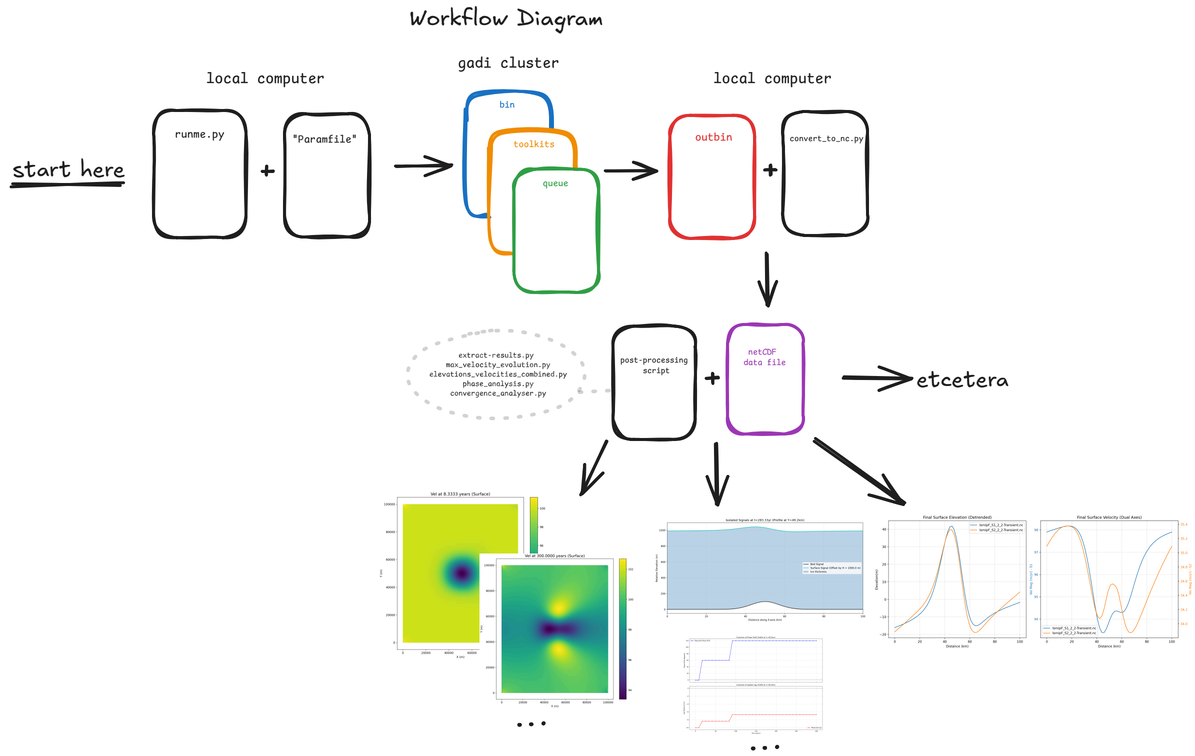


Figure 5.2: Diagrammatic representation of the current workflow using my ice simulation and analysis suite.

The scripts I've developed include a binary file to into NetCDF converter, a transient simulation analyser that generate visualisations of key fields like velocity and pressure. and other additional scripts that create specific scientific analysis and plots.

5.2.1 Grid Independence

Grid optimisation testing involved simulations with 16 distinct mesh resolutions, varying both the horizontal (H) and vertical (V) grid densities independently. The resolution scaling factors tested are 2.0 (double resolution), 0.5 (half resolution), 1.0 (no scaling) and 1.5 (50% scaling). I designated the solution from the highest resolution mesh, corresponding to scaling factors of ($H = 2.0, V = 2.0$) as the reference solution. Refined meshes (either horizontal or vertical) often require smaller time steps to satisfy the Courant-Friedrichs-Lewy (CFL) condition and maintain solver stability. To satisfy this criterion I scaled the time step for each simulation matching the largest resolution factor independently if it was horizontal or vertical scaling.

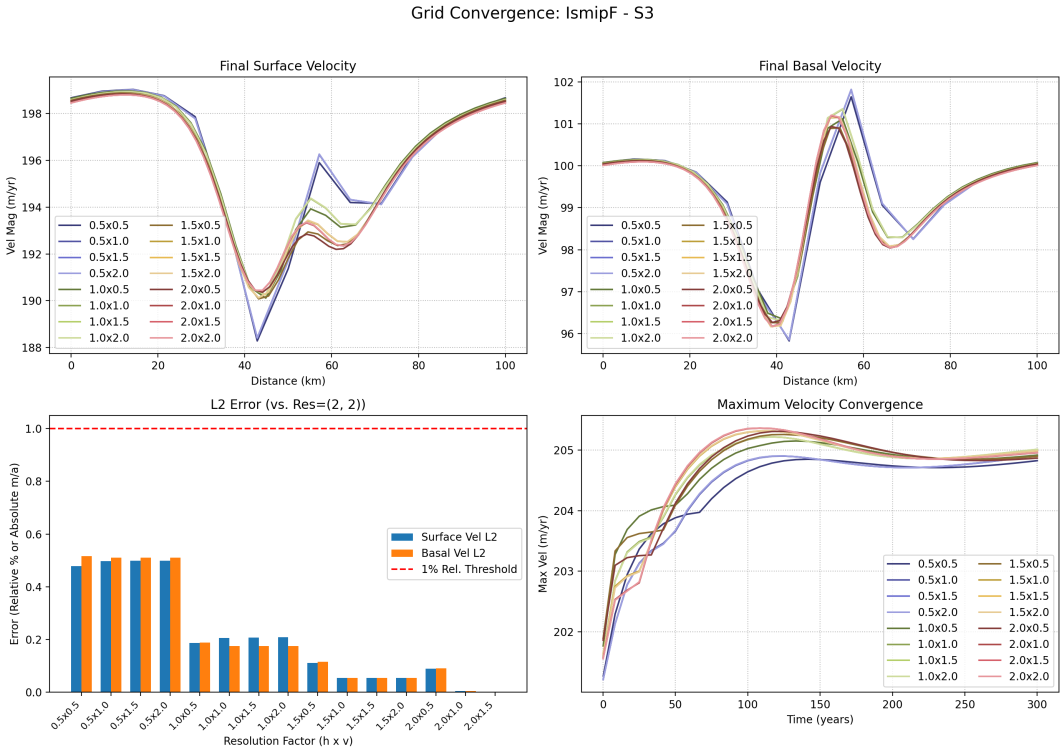


Figure 5.3: Grid convergence analysis for Scenario S3 (linear sliding, linear rheology, $n = 1$). The four panels show: (top-left) final surface velocity profiles and (top-right) final basal velocity profiles for 16 different mesh resolutions; (bottom-left) the L2 relative error of each simulation compared 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

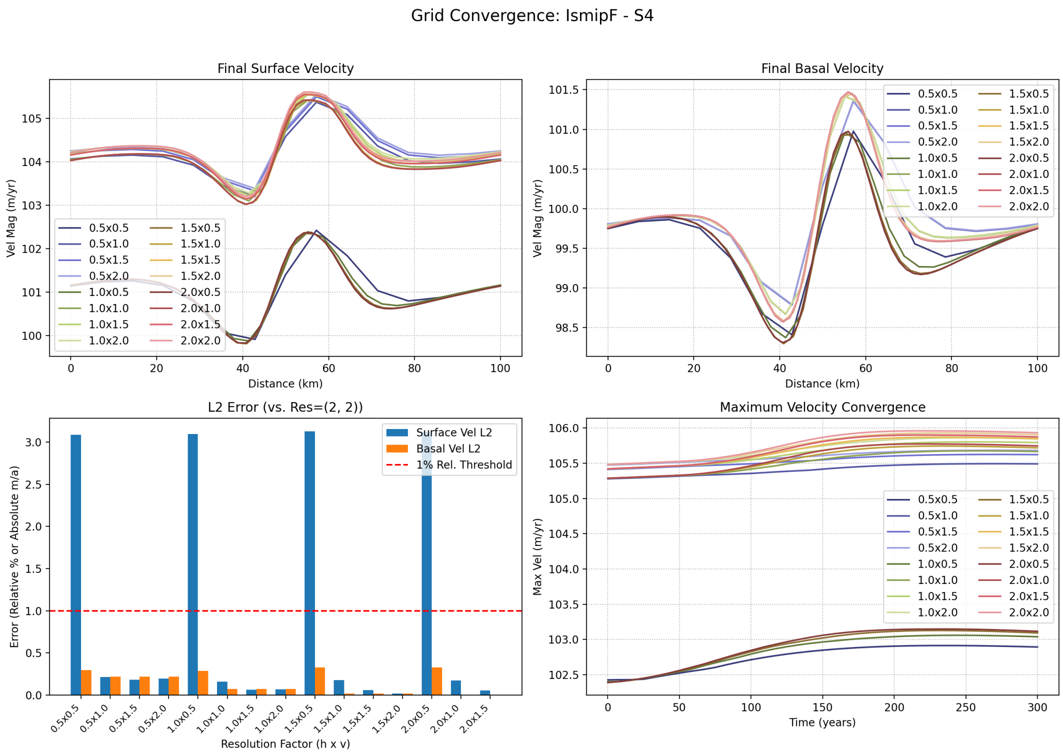


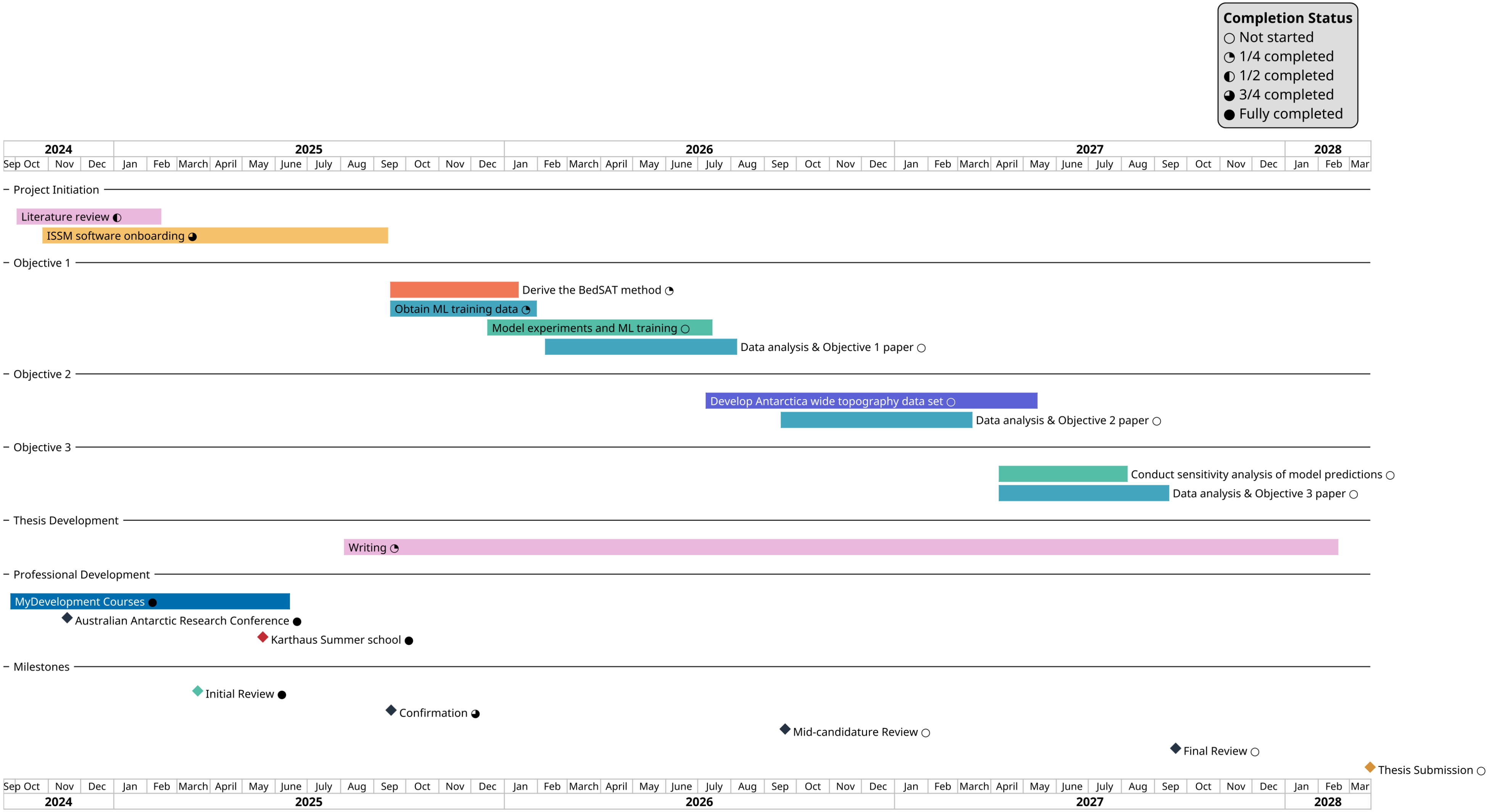
Figure 5.4: Grid convergence analysis for Scenario S4 (linear sliding, non-linear rheology, $n = 4$). Another extension of ISMIP-HOM Experiment F. The convergence analysis demonstrates that non-linear scenarios exhibit high sensitivity to vertical resolution refinement, with low-resolution simulations showing the highest errors (with the relative error threshold only being achieved for simulations using the highest vertical resolution factor (2.0)) and converging to a slower flow state ($\approx$ 103 m/a) compared to high-resolution runs ($\approx$ 106 m/a).

The primary metric of this analysis is the L2 relative error, a global, scale-dependent measure that quantifies the overall difference between two solutions. In my analysis, I chose a convergence threshold of 1%—since estimates of other uncertainties are expected to be larger than this grid error—when comparing the solutions to the baseline. If the L2 norm of the data is very close to zero (less than 10^{-6}), the analysis reports the absolute error to avoid division by a tiny, unstable number. Otherwise, it calculates and reports the standard relative error as a percentage.

Convergence analyses show the simulations as most sensitive to vertical resolution. Particularly, non-linear rheology scenarios, where refining vertical resolution produces qualitatively different results. The convergence threshold of 1% is only achieved for both S2 and S4 in Figure 5.4 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.

Project timeline



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