# 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 meters 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

# Antarctica's Landscape

## 1.1 Climate Impacts and Global Significance

The polar regions are losing ice, and their oceans are changing rapidly [1]. 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.

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 [1]. 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 [2]. In addition, cold freshwater can dissolve larger amounts of $CO_2$ than regular ocean water creating corrosive conditions for marine life [1].

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 [3]. Uncertainty increases in regions with variable bed conditions, where characteristics like "slipperiness" and "roughness" are difficult to verify via direct observations. Other problematic areas involve the ice sheet's grounding line (GL), the zone that delineates ice grounded on bedrock from ice shelves floating over the ocean. The retreat rate depends crucially on topographical features like pinning points [3], 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 [4]. 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.

# Topography of Antarctica

Bed topography is one of the most crucial boundary conditions that influences ice flow and loss from the Antarctic Ice Sheet (AIS) [5]. Bed topography datasets are typically generated from airborne radar surveys, which are sparse and unevenly distributed across the Antarctic continent (see figure 2.1). 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 [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.
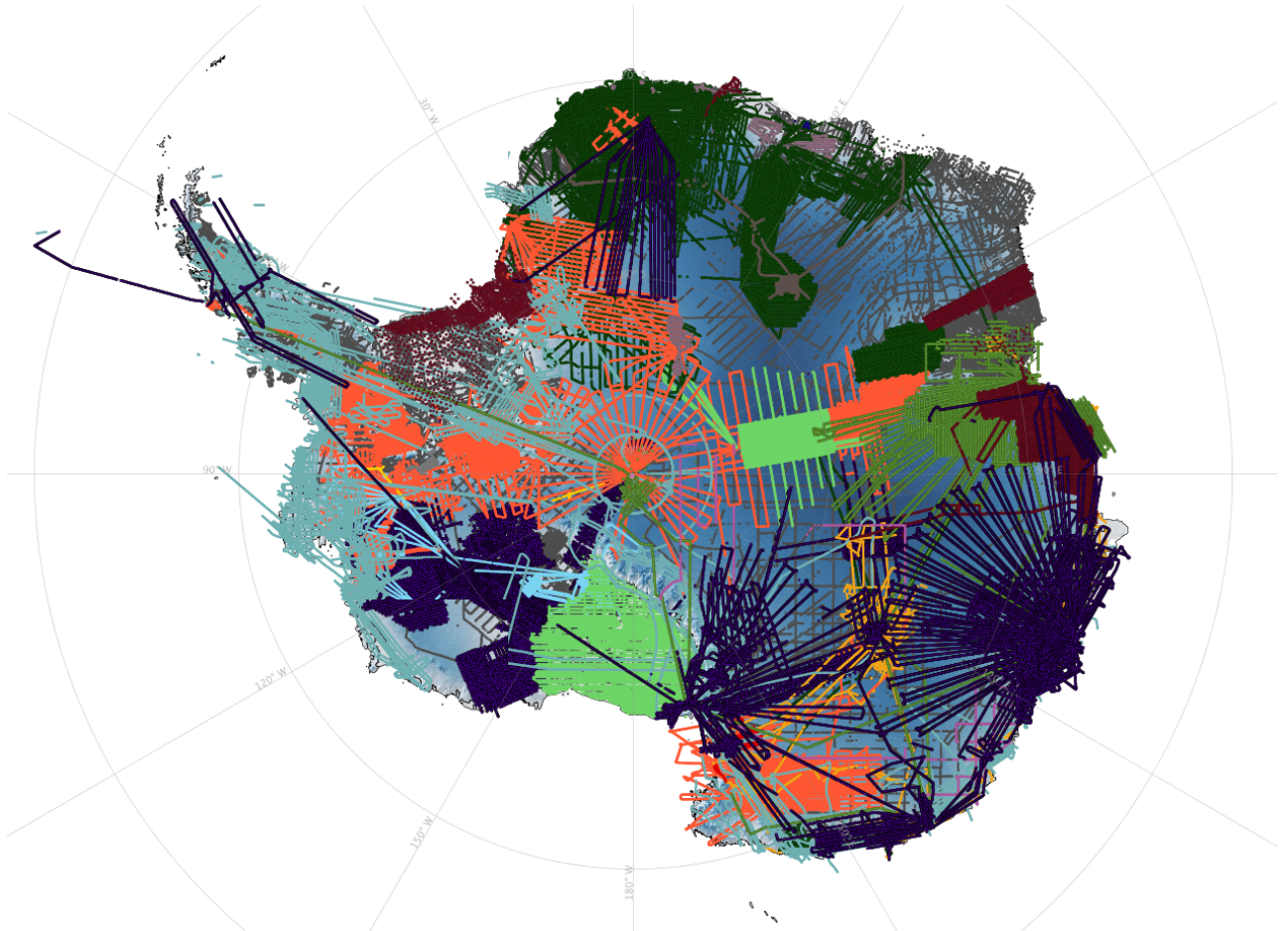


**Figure 2.1:** Distribution of BedMAP{1,2,3} data tracks (Source: bedmap.scar.org).

## 2.1 Approaches to Bed Topography Reconstruction

A key objective of this study is to understand the bed topography itself and how it influences ice dynamics. There are two ways to can 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. In this example geostatistical methods can be used to generate bed topographies that either preserve elevation or texture:

  - **Geostatistics** Statistical methods specialized for analyzing spatially correlated data. In glaciology, this approach is used to interpolate between sparse measurements and characterise spatial patterns in bed properties, often employing techniques like kriging [7].

- **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 [8]. Often needs regularization terms to prevent non-physical features or over-fitting [9].

  - **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 [9]. Can handle time-varying data and evolving glacier states, making it more suitable for dynamic systems unlike control methods, this makes them more computationally demanding [9].

  - **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 [5, 10]. Requires (contemporary) measurements of ice thickness at the inflow boundary to properly constrain the system [9].

  - **Markov Chain Monte Carlo (MCMC)**: A probabilistic method that generates sample distributions to quantify uncertainties in ice sheet parameters and models [9]. While powerful for uncertainty quantification, these methods remain computationally intensive for continental-scale ice sheet models [9].

  - **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 [9].

This study 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. Despite revolutionary advances in satellite technology that provide unprecedented surface detail, a key challenge in glaciology remains: how to fully utilize this wealth of information in regions where our understanding of subglacial conditions is limited. Our approach will integrate more comprehensive dynamical ice models with modern computational capabilities to develop better bed topography.

## 2.2    Theoretical Frameworks

Understanding how bed features manifest in surface observations requires a theoretical framework that connects these two domains. The modelling approach used in this project relies on two different theoretical frameworks that relate bed topography and surface features. Using synthetic data, observations and these modelling frameworks, my goal is understanding the limitations of each approach and how they can be improved.

### 2.2.1    Ice Flow Over Bedrock Perturbations - Budd 1970

The first framework was originally developed by Budd [11]. This model relates ice flow over bedrock perturbations to surface expressions using a two-dimensional biharmonic stress equation. The modelling carried out in [11] determined ice-sliding velocities for wide ranges of roughness, normal stress, and shear stress relevant to real glaciers [11]. Budd's framework fits in my project as a means of verifying the validity of the physics in my ice-sheet model, since it describes important effects of bedrock disturbances on the transient evolution of the transferred basal disturbances onto the surface. The theory makes several key predictions that have been confirmed through spectral analysis of real ice cap profiles:

1. A 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.

Importantly, Budd's 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 nonlinear relationship between stress and strain rate. 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: linear rheology ($n = 1$) produces different amplitude dampening and phase relationships compared to nonlinear rheology ($n = 3$), particularly for wavelengths around the critical 3.3 times ice thickness scale. My current experimental framework systematically explores this in 1D by generating forward models for multiple synthetic bedrock profiles across four scenarios combining rheological assumptions ($n = 1$ vs $n = 3$) 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.

### 2.2.2 Ice flow perturbation analysis - Ockenden 2023

The second framework in my analysis builds upon these foundational concepts through some of the recent work by Ockenden et al. in [12], which uses observed surface perturbations (in velocity and elevation) to invert for unknown basal perturbations. Ockenden et al. improve from their previous work in [13] by using full-Stokes transfer functions, which greatly improves their method when dealing with steep topography where the shallow-ice-stream approximation breaks down. Ockenden et al. find this is crucial for better resolving the topographic features they are interested in. The core principle of the method by Ockenden et al. (2023) 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. This relationship can be expressed as $y = f(x)$, where $y$ represents surface measurements (velocity and topography), $x$ represents bed properties (topography and slipperiness), and $f$ is the forward model transfer function refined by Gudmundsson and Raymond in 2008 [14] this by deriving analytical transfer functions.

In their work Ockenden et al apply this framework in reverse $x = f^{-1}(y)$, 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", in glaciology this is equivalent to assuming a linear rheology, where the stress exponent, $n$, is equal to 1. 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. This earliest phase in my PhD project has as a goal to determine whether treating the rheology of ice as linear is adequate. Ockenden et al account for a non-linear sliding law at the base of the ice, mentioning the "sliding law parameter m". However, the transfer of stress through the body of the ice—the core of the perturbation analysis—relies on the linear rheology (constant viscosity) assumption from the foundational work of Gudmundsson and Raymond 2008.

### 2.2.3 Bridging Classical and Modern Approaches

While both frameworks address the fundamental bed-to-surface relationship, they operate at different levels of complexity and make different assumptions. Budd's approach provides the 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. My research aims to bridge these approaches by combining Budd's rigorous

transfer function analysis with comprehensive forward modeling that relaxes some of the restrictive assumptions inherent in linear perturbation methods. By systematically exploring how different rheological models ($n = 1$ vs $n = 3$) and basal conditions affect the bed-to-surface transfer functions, this work aims to develop a robust inversion method that can better handle the nonlinear physics of ice flow while maintaining the theoretical rigor established by Budd's foundational analysis.

## 2.3   Current Opportunities

Current Antarctic bed topography reconstruction methods fail to utilize the wealth of presently available satellite-derived surface data. While mathematical models linking bed to surface through ice dynamics (such as those by Ockenden and Budd) provide a foundation for inferring bed topography from satellite data, they have significant limitations. 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 will feed into ice dynamics models with these improved assumptions, allowing comparison between model predictions and established datasets like NASA's ITS_LIVE. I expect to utilise Machine learning methods to systematize this process, enhancing the analytical capabilities for the project's final phase.

# Methods

## 3.1 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.

## 3.2 Research plan methodology

In order to achieve these objectives, each 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), and then use that knowledge to build a better inverse model (BedSAT). This foundational study will be the basis for my first peer-reviewed paper.

### 3.2.1 Foundational 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) with a custom-built computational framework based on a synthetic bed topography database. See Chapter 4 for detailed information. This systematic study will verify and validate the necessary set of constraints on bed-to-surface transfer functions that account for realistic ice dynamics. This comprehensive analysis will form the basis of the the first peer-reviewed manuscript of this PhD.

### 3.2.2   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 [15]). 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. Furthermore, the robustness of the model will be ensured through grid independence testing and a sensitivity analysis of model assumptions.

### 3.2.3   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.

### 3.2.4   Evaluate the impact of the 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

## 4.1 Recreating ISMIP-HOM

As a first step in validating the computational framework for this project and to build a foundation of the capabilities and functionality of ISSM, I replicated a series of benchmark experiments from the Ice Sheet Model Intercomparison Project for Higher-Order Models (ISMIP-HOM) [16]. Successfully replicating these benchmarks demonstrates that the simulation setup is configured accurately capturing the fundamental physics of ice flow.

My recreation focused on the first four diagnostic experiments (A, B, C, and D), which test a model's ability to simulate ice flow under a range of conditions. Experiments A and B involve flow over a sinusoidally varying bed topography (a "bumpy" 3D bed and a "rippled" 2D bed, respectively) with no basal sliding. These experiments are designed to evaluate the model's handling of longitudinal and vertical stress gradients induced by basal topography. Conversely, Experiments C and D feature a flat bed but introduce spatially variable basal friction, simulating the dynamics of an ice stream with slippery and sticky patches.
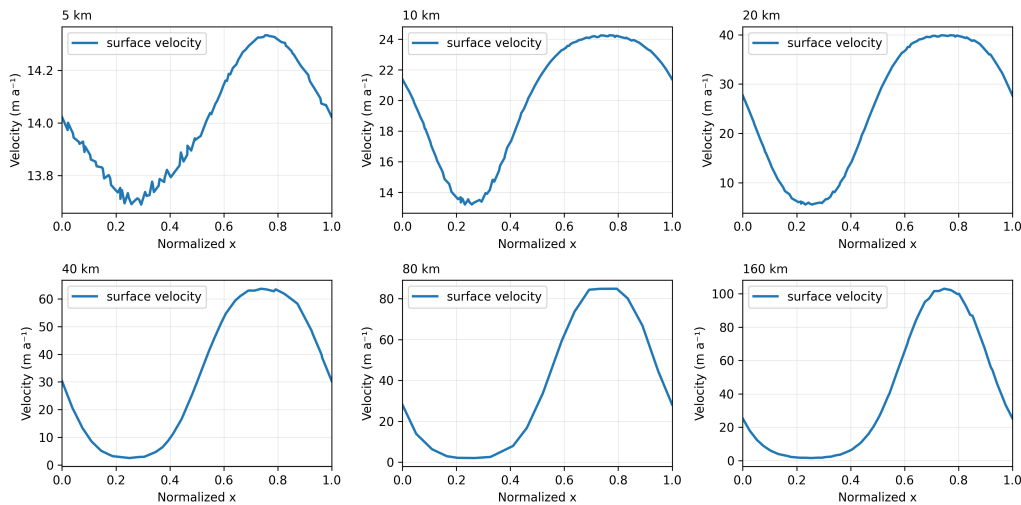


**Figure 4.1:** ISSM recreation of ISMIP-HOM Experiment A: Ice flow over a bumpy bed. The panels show the norm of the surface velocity for a 3D ice flow simulation over a sinusoidal bed with no basal sliding ($v_b = 0$). Each panel corresponds to a different domain length scale (L), from 5 km to 160 km.

**Figure 4.2:** ISSM recreation of ISMIP-HOM Experiment B: Ice flow over a rippled bed. The panels show the surface velocity for a 2D flowline simulation. The setup is identical to Experiment A, but the basal topography does not vary in the y-direction, isolating longitudinal stress effects.



**Figure 4.3:** ISSM recreation of ISMIP-HOM Experiment C: Ice stream flow I. The panels show both surface (blue) and basal (orange) velocity for a 3D simulation over a flat bed where basal motion is governed by a spatially variable friction coefficient, $\beta^2(x,y)$.
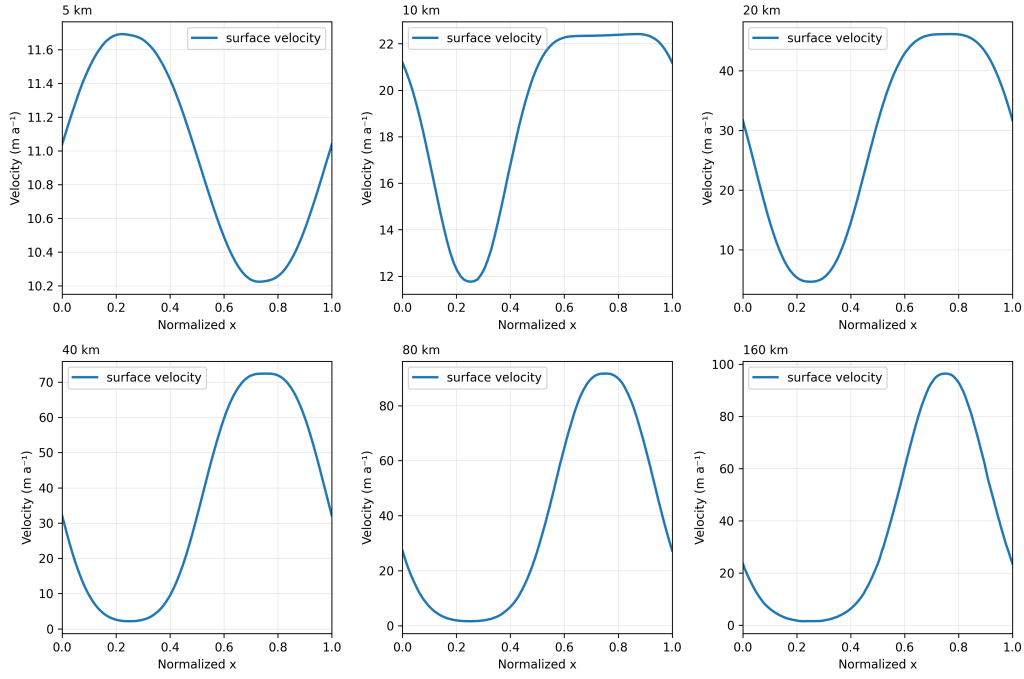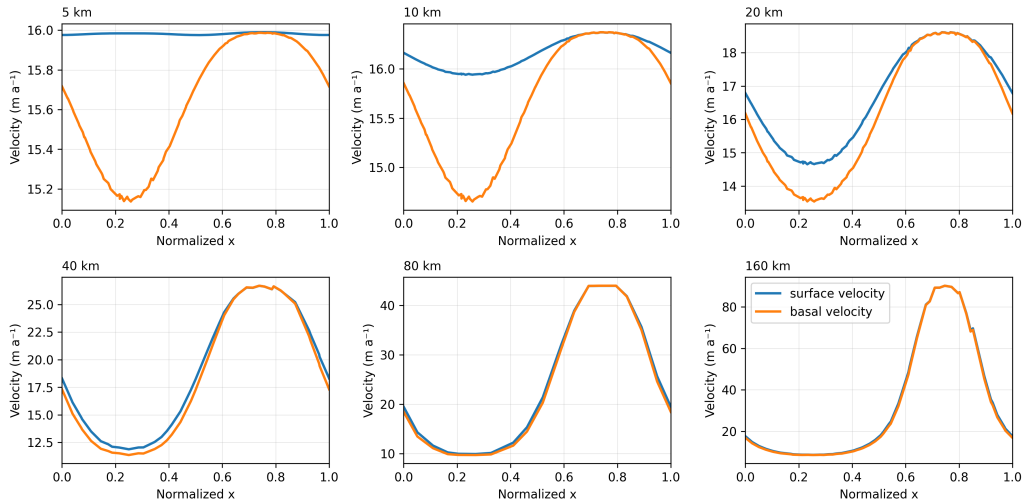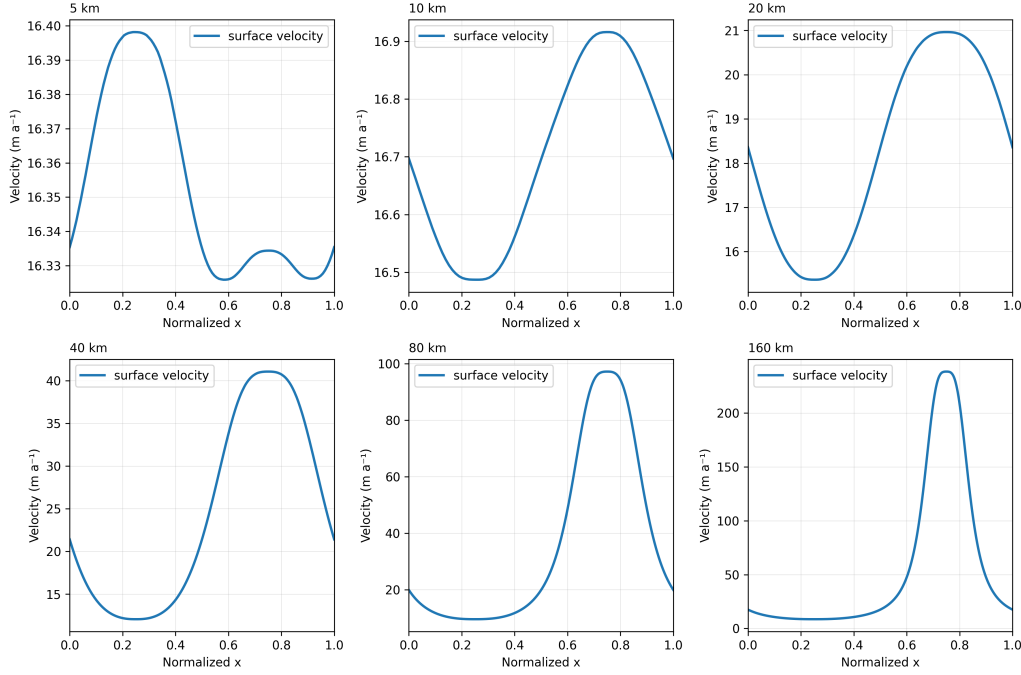
**Figure 4.4:** ISSM recreation of ISMIP-HOM Experiment D: Ice stream flow II. The panels show the surface velocity for a 2D flowline over a flat bed with variable basal friction. The setup is identical to Experiment C, but the friction coefficient varies only in the x-direction, $\beta^2(x,y)$.

The results from these simulations demonstrate a strong agreement with the published findings in [16]. For all experiments and across the different prescribed length scales (L = 5 km to 160 km), my model's calculated surface velocities closely matched the behaviour of the full-Stokes (FS) models from the original ISMIP-HOM. This successful validation confirms that my computational framework is robust and reliably simulates complex ice dynamics. This verification provides a high degree of confidence in the model's physical basis, establishing a solid foundation for the application of my framework to more complex simulation settings and its subsequent research questions. In section 4.2, I extend these principles to investigate the transfer of more complex synthetic bed topography signals to the ice surface. Varying the experimental conditions by combining sliding and frozen beds with different rheological conditions.

## 4.2 Rheology and Sliding Study

Budd's sliding theory describes stress propagation through flowing ice over undulating bedrock. The stress field propagates upward at an angle, creating surface (elevation) waves that are phase-shifted by approximately $\pi/2$ relative to bedrock (elevation) features, in Budd's words: `the maximum shear stress occurs at the tops of the waves and the minimum in the troughs''` [11].

As mentioned in section 3.2.1, my work up until now has been focused in building a comprehensive computational framework developed for the systematic investigation of ice dynamics. The first part of this framework is to study via simulations in 2D the ice flowline behavior over a variety of synthetic bedrock topographies to understand the relationship between basal geometry, ice rheology, and overall flow response. A key aim of this work is to understand the effect of commonly made assumptions in ice sheet modelling and their repercussions in the validity of resulting models. This initial stage is designed

to be a complete, end-to-end pipeline, from environment setup to final scientific analysis.

## 4.3   The Computational Framework of this Study

This study is supported by a suite of interconnected scripts and tools designed for generating conditions, running simulations, processing output, and performing scientific analysis.

### 4.3.1   Synthetic Bedrock Generation

The `bedrock_generator.py` script generates synthetic 1D bedrock profiles for ice flow modeling. the core functionality of this script is the creation of realistic bedrock topographies with configurable geometric properties. The bedrock profiles are defined by the following four key parameters that can be varied systematically:

- Amplitude Controls the vertical scale of undulations (e.g., 19.2 m to 38.4 m).

- Wavelength Controls the horizontal scale of undulations (e.g., 3.84 km to 19.2 km).

- Skewness Controls the asymmetry of the undulations.

- Kurtosis Controls the peakedness or flatness of the features.

The generated profiles are saved to `.npz` files and are loaded by the ice flow simulation script to ensure consistent and reproducible experimental setups.
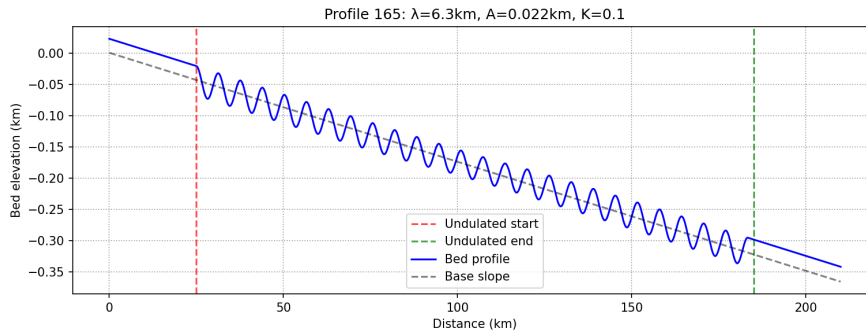


**Figure 4.5:** Database sample: Profile 165 has perturbation wavelength $\lambda = 6.336$ km, amplitude 0.022 km, kurtosis $K = 0.1$

The domain length for all bedrock profiles is 210 km with 100 m horizontal resolution, however the undulated (perturbation) region is 160 km in length leaving 25 km flattened areas in the outer regions of the bedrock are there to minimise large driving stress differences between boundaries (something that can be particularly problematic for simulating non-linear rheology scenarios), they also ensure physically consistent periodicity for the numerical simulation.

### 4.3.2   Ice Flow Simulation

The core of this study is a time evolution flow simulation of fully grounded ice over 300 years with 5 day 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 [16] that can later be analysed in detail with other data processing tools 4.3.3. The simulations solve the full-Stokes ice flow equations for a static diagnostic stress balance and a transient run (which includes stress balance and mass transport configurations). The simulations utilise the Bidimensional Anisotropic Mesh Generator (BAMG) for the case of 2D flowband meshes (`bamgflowband`) to create meshes where the mesh resolution is refined based on the underlying bedrock wavelength to capture key physics efficiently.

The simulation utilises periodic boundary conditions which represents a section of an infinitely long flowline, effectively eliminating edge effects that would arise from standard inlet/outlet boundaries. The script couples the inlet and outlet velocities by matching vertices based on their relative depth within the ice column. This ensures that the ice flow is continuous and that the dynamics are driven solely by the underlying topography and internal stresses, which is crucial for studying the transfer of bedrock signals to the surface.

The experimental design is built around four benchmark experiments to test different physical conditions:

- S1 No-slip (frozen) bed + Linear rheology ($n = 1$).

- S2 No-slip (frozen) bed + Non-linear rheology ($n = 3$).

- S3 Linear sliding + Linear rheology ($n = 1$).

- S4 Linear sliding + Non-linear rheology ($n = 3$).

The main simulation scripts produce `.nc` files and binary `.outbin` files for full simulation results (when run locally and on the NCI Gadi system respectively). The `periodic_flowline.py` script can also generate text files for quick analysis in the case of the static diagnostic runs.

The simulation framework in this study includes capabilities for systematic grid convergence testing, comparing solutions across multiple mesh resolutions (e.g., factors of 0.5, 0.75, 1.0, 1.25) to ensure the results are independent of the mesh discretisation, see sections 4.3.4.

### 4.3.3 Data Processing and Visualization Tools

I have developed a set of robust, high-performance scripts to handle the large volume of data produced by the ice flow simulations. (Note that: All these scripts have individual file processing capabilities)

1. Binary to NetCDF Conversion A batch-capable tool (`batch_convert.py`) converts ISSM `.outbin` files into the standard, portable NetCDF format. This script supports parallel processing for high throughput.

2. Result Extraction and Visualization A batch script (`batch_extract_results.py`) that automatically finds and processes NetCDF files to generate visualisations of key fields like velocity and pressure.

3. Targeted Scientific Plotting Additional scripts (`batch_plots.py`) are used to create specific scientific plots, such as basal and surface velocities, basal velocity colored over the bed topography and basal shear stress distributions, to analyse the direct impact of the bedrock on flow.

### 4.3.4 Scientific Analysis Tools

**Key Findings: The Grid Independence Study**

In order to perform quantitative analysis on the simulation results. I developed a pair of Grid Convergence Analysis scripts capable of analysing the resolution convergence in both the static and transient runs `analyse_grid_convergence.py` and `analyse_transient_convergence.py` respectively. Convergence is assessed by comparing solutions from different mesh resolutions (e.g., factors of 0.5, 0.75, 1.0, 1.25) against the finest mesh solution. The primary metric of this script is the L2 relative error, a global, scale-independent measure that quantifies the overall difference between two solutions. An error below 1% is typically considered a sign of good convergence. A standardized $2 \times 2$ plot **??**is generated to provide a comprehensive view of convergence, showing visual velocity comparisons of surface and basal velocities for each mesh resolution tested, numerical L2 error bars, and the computational cost of each resolution.

**Mesh and Transient Fields**

**Phase Analysis**

To quantify the spatial phase shift between the bedrock topography and the ice surface response and verify the physical validity of my simulation based on the criteria in [11], I developed a single and a batch-processing scripts (`phase_analysis.py` and `batch_phase_analysis.py`) that use cross-correlation to calculate the lag and phase shift between the de-trended bed and surface signals for each time step in a given simulation. The scripts generates time-series plots of phase shift evolution and summary text files with numerical results. For each batch or single simulation analysed.

**Transient Analysis**

# Project timeline

**Completion Status**
○ Not started
◔ 1/4 completed
◑ 1/2 completed
◕ 3/4 completed
● Fully completed

| | **2024** | | | **2025** | | | | | | | | | | | | **2026** | | | | | | | | | | | | **2027** | | | | | | | | | | | | **2028** | |
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**− Project Initiation**

Literature review ◔
ISSM software onboarding ●

**− Objective 1**

Derive the BedSAT method ◔
Obtain ML training data ◔
Model experiments and ML training ○
Data analysis & Objective 1 paper ○

**− Objective 2**

Apply methodology Antarctica wide ○
Develop Antarctica wide topography data set ○
Data analysis & Objective 2 paper ○

**− Objective 3**

Conduct sensitivity analysis of model predictions ○
Data analysis & Objective 3 paper ○

**− Thesis Development**

Writing ◔

**− Professional Development**

MyDevelopment Courses ●
◆ Australian Antarctic Research Conference ●
◆ Karthaus Summer school ●
◆ visit Edinburgh, UK ○

**− Milestones**

◆ Initial Review ●
◆ Confirmation ●
◆ Mid-candidature Review ○
◆ Final Review ○
◆ Thesis Submission ○

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