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.

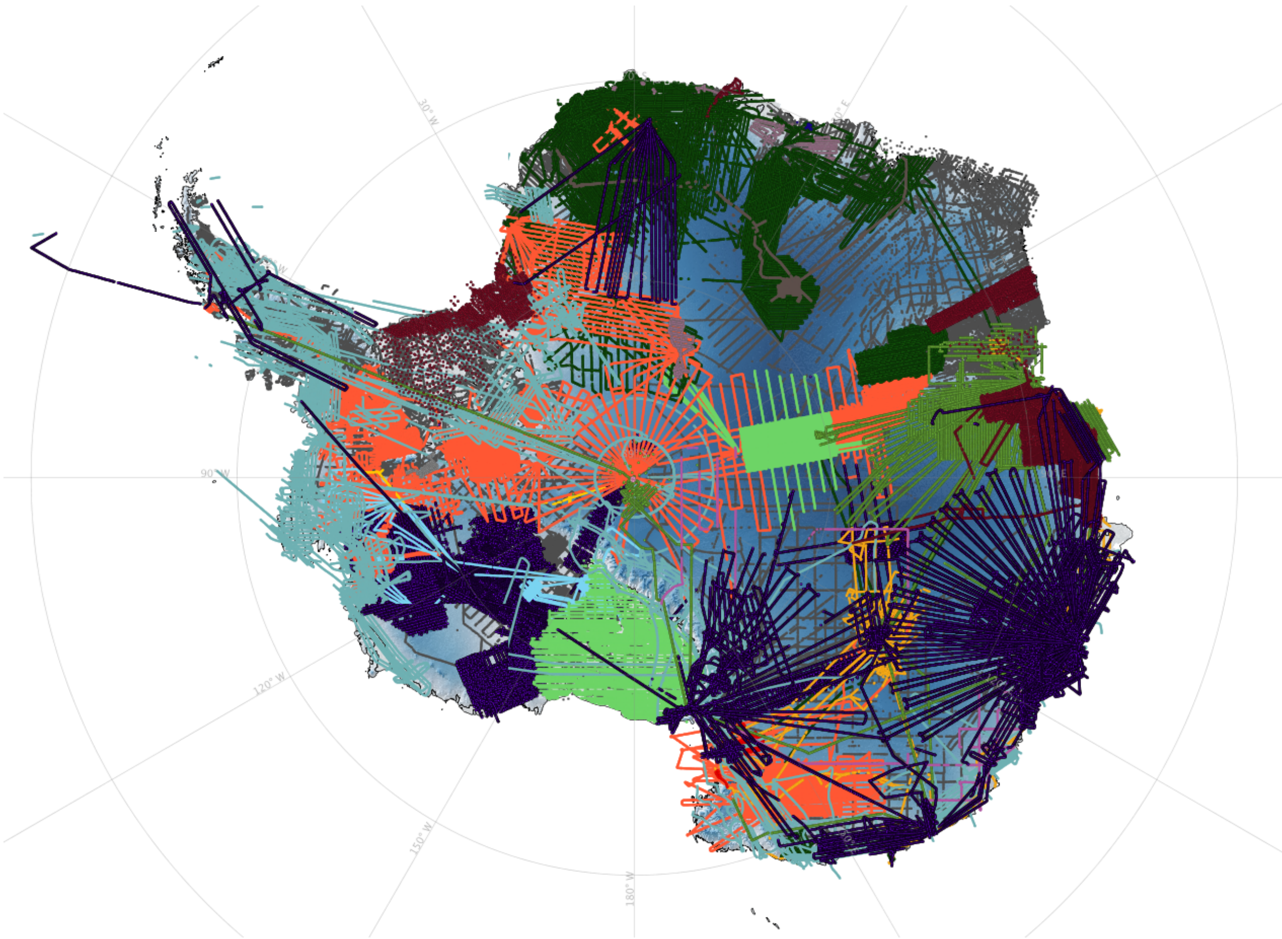


Figure 2.1: Distribution of BedMAP{1,2,3} data tracks (Source: bedmap.scar.org).

2.1 Approaches to Bed Topography Reconstruction

A key objective of this study is to understand objective is to understand the bed topography itself and how it influences ice dynamics. There are two ways that we 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 observations and these modelling frameworks, my goal is understanding the limitations of each approach and how they can be improved.

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 model's foundation rests on two key simplifications:

- Most shear deformation occurs at the base of the ice sheet
- Explicit consideration of longitudinal stresses and strain-rates

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]. Despite its robustness, Budd's mathematical framework remains notably underutilized in modern ice sheet modeling.

The second framework in my plan analyses how shape and mechanical properties of the ice bed significantly influence how ice flows, with changes at the bed potentially leading to large differences in predicted ice loss rates [12]. Recent work by Ockenden et al. demonstrates both the capabilities and limitations of current inversion approaches in addressing this problem. The core principle of the method by Ockenden et al. (2022) 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 [13]. The inversion process, $x = f^{-1}(y)$, estimates bed conditions from surface observations.

The method works best when analyzing perturbations that are small relative to mean properties, under specific conditions including:

1. A linear viscous medium ($n = 1$)
2. Non-linear sliding law ($m > 0$)
3. Steady-state conditions
4. Spatially constant zero-order solutions

Using high-resolution datasets (REMA surface elevation at 8m resolution and NASA ITS_LIVE velocity at 120m resolution), their approach performs well for:

- Areas with moderate topographic gradients
- Features not aligned with ice flow direction
- Medium-wavelength (5-50km) bedrock features

Nevertheless, significant limitations emerge when:

- Dealing with steep topography where the shallow-ice-stream approximation breaks down
- Handling variable slipperiness parameters
- Attempting to validate slipperiness predictions due to lack of ground-truth data

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 Budd's 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

I will address the following 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 influence the rate of GL retreat in continental ice sheets?

Underpinning these research questions are the following objectives:

1. 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;

2. Derive a new bed topography for Antarctica using BedSAT;

3. 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

Objective 1 is to derive the BedSAT method. I will use a regional catchment in Antarctica for which relatively more radar data are available and has an indicative range of topography features, e.g. the Aurora Subglacial Basin, East Antarctica, extensively surveyed by Collaborative Exploration of the Cryosphere through Airborne Profiling (ICECAP) [14]. In developing my inversion approach, I will consider important factors like sliding variability, to distinguish between topographical signatures and sliding-induced features in surface expressions. I will implement a realistic sliding-law in the Ice-sheet and Sea-level System Model (ISSM) that incorporates Budd's determinations of ice-sliding velocities across varying roughness, normal stress, and shear stress conditions. By calibrating these advanced models against known radar-surveyed regions with varying sliding conditions and validating with other observational data, I can better isolate true bed topographical features from friction-related artifacts and create a more robust inversion framework.

The second phase of the project (objective 2) will apply the methodology developed in objective 1 to the whole Antarctic continent, deriving a continent-wide bed topography dataset. Using covariance properties from existing radar surveys, I will generate a number of realisations of bed topography with unique high-resolution, and statistically-consistent topographic roughness. In the third phase of the project will use the new bed topography datasets to conduct a sensitivity analysis of ice sheet model projections to 2300 CE, investigating the impact of the new topography and different realisations of roughness on ice and subglacial hydrological flow and ice mass loss from Antarctica.

Objective 1

1. 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;

Key Investigation Areas for Objective 1

1. **Model Development Strategy**
   - I will maintain invariant (but spatially variable) bed traction throughout the modeling timeframe to isolate topographical effects in the inversion approach.
   - My model will incorporate available thermal distribution, velocity field, and ice thickness data, as these parameters be constrained using observations.
   - Through spectral analysis of surface expressions, I will identify the topographical features that most strongly influence surface patterns.
   - To account for variations in ice behavior with thickness, I will simulate scenarios ranging from thick ice with slippery base to thin ice with sticky base, using observed velocity patterns as constraints.
2. **Transfer Functions**
   - I will develop efficient transfer function methods for rapid bed topography inversion, validating against known bed configurations from radar data.
   - My transfer functions will be tested across various ice thickness and flow conditions.
   - Cross-validation against radargrams will provide direct verification of my inversion results.
   - Spatial covariance analysis of existing radar data will inform my statistical framework and error propagation through the inversion process.
   - I will account for friction roughness and high-amplitude variations, using observed surface velocity patterns as constraints.
3. **Model Validation**
   - I will apply quantitative error reduction metrics and compare systematically against existing bed topography products.
   - Model limitations and breaking points will be identified through systematic testing across extreme scenarios, constrained by physical principles.

- Grid independence testing will ensure solution robustness across different spatial resolutions.
- Sensitivity analysis will examine the impact of my model assumptions.

Note: Detailed methodological outlines for Objectives 2 and 3 will be developed following the completion and refinement of the BedSAT method in Objective 1.

Resources

I require high performance computing resources (including compute and storage) from the National Computing Infrastructure (NCI). These resources are already available via a Flagship between NCI and the Monash-led Australian Research Council project Securing Antarctica's Environmental Future (SAEF).

Currently available data and Framework

The project will make use of a number of new remote sensing datasets and software tools.

1. **Reference Elevation Model of Antarctica (REMA)**
   Constructed from hundreds of thousands of Digital Elevation Models (DEMs) derived from high-resolution Maxar satellite imagery, REMA is calibrated with Cryosat-2 and ICESat altimetry [15].

2. **ITS_LIVE Antarctic surface velocities and elevation**
   The NASA-administered ITS_LIVE website provides automated, high-resolution datasets of Antarctic surface velocities and ice surface elevation change, derived from satellite observations [16].

3. **BedMAP**
   A suite of gridded products describing surface elevation, ice-thickness and the seafloor and subglacial bed elevation of Antarctica, based on a compilation of data collected by a large number of researchers using a variety of techniques, with the aim of representing a snap-shot of understanding of the Antarctic region [17]. BEDMAP lacks detailed information on bedrock type, sediment layers, or geothermal heat flux, all of which affect ice dynamics intruducing model uncertainty.

4. **BedMachine Antarctica**
   A high-resolution map of Antarctic subglacial bed topography that provides unprecedented detail of basal features. The dataset combines multiple ice thickness measurements with mass conservation principles, satellite-derived ice flow velocities, and surface mass balance from regional atmospheric models [5]. Similarly to BedMAP, BedMachine does not explicitly model basal properties.

5. **Collaborative Exploration of the Cryosphere through Airborne Profiling (ICECAP)**
   Since 2012, the project has obtained extensive data on ice thickness mapping and surface elevation in regions of the East Antarctic grounding zone, also comprehensive gravity mapping in areas beneath the Totten Glacier cavity [18].

6. **Ice-sheet and Sea-level System Model (ISSM)**
   ISSM is a finite-element numerical ice sheet model. It has been used to simulate the Antarctic Ice Sheet's response to various climate scenarios and assess future mass loss contributions to sea level rise [5, 8, 19].

Data management and archiving

Data will be published adhering to FAIR principles (Findable, Accessible, Interoperable, Reusable), ensuring transparency and accessibility. The final bed topography datasets will be published at the Australian Antarctic Data Centre (AADC) under an open source licence. All production model outputs will be published with unique DOIs at repositories aligned with the corresponding journal articles. Model outputs will be archived to tape at NCI using existing SAEF resources, as well as backed up to storage available through Monash MASSIVE M3 account aligned with project supervisor Dr McCormack. All journal articles published through this project will be open source, and tier 1 journals will be targeted.

Risk

The project is highly feasible and low risk, given that it is a desk-based modelling and data assimilation project. All the data to be used in this project are freely available for download, and project supervisors are experts in ice sheet modelling using ISSM.

Fieldwork

Fieldwork is not necessary to achieve the objectives of the project; however, there may be the opportunity to participate in fieldwork through the ICECAP airborne geophysics project (led CI of ICECAP is project supervisor Dr Jason Roberts, Australian Antarctic Division), which will be instrumental in training of geophysical instruments and in developing broader expertise in the field.

Career Development

I have secured a position in the highly competitive Karthaus Glaciology Summer School taking place in northern Italy in May 2025. This prestigious program will provide comprehensive training across all aspects of glaciology directly relevant to my research, offering not only technical knowledge but also valuable networking opportunities with leading researchers in the field.

Progress

Budd's sliding theory describes stress propagation through flowing ice over undulating bedrock. The stress field propagates upward at an angle, creating surface waves that are phase-shifted by approximately $\pi/2$ relative to bedrock features, in Budd's words: "the maximum shear stress occurs at the tops of the waves and the minimum in the troughs" [11]. To test this theory, my ISSM simulation uses a flowband model in a 27 km domain (triangular elements sized at 0.8 km), 2.7 km mean ice thickness, bedrock at 1 km elevation with -0.1 radian slope, and cosine undulations (9.72 km wavelength, 0.054 km amplitude). I chose these parameters based on the most ideal transference conditions explained in [11]. I ran a 300-year Full-Stokes transient simulation with 1-year time steps. The results show that the relationship between surface and bedrock profiles does not exhibit the expected $\pi/2$ phase shift but instead shows a shift of -0.04π radians, which corresponds to a spatial shift of -0.200 km (see Figures 5.5 and 5.4). This effect is directly attributable to Budd's shear stress function (see Figure 5.1). The discrepancy between my results and Budd's theory could very well be due to my simulation not yet reaching steady state. Given my recent acquisition of ISSM skills, I have not yet had the opportunity to utilize the NCI supercomputing platform Gadi, but I am in the process of transitioning from local simulations to this more powerful to achieve the extended run times necessary for steady-state analysis.

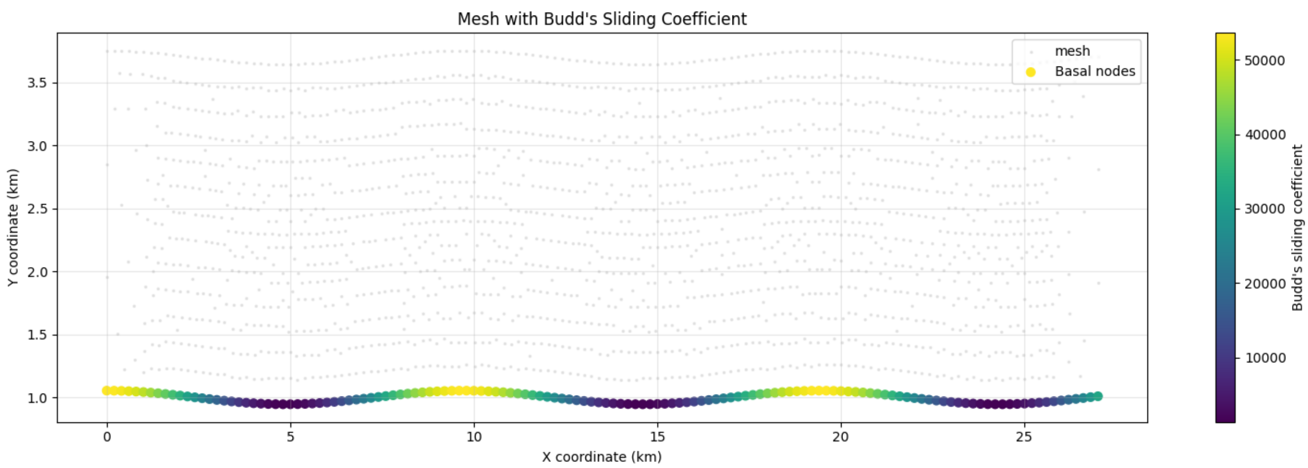


Figure 5.1: Slope parallel visualisation of the computational mesh with basal nodes highlighted. The gray dotted lines represent the complete finite element mesh with multiple vertical layers conforming to the undulating geometry. Basal nodes (purple to yellow) follow the periodic undulated bed topography with wavelength 9.72 km and amplitude 0.054 km. The colour gradient along the basal nodes displays the imposed variations in basal shear stress corresponding to Budd's sliding law, with lighter colours indicating regions of higher basal drag. Note that maximum basal drag occurs near the peaks of the bedrock undulations, consistent with the expected shear stress pattern in the sliding theory. The 27 km domain contains approximately three complete undulation cycles.

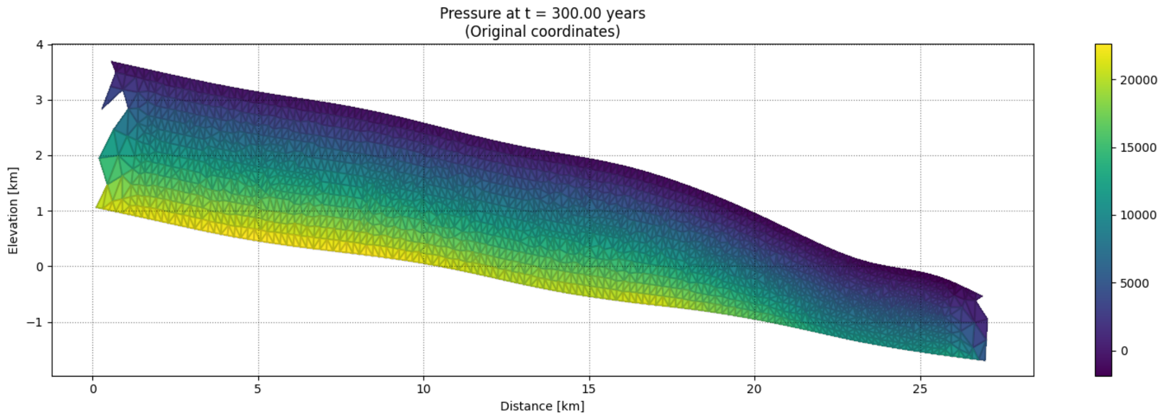


Figure 5.2: Pressure field distribution at t = 300.00 years shown in original coordinates. The color scale reveals the spatial pressure variations throughout the ice body, with higher pressures (yellow) concentrated at the base and particularly near bedrock peaks. The triangular mesh elements display the finite element discretisation used for solving the Full-Stokes equations. The overall pressure gradient follows ice thickness with maximum values at the base with a visible influence of bedrock undulations on the pressure field. The downward-sloping ice surface reflects the -0.1 radian background slope condition, while subtle surface undulations are apparent in response to the bed topography. This visualization captures the result after 300 years of transient simulation, providing insight into the stress propagation patterns described in Budd's sliding theory.

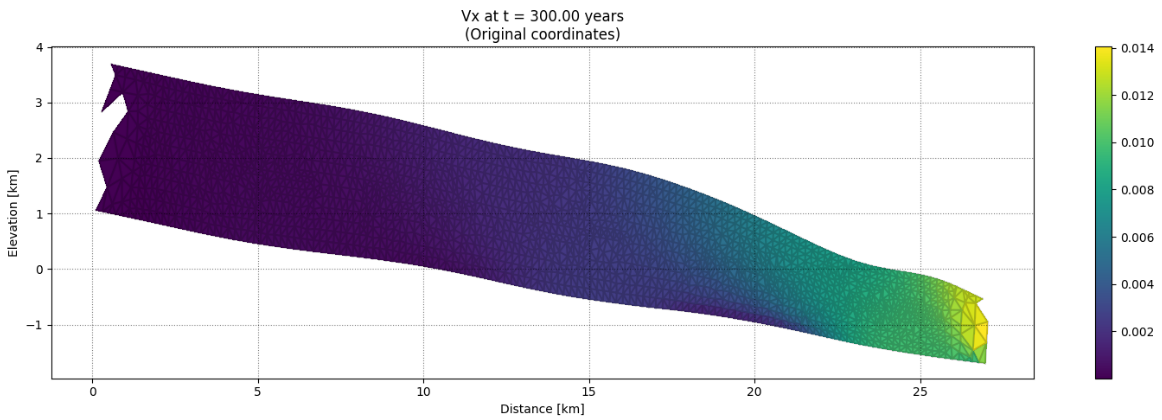


Figure 5.3: Horizontal velocity field (V_x) at t = 300.00 years displayed in original coordinates. The color scale indicates velocity magnitudes ranging from 0 to 0.0147 km per year with flow direction from left to right. The velocity pattern shows clear acceleration as the ice flows downslope, with highest velocities (yellow) occurring near the terminus region. The fixed upstream boundary condition constrains flow at the inlet, while the progressive acceleration downstream results from gravitational forcing along the -0.1 radian sloped bed. Note the visible influence of the bedrock undulations on the velocity field, particularly near the base. The contrast between slow-moving upper ice (purple) and faster basal ice in the terminal region demonstrates the development of vertical velocity gradients.

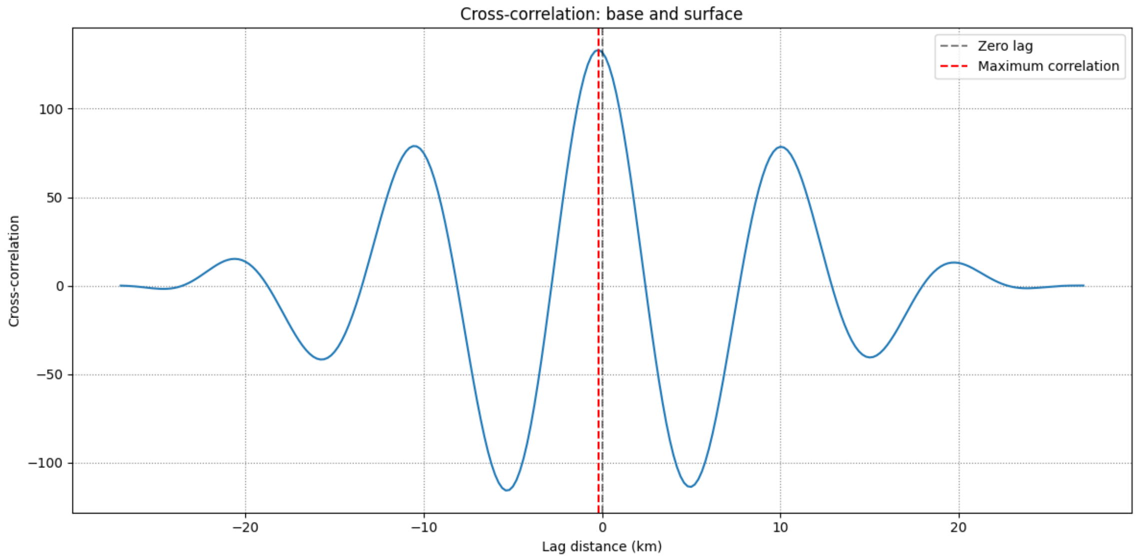


Figure 5.4: Cross-correlation between the bedrock elevation and surface slope signals across spatial lags. The blue curve shows normalized correlation coefficients as a function of lag distance. The maximum correlation (red dashed line) occurs at a lag distance of -0.2 km, which translates to a phase shift of -0.04π radians (-7.4 degrees). This observed phase shift significantly deviates from Budd's theoretical prediction of $\pi/2$ (90 degrees), suggesting that in this simulation at t = 300 years, the relationship between bedrock topography and surface features differs from theory. The zero lag position (black dashed line) represents perfect spatial alignment. The periodic nature of the cross-correlation function reflects the underlying 9.72 km wavelength of the bedrock undulations, with correlation peaks appearing at approximately 10 km intervals.

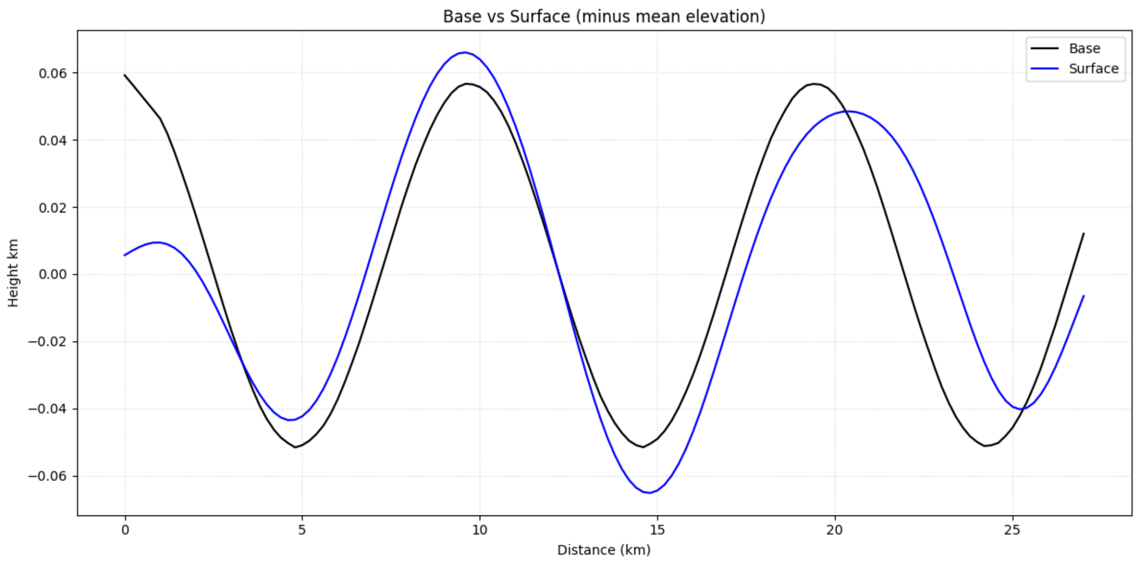


Figure 5.5: Direct comparison between bedrock topography (black) and ice surface elevation (blue) with mean elevations removed to highlight the undulation patterns. Both profiles are plotted in slope-parallel coordinates along the 27 km domain. The surface undulations exhibit a visible phase shift relative to the bedrock features, though this shift is noticeably less than the theoretical $\pi/2$ predicted by Budd's sliding theory. The surface amplitude appears damped compared to the bed amplitude, particularly evident in the central wavelengths. However, boundary effects near $x = 0$ and $x = 27$ km complicate the interpretation, as the amplitude damping and phase relationships may be influenced by the finite domain and boundary conditions. This comparison at t = 300 years reveals a complex and still-evolving relationship between bed topography and surface expression, with the phase relationship varying slightly across the domain. The dominant wavelength of approximately 9.72 km is preserved in both signals, indicating effective stress transmission through the 2.7 km ice thickness despite the reduced phase shift.

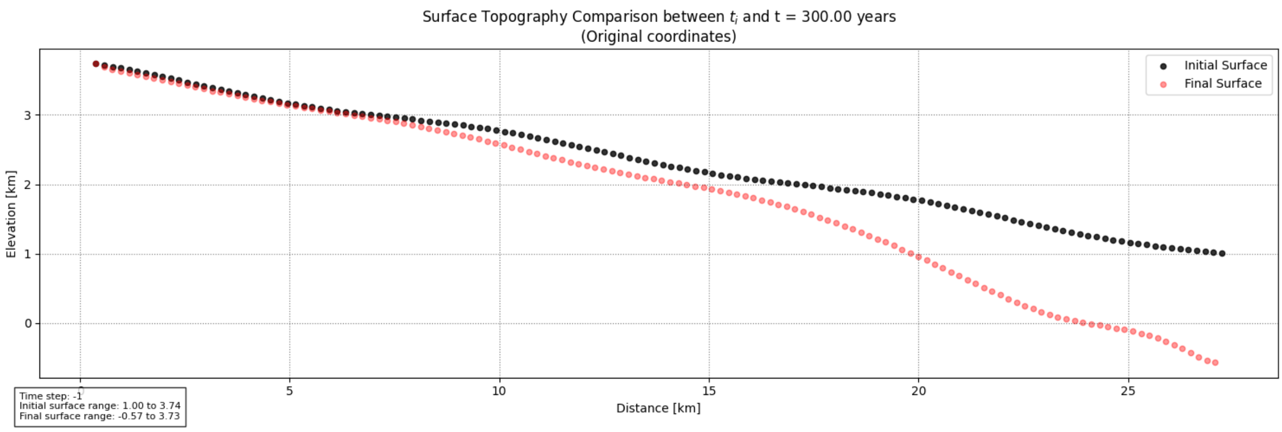
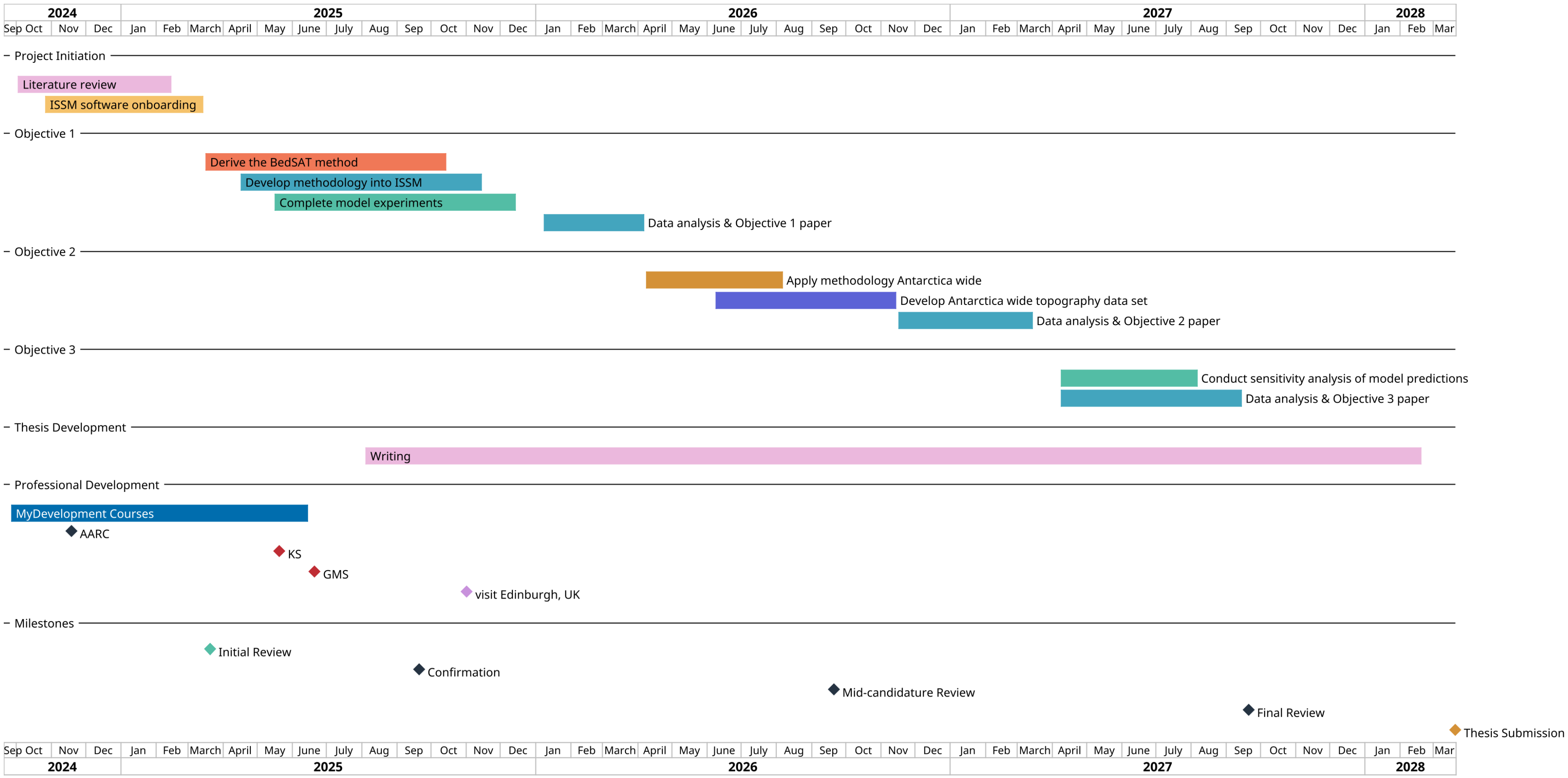


Figure 5.6: Evolution of ice surface topography from initial condition (black) to final state at t = 300.00 years (red) displayed in original coordinates. The simulation shows significant ice thinning and terminus retreat, with the final surface elevation ranging from -0.57 to 3.73 km compared to the initial range of 1.00 to 3.74 km. The final surface exhibits a steeper overall slope, particularly in the lower half of the domain ($x > 15$ km), indicating a dynamic response to the applied flow conditions. Surface undulations have developed in the final state, though these are subtle relative to the overall elevation change. The preservation of similar elevation at the upper boundary ($x = 0$ km) reflects the fixed inflow boundary condition, while the downstream region shows maximum adjustment. This 300-year evolution demonstrates that the ice mass is still adapting to the prescribed basal conditions and has not yet reached a steady state, which may explain the discrepancy between the observed phase shift and Budd's theoretical prediction.

Project timeline



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