BedSAT: Antarctica

Exploring what lies beneath using big data and modelling

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Impact Statement

Antarctica's bed topography data currently has 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 Bed-SAT 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. We 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. Our 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 [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 samples. Other problematic areas involve the ice sheet's grounding line (GL). The retreat rate depends crucially on topographical features like pinning points, as these are locations where the GL is most stable and ice-sheet retreat will slow [3]. However, 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 systematic mapping efforts 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 in 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.

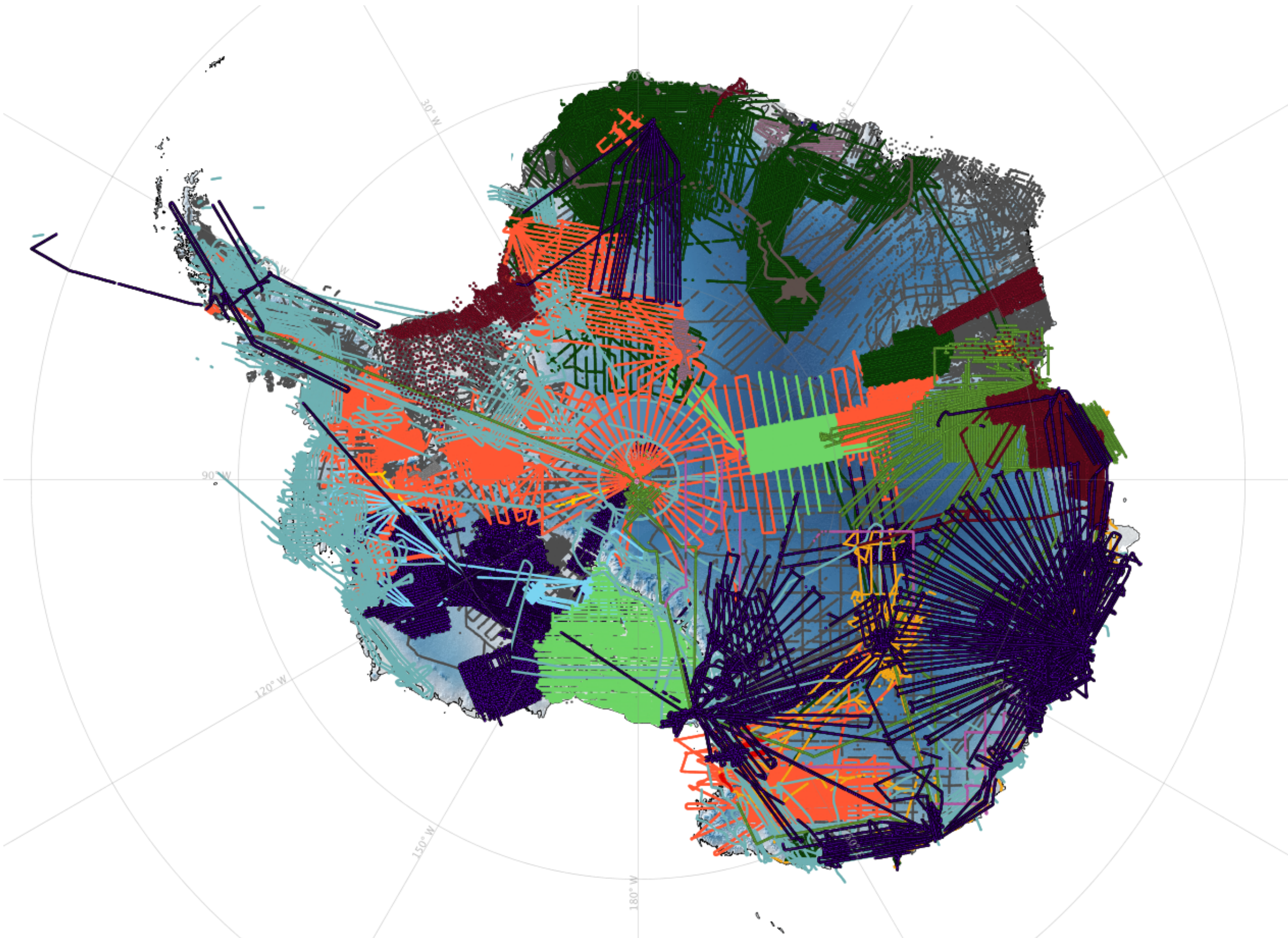

Figure 2.1: Distribution of BedMAP{1,2,3} data tracks (Source: bedmap.scar.org).

2.1 Approaches to Bed Topography Reconstruction

Obtaining information about the conditions at the base of the ice-sheet often relies on indirect modelling methods that operate in two fundamentally different directions:

- **Forward models** From bed topography data, simulate ice flow to predict surface conditions. They use known or assumed basal properties to model how the ice sheet will respond.
  - **4dvar**: Four-dimensional variational data assimilation - Minimizes the difference between model predictions and observations across a time window. Mainly used to optimize model parameters and initial conditions [7]. 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 [7].
  - **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 [8].
  - **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 [7].
- **Inversion models** Retrieval (or update) of bed topography and basal slipperiness from surface topography and velocity measurements [9].
  - **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 [9]. Often needs regularization terms to prevent non-physical features or over-fitting [7].
  - **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 [7].
  - **Markov Chain Monte Carlo (MCMC)**: A probabilistic method that generates sample distributions to quantify uncertainties in ice sheet parameters and models [7]. While powerful for uncertainty quantification, these methods remain computationally intensive for continental-scale ice sheet models [7].

While each method has its strengths and limitations, the choice of approach often depends on the specific research objectives, data availability, and computational resources. Control methods and mass conservation approaches are widely used for steady-state reconstructions, while 4dvar and EnKF methods are better suited for time-evolving systems. Recent advances in computational power have made probabilistic methods like MCMC more feasible, offering valuable insights into parameter uncertainties.

2.2 Theoretical Frameworks

These modeling approaches, particularly forward models, rely on theoretical frameworks that describe the relationship between bed topography and surface features. Many authors have explored this relationship to understand how basal conditions influence the ice surface profile features. Understanding how bed features manifest in surface observations requires a theoretical framework that connects these two domains. A pioneering contribution to this field was made by Budd [11], who developed a model relating 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. This gap in application is particularly striking given today's advanced computational capabilities and high-resolution satellite observations. This begs the questions: What specific computational or theoretical advances are required to effectively integrate Budd's mathematical framework with contemporary high-resolution satellite observations? And once we integrate this model into modern ice sheet modelling, how does the accuracy of Budd's model compare to more complex modern approaches when predicting surface expressions from known bed topography features across different ice flow regimes?

2.3 Modern Inversion Methods

The 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

However, 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

While modern satellite technology has revolutionized our understanding of ice sheets by providing unprecedented detail of surface features, these limitations highlight a key challenge in glaciology: we have yet to fully leverage this wealth of information to improve bed topography estimates in regions where radar data is sparse. This gap between rich surface datasets in certain regions and limited subglacial understanding motivates this investigation. It is of particular interest to us to develop the integration of more comprehensive models and modern computational capabilities.

2.4 Current Opportunities

We have highlighted above several persistent challenges in Antarctic bed topography reconstruction, and I have also included a description of current approaches. The works I chose to exemplify here, while theoretically robust, faces practical limitations. The inversion method employed by Ockenden et al. provides valuable insights but is limited by assumptions that do not capture the full complexity of ice-bed interactions, particularly when dealing with steep topography where the shallow-ice-stream approximation breaks down. Similarly, the sliding theory developed by Budd offers important physical insight but remains underutilized in modern ice sheet modeling despite today's advanced computational capabilities and high-resolution satellite observations.

A key question in this work is how surface features relate to ice thickness. Our current models struggle to capture the complex relationships created by basal roughness and variable friction zones. Additionally, we lack crucial data like basal friction measurements for accurate reconstruction. These challenges mean the results depend heavily on the assumptions built into models. Another key factor involves the dynamics at ice sheet margins. As noted by Nias (2018) in [14], "subtle variation in the geometry near the grounding line can trigger a response in the ice sheet that is felt hundreds of kilometers upstream." I want to understand how do changes in bed conditions and topographical features like "slipperiness","roughness" and pinning points specifically influence the rate of grounding line retreat in continental ice sheets? This question is essential for accurate bed topography reconstruction and subsequent ice sheet evolution modeling. Similarly, ice viscosity is a critical factor since high viscosity ice near the surface tends to dampen bed topography signals significantly [9], creating potential misinterpretations of surface expressions.

With BedSAT, I aim to build upon the theoretical foundations established by Budd and recent inversion methods. Our approach will help bridge the disconnect between surface observations and bed topography by utilizing a more realistic set of rheological and geometric assumptions. This addresses another fundamental question in our field: To what extent do interpolation uncertainties in bed topography datasets affect the accuracy of Antarctic Ice Sheet evolution simulations under different climate change scenarios?

In addition, I plan to implement the methods in an iterative way, allowing us to improve results via an inversion-forward modelling validation cycle: The initially inverted bed topography will be used in the ice dynamics (forward) model with BedSAT's improved rheological and geometric assumptions, to then compare the resulting surface predictions with products like NASA'S ITS_LIVE (see Chapter 4). Part of my plan involves a systematization of this process via Machine learning methods. This will ultimately enhance the analyses in the final phase of my project.

1713 words in this section.

Methods

3.1 Aims

The project specific objectives are

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 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 the Collaborative Exploration of the Cryosphere through Airborne Profiling (ICECAP) [15]. 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 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.

Specific outline for Objective 1 (ONLY)

1. Develop a method to interpolate topography that ensures surface expressions consistent with observations

Key Investigation Areas for Objective 1 (ONLY)

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 radar 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.

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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 [16].

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 [17].

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 [18]. 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. **ICECAP**
   Collaborative Exploration of the Cryosphere through Airborne Profiling. 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 [19].

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, 9, 20].

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.

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Progress

The current objective is understanding the relationship between surface and bed topography in glaciers using ice-sheet modeling with ISSM. This simulation examines how bed undulations manifest at the surface. The simulation implements a flowband ice model across a 10 km domain with 100 m resolution. Featuring an 800 m mean ice thickness over bedrock at 1 km elevation, with a -0.1 radians downward slope and imposed cosine undulations (2.64 km wavelength, 0.1 km amplitude). The main objective of this simulation is to verify the sliding law proposed in [11]. The main model, `flowline8.py`, executes a 300-year transient Full-Stokes simulation using 1-year time steps. Supporting tools include `phase_analysis.py` for examining bed-surface relationships and `plotting.py` for visualizing resulting simulation fields. The implementation of this simulation does not yet demonstrate how basal topography influences surface expression through a spatially varying basal friction governed by a simplified version of Budd's sliding law.

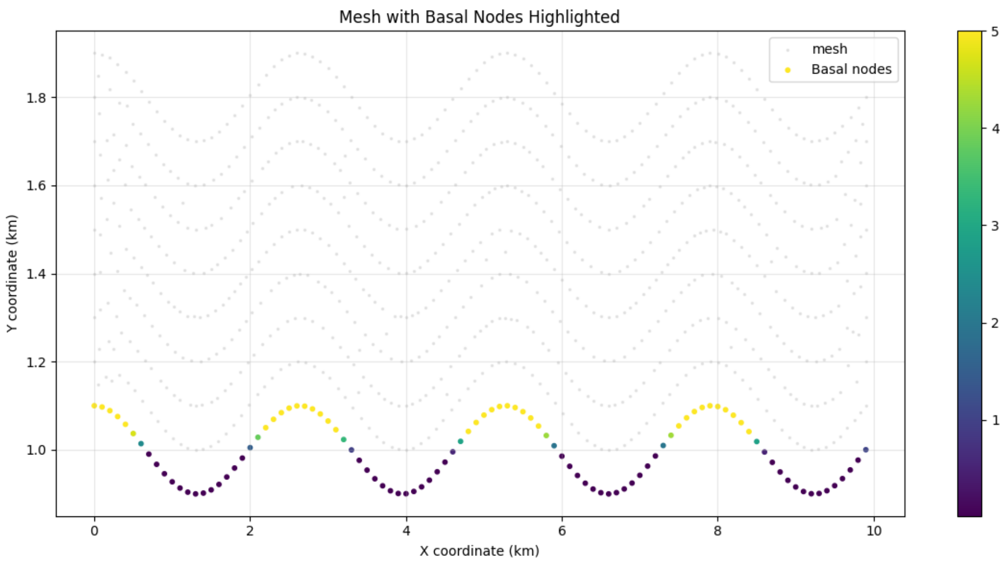

Figure 5.1: Slope parallel visualisation of the computational mesh with basal nodes highlighted. The gray dotted lines represent the complete finite element mesh with multiple vertical layers conforming to the undulating geometry. Basal nodes (yellow to purple) follow the periodic bed topography with a wavelength matching the dominant frequency observed in the filtered signals. The colour gradient along the basal nodes represent variations in basal friction coefficient implemented through a simplified version of Budd's sliding law, with lighter colours indicating regions of higher basal drag

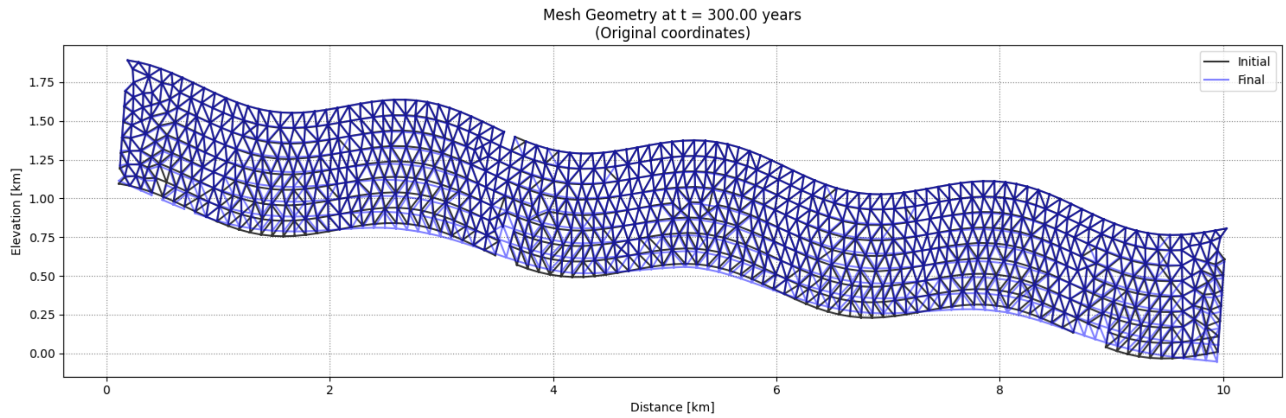

Figure 5.2: Mesh geometry evolution from initial state (black mesh) to final configuration at t = 300.00 years (blue mesh) shown in original coordinates. The unstructured triangular finite element mesh adapts to the changing ice geometry while maintaining numerical stability. Presently both the surface and basal boundaries preserve the wavelength of the underlying bed topography ($\lambda = 2.64$ km), with similar amplitudes and phase relationships. This is not the expected result. The final mesh appears to be moved near the base when compared to the initial mesh setup which is unphysical. This demonstrates that there may be a problem in the transient computation.

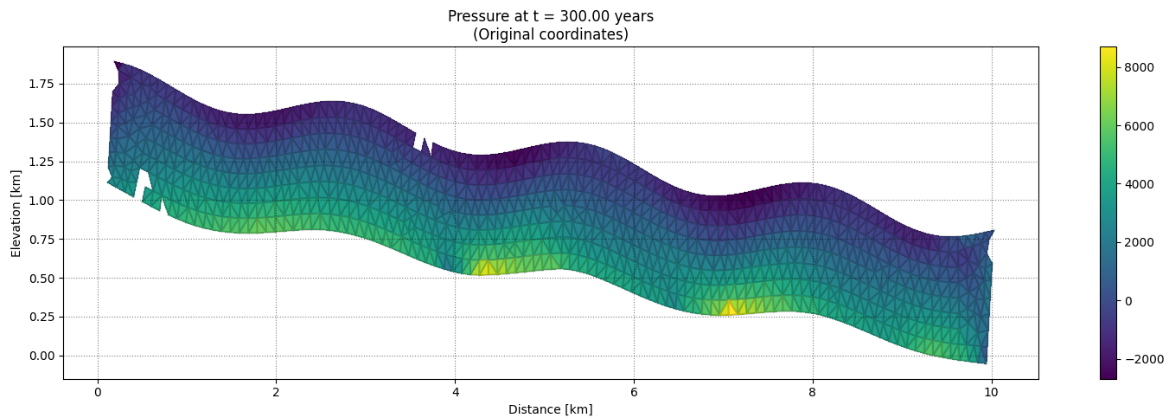

Figure 5.3: Pressure field distribution at t = 300.00 years shown in original coordinates. The color scale (ranging from -2000 to 8000 Pa) reveals the spatial pressure variations throughout the ice body, with higher pressures (yellow) concentrated before the peaks of the bed undulations. The triangular mesh elements display the finite element discretisation used for solving the Stokes equations. The development of low-pressure zones near the surface aligning with the undulating basal topography suggests stress transfer from the imposed variation in basal friction.

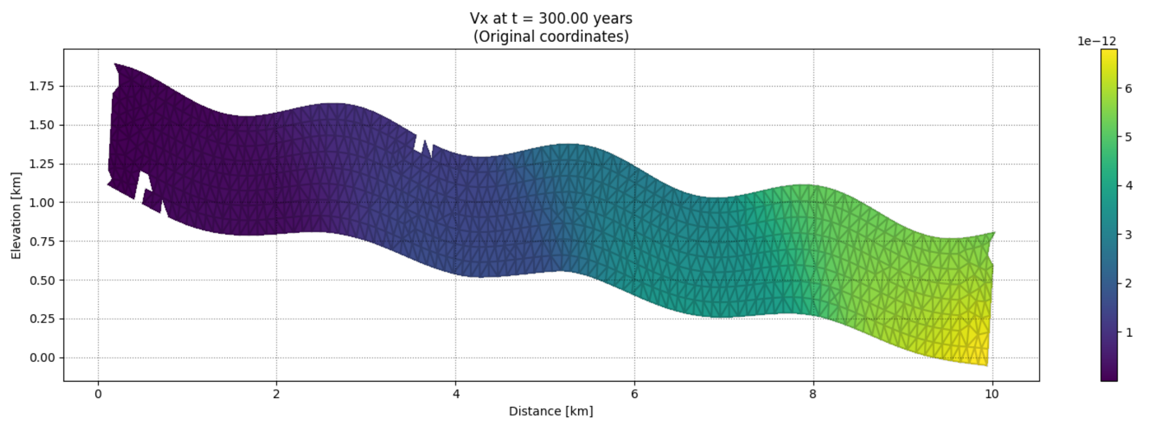

Figure 5.4: Horizontal velocity field (Vx) at t = 300.00 years displayed in original coordinates. The color scale indicates velocity magnitude (10^{-12} km/s, equivalent to ≈ 31.5 mm/year at the maximum) with flow direction from left to right. The velocity pattern shows clear acceleration as the ice flows downslope, with highest velocities (yellow) occurring near the terminus. The fixed upstream boundary condition constrains flow at the inlet, while the progressive acceleration downstream results from gravitational forcing along the sloped bed.

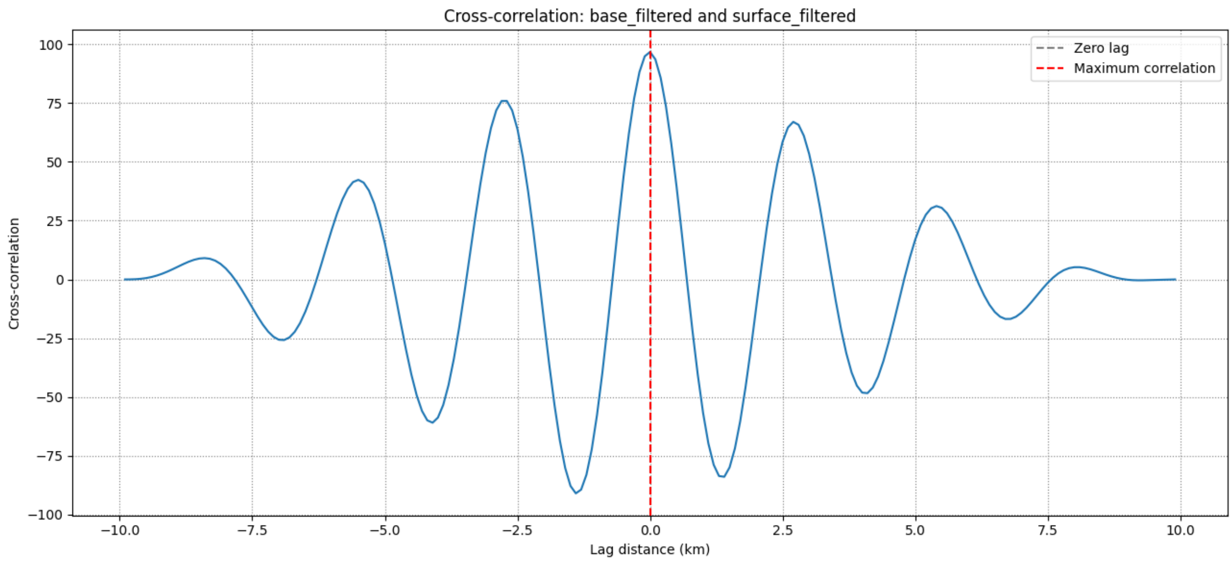

Figure 5.5: Cross-correlation between the filtered base and filtered surface signals across spatial lags. Maximum correlation of approximately 98% occurs at zero lag, with periodic oscillations of decreasing amplitude at increasing distances. The symmetric pattern indicates similar signal structures in both datasets, with a characteristic wavelength of approximately 2.5 km (bedrock signal is $\lambda = 2.64$ km) between correlation peaks.

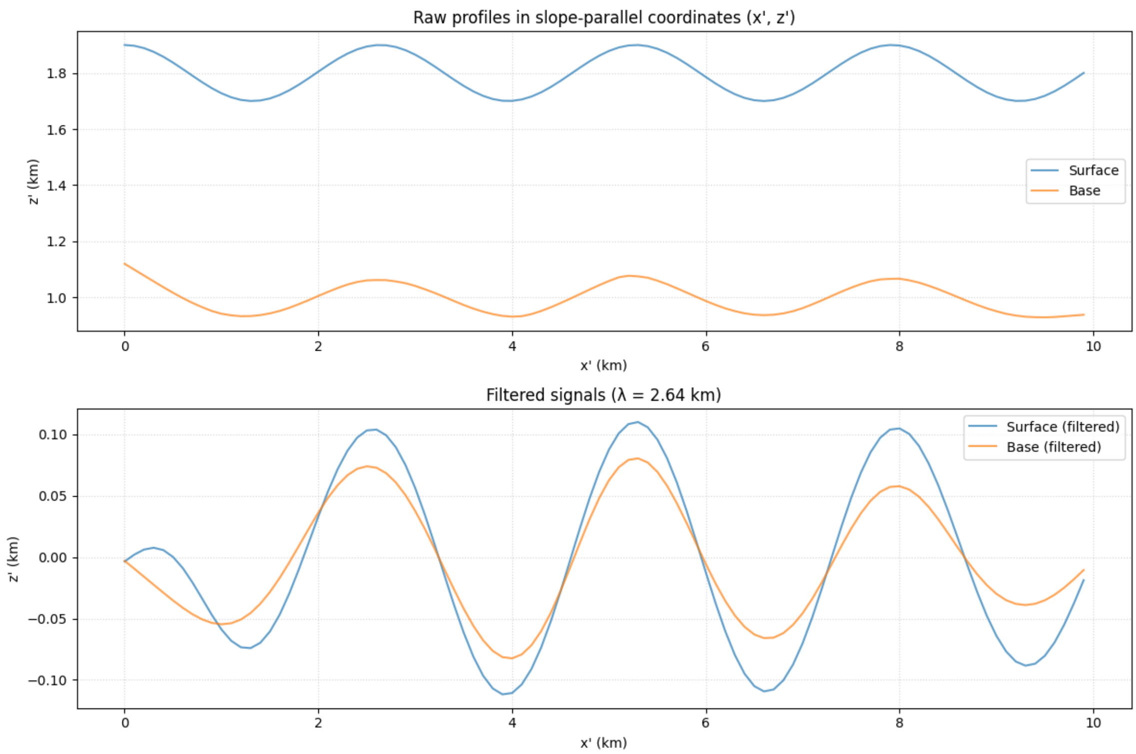

Figure 5.6: Topographic profiles and filtered signals in slope-parallel coordinates. Upper panel: Raw elevation profiles showing surface (blue) and base (orange) interfaces with periodic undulations along a 10 km domain. Lower panel: Filtered signals ($\lambda = 2.64$km) highlighting wavelength-specific components of surface and base topography after removing the mean trend.

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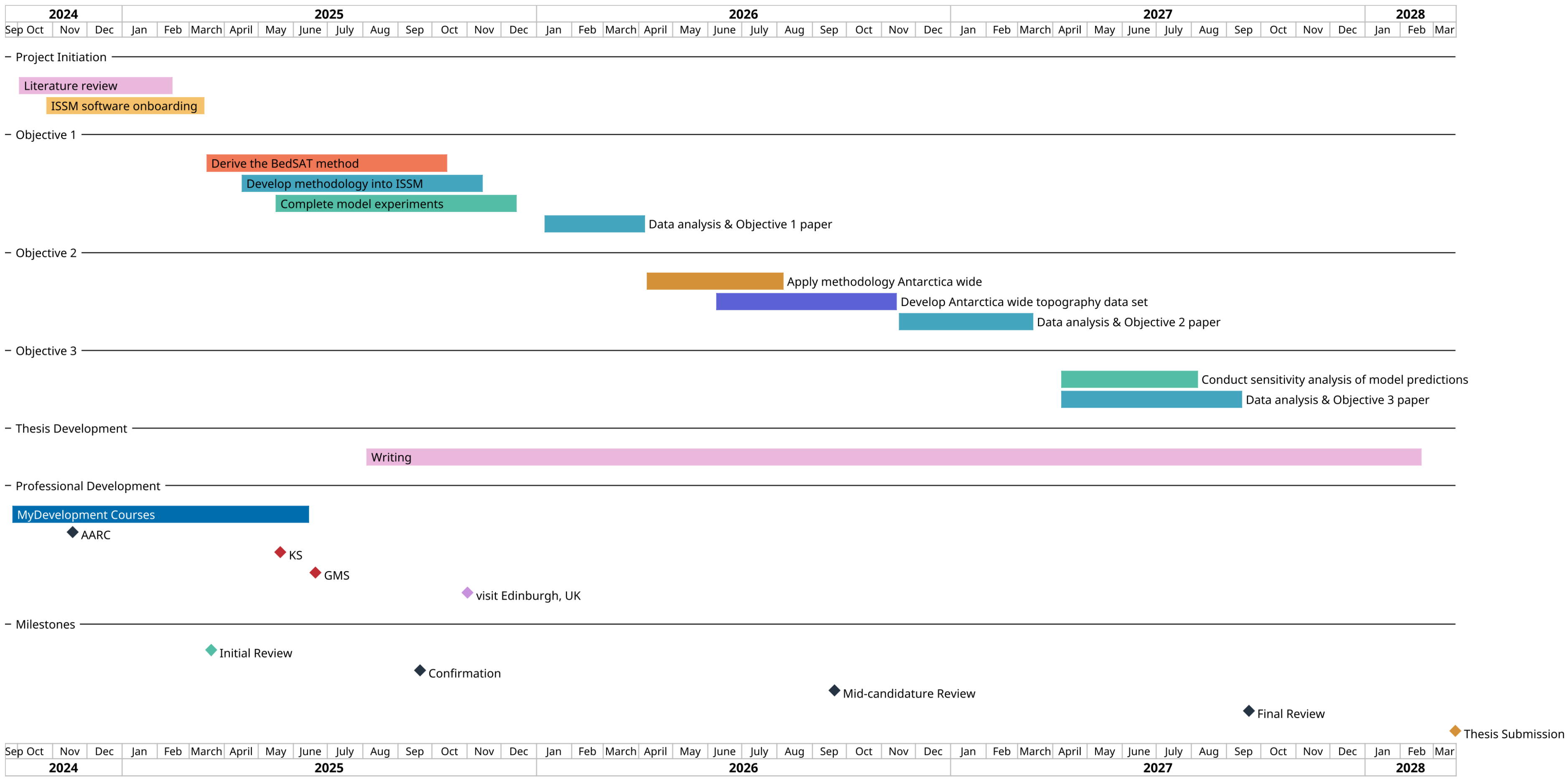
Project timeline



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