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, we are 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. Our open-source approach and FAIR data principles will ensure these improvements benefit the broader scientific community and support more effective climate change mitigation planning for vulnerable coastal communities.

Contents

Antarctica's Landscape

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.

The consequences of changes in different kinds of polar ice manifest across multiple interconnected systems. Of particular concern is the accelerating loss of continental ice sheets (permanent 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. Cold freshwater can dissolve larger amounts of CO_2 than regular ocean water. Increased CO_2 uptake by polar oceans is creating corrosive conditions for calcifying organisms [1]. In addition, freshwater stratification threatens to disrupt global thermohaline circulation [2] by decreasing the natural mixing of the ocean layers.

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.

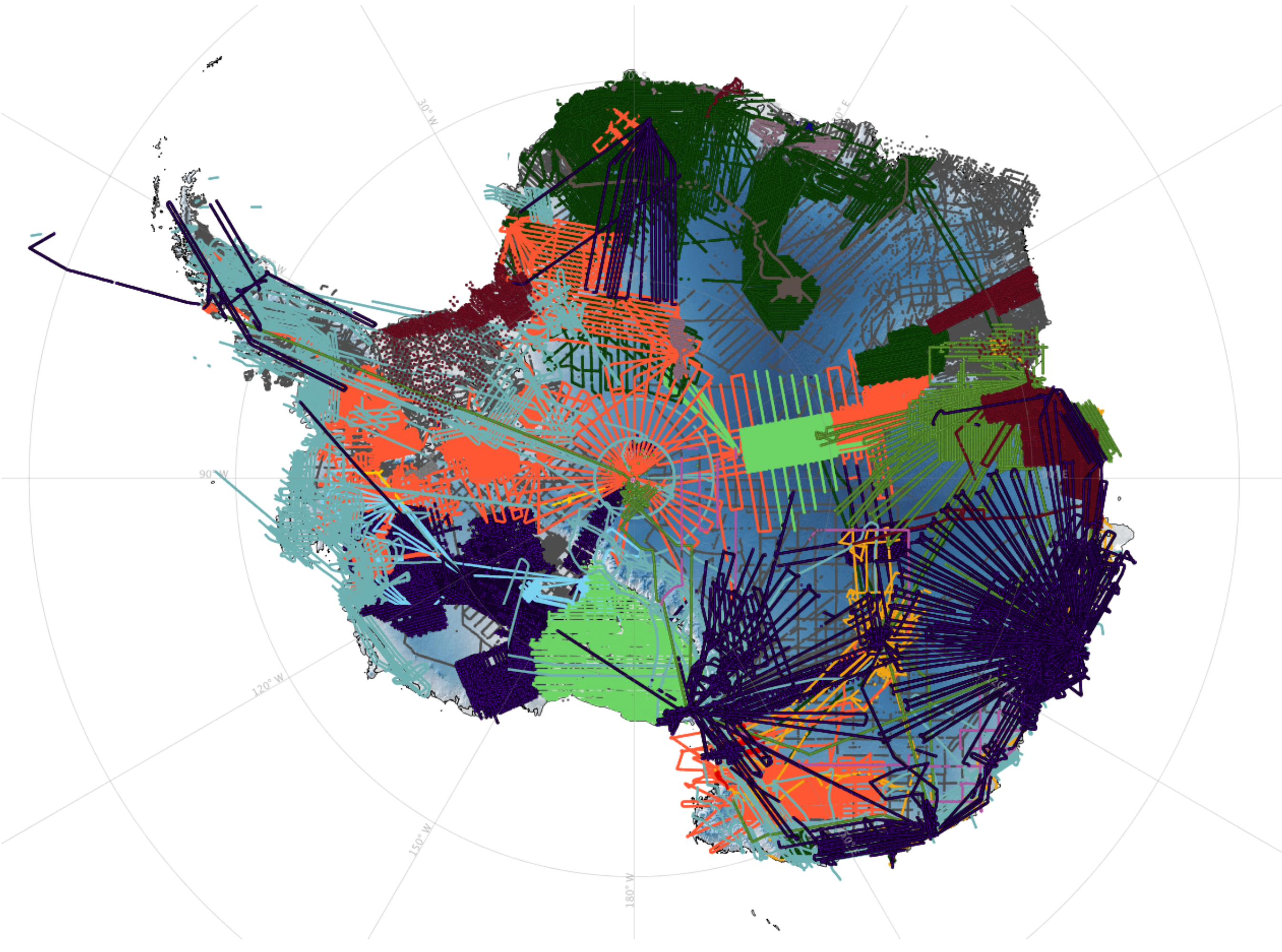

Figure 2.1: Distribution of BedMAP{1,2,3} data tracks (Source: bedmap.scar.org).

Obtaining information about the conditions at the base of the ice-sheet often relies on indirect modelling methods like

- **Inversions** Retrieval (or update) of bed topography and basal slipperiness from surface topography and velocity measurements [7]. See section 2 for an outlined example using **linear perturbation analysis**.
  - **Control method inversion**: A variational approach that minimizes mismatches between observed and simulated fields through a cost function approach, using remote sensing data and theoretical ice flow models to obtain basal conditions [7]. Often needs regularization terms to prevent non-physical features or over-fitting [8].
  - **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, 9]. Requires (contemporary) measurements of ice thickness at the inflow boundary to properly constrain the system [8].
  - **Markov Chain Monte Carlo (MCMC)**: A probabilistic method that generates sample distributions to quantify uncertainties in ice sheet parameters and models [8]. While powerful for uncertainty quantification, these methods remain computationally intensive for continental-scale ice sheet models [8].
- **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 [8]. 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 [8].
- **Geostatistics** Statistical methods specialized for analyzing spatially correlated data. In glaciology is used to interpolate between sparse measurements and characterise spatial patterns in bed properties, often employing techniques like kriging [10].
- **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 [8].

Many authors have considered the influence of the bed topography on the ice surface profile features. Understanding this relationship is crucial for accurate ice sheet bed reconstruction [11]. 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.

Ice Sheet Bed Reconstruction via Surface Data Inversion

Features in the ice bed often show up as subtle patterns in the ice surface topography above them [12]. These bed conditions - both their shape and mechanical properties

- significantly influence how ice flows. changes at the bed potentially leading to large differences in predicted ice loss rates [12]. To address this challenge, it is common to use inversion methods to estimate the geophysical conditions at the ice sheet bed. An example is outlined below.

Theoretical Framework

Inversion is based on the principle that variations in basal topography, slipperiness, and roughness cause disturbances to the surface flow of the ice. By measuring these disturbances in surface velocity and topography, and using equations like the shelfy-stream approximation (SSA) to relate those disturbances back to their source, we can estimate the basal conditions. The indirect estimate of basal property x and surface property y are related through $y = f(x)$, where f is referred to as the forward model, this makes $x = f^{-1}(y)$ the inversion. Property y can be measurements of velocity and topography along the upper surface of a glacier, while the quantity x to be estimated represents basal topography and basal slipperiness [13]. The inversion method developed by Ockenden et al. in [12] introduces perturbations to study how small changes in ice thickness (h), surface elevation (s), basal topography (b), and ice velocity (u) affect ice flow. This means that the method is most accurate when applied to perturbations, small relative to the mean of each studied property (based on a reference state). Ockenden et al. explain in [12] that the shallow-ice-stream equations can be linearised and solved analytically when assuming:

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

The SSA system described in Ockenden et al. [12] is as follows:

$$\partial_x(4h\eta\partial_x u + 2h\eta\partial_y v) + \partial_y(h\eta(\partial_x v + \partial_y u)) - (u/c^{1/m}) = \rho g h(\partial_x(s)\cos(\alpha) - \sin(\alpha)) \quad (2.1)$$

$$\partial_y(4h\eta\partial_y v + 2h\eta\partial_x u) + \partial_x(h\eta(\partial_y u + \partial_x v)) - (v/c^{1/m}) = \rho g h(\partial_y(s)\cos(\alpha) \quad (2.2)$$

The linearised system described by Equations 2 and 2 is based around a reference model $(\bar{h}, \bar{s}, \bar{b}, \bar{u}, \bar{v}, \bar{c})$, leading to first-order momentum balance equations:

$$4\eta\bar{h}\partial_{xx}\Delta u + 3\eta\bar{h}\partial^2_{xy}\Delta v + \eta\bar{h}\partial^2_{yy}\Delta u - \gamma\Delta u = \rho g\bar{h}\cos(\alpha)\partial_x\Delta s - \rho g\sin(\alpha)\Delta h \quad (2.3)$$

$$4\eta\bar{h}\partial_{yy}\Delta v + 3\eta\bar{h}\partial^2_{xy}\Delta u + \eta\bar{h}\partial^2_{xx}\Delta v - \gamma\Delta v = \rho g\bar{h}\cos(\alpha)\partial_y\Delta s \quad (2.4)$$

where h represents ice thickness, s surface elevation, (u, v) horizontal components of surface velocity, c basal slipperiness, η effective ice viscosity, m sliding law parameter, ρ ice density, α mean surface slope in x-direction (zero mean slope in y-direction), and g acceleration due to gravity.

A disadvantage of the assumptions above is that they can limit how well we can model the behavior of real ice which exhibits nonlinear rheology.

Transfer Functions and Implementation

The methodology in [12] employs transfer functions. Transfer functions are mathematical expressions that describe how perturbations in basal topography and slipperiness affect surface topography and velocity. They are derived from the SSA equations

$$\begin{bmatrix} \hat{s} \\ \hat{u} \\ \hat{v} \end{bmatrix} = \begin{bmatrix} T_{sb} & T_{sc} \\ T_{ub} & T_{uc} \\ T_{vb} & T_{vc} \end{bmatrix} \begin{bmatrix} \hat{b} \\ \hat{c} \end{bmatrix}$$

The system is solved using a weighted least-squares approach, minimizing:

$$\Sigma s(s_{\text{obs}} - s_{\text{pred}})^2 + \Sigma u(u_{\text{obs}} - u_{\text{pred}})^2 + \Sigma v(v_{\text{obs}} - v_{\text{pred}})^2 \tag{2.5}$$

Inversion combines the surface data with the transfer functions to estimate the bed properties that would cause the surface changes.

Application and Limitations

Ockenden et al. report to have successfully implemented their inversion method using REMA surface elevation data (8m resolution) and NASA ITS_LIVE velocity data (120m resolution). The method performs particularly well in:

- Areas with moderate topographic gradients in the central trunk of glaciers
- Features not aligned with ice flow direction
- Medium-wavelength (5-50km) bedrock features

However, the method faces limitations in cases of:

- Steep topography where shallow-ice-stream approximation breaks down
- Features aligned with ice flow direction
- Variable slipperiness parameters
- Lack of validation data for slipperiness predictions

This work represents a significant advance in our ability to reconstruct bed conditions using surface data. Modern satellite technology provides unprecedented detail of ice sheet surface features through high-resolution elevation models and velocity measurements. However, we have yet to fully harness this wealth of surface information to improve bed topography estimates, particularly where radar estimates might be sparse.

Forward Model

The model developed by Budd in [11] relates ice flow over bedrock perturbations to surface expressions using a two-dimensional biharmonic stress equation. Budd's model simplifies the stress balance within the ice by assuming that most of the shear deformation happens at the base.

It also explicitely considers longitudinal stresses and strain-rates. All these assumptions are similar to those of the SSA approach in Ockenden et al. While not directly using

SSA equations, the concepts and relationships described by Budd in [11] emphasize how the stress and strain components are influenced by bed topography which in turn has a strong effect on surface features and ice flow.

Similarly to Ockenden et al., Budd's model goes beyond a simple relationship between surface-slope variation and perturbation size, which is a limitation of simplified SSA models.

Interestingly, Budd's mathematical framework, despite being around for over five decades, is yet to be put to use in modern ice sheet modeling. This is especially surprising now that we have the computational power and high-resolution satellite data required for the broad scale application of the method. In this project, we aim to integrate this framework into ice sheet models using the Ice-sheet and Sea-level System Model (ISSM),

potentially creating a systematic way to link what we can see on the surface observations to what's happening at the bed - especially in areas of sparse bed measurements.

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Methods

Objectives

The overall aim of this project is to derive a new Antarctic bed topography using remote sensing data, airborne derived-estimates of the bed and ice sheet modelling. Using the new bed topography to improve understanding of the impact of fine-scale topographic roughness on ice and subglacial hydrological flow, and projections of ice mass loss under climate warming.

The 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. Conduct sensitivity analyses to understand the impact of the improved bed topography on projections of ice mass loss from Antarctica under climate warming.

Research plan methodology

Objective 1 is to derive the BedSAT method. This will involve the integration of the Budd [11] mathematical model relating ice surface elevation and bed topography into ISSM, and the development of a methodology for the data assimilation into ISSM. We 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) [14]. 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, we will generate a number of realisations of bed topography with unique high-resolution, and statistically-consistent topographic roughness. 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

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

2. Reduce RMS error between observations and model predictions

Key Investigation Areas

1. **Model Development Strategy**

   - We will maintain invariant (but spatially variable)bed traction throughout our modeling timeframe to isolate topographical effects in our inversion approach.
   - Our 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, we will identify the topographical features that most strongly influence surface patterns.
   - To account for variations in ice behavior with thickness, we 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**

   - We will develop efficient transfer function methods for rapid bed topography inversion, validating against known bed configurations from radar data.
   - Our transfer functions will be tested across various ice thickness and flow conditions.
   - Cross-validation against radargrams will provide direct verification of our inversion results.
   - Spatial covariance analysis of existing radar data will inform our statistical framework and error propagation through the inversion process.
   - We will account for friction roughness and high-amplitude variations, using observed surface velocity patterns as constraints.

3. **Model Validation**

   - We 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 our model assumptions.

Confounding Factors to Consider

Understanding how different factors affect basal friction is essential for accurately interpreting surface expressions and inverting them to determine bed topography:

- Sliding behavior: Areas with enhanced sliding can mask bed features in surface expressions, while areas with stronger friction tend to show more pronounced surface expressions of bed topography.
- Rheological properties: Softer ice tends to dampen bed topography signals more than stiffer ice.
- Thermomechanical responses: The temperature-dependent nature of ice deformation means that warmer, softer ice near the bed behaves differently from colder, stiffer ice above.
- Slippery spots: Localized areas of reduced friction, often due to the presence of water or deformable sediments, can create surface expressions that might be misinterpreted as bed topography features.

These factors directly impact our ability to invert surface data for bed topography, as they can either enhance or mask the relationship between bed features and their surface expressions. Our methodology must account for these effects to avoid misinterpreting surface features.

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Resources

We 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)**
   REMA provides a high-resolution (2-metre) terrain map of nearly the entire continent, allowing for precise measurements of elevation changes over time. REMA supports various remote sensing activities. Constructed from hundreds of thousands of Digital Elevation Models (DEMs) derived from high-resolution Maxar satellite imagery (including WorldView and GeoEye data), REMA is calibrated with Cryosat-2 and ICESat altimetry, ensuring high elevation accuracy with uncertainties of less than 1 meter over most areas [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. The datasets are available on annual timesteps from 1985 to present. ITS_LIVE employs various statistical and computational methods to process data from satellites including Landsat and Sentinel, ensuring precise and timely updates for scientific research [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. This methodology has led to significant corrections in known glacier depths (e.g., 200m deeper for Pine Island Glacier) and revealed previously unknown features, with bed slopes found to be steeper in 62% of the mapped area compared to previous datasets [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 [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, 7]. This project will involve numerical modeling using advanced mathematical approaches, including the Blatter-Pattyn approximation to the full Stokes equations for ice flow (i.e. conservation of momentum equations). Additionally, data assimilation, machine learning, and geostatistics will be employed, with the full Stokes equations used if necessary [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

Conferences

At least one conference will be attended each year. An international conference relevant to the discipline, e.g. the European Geophysical Union General Assembly, will be attended in the final year of the project.

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Progress

Have the relationship between surface and bed topography in glaciers using ISSM and ice-sheet modeling, examining how bed undulations manifest at the surface with potential phase shifts. The model employs Full-Stokes equations, implementing a flowband ice model across a 4km domain with 50m resolution. The simulation features an 800m mean ice thickness over bedrock at 1000m elevation, with a -0.1 radians downward slope and cosine undulations (2640m wavelength, 100m amplitude). One goal is to verify [11]'s proposition about ice surface behaviour over bedrock undulations. The main model, `flowline7.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 simulation fields, while accounting for thermal and mass balance parameters.

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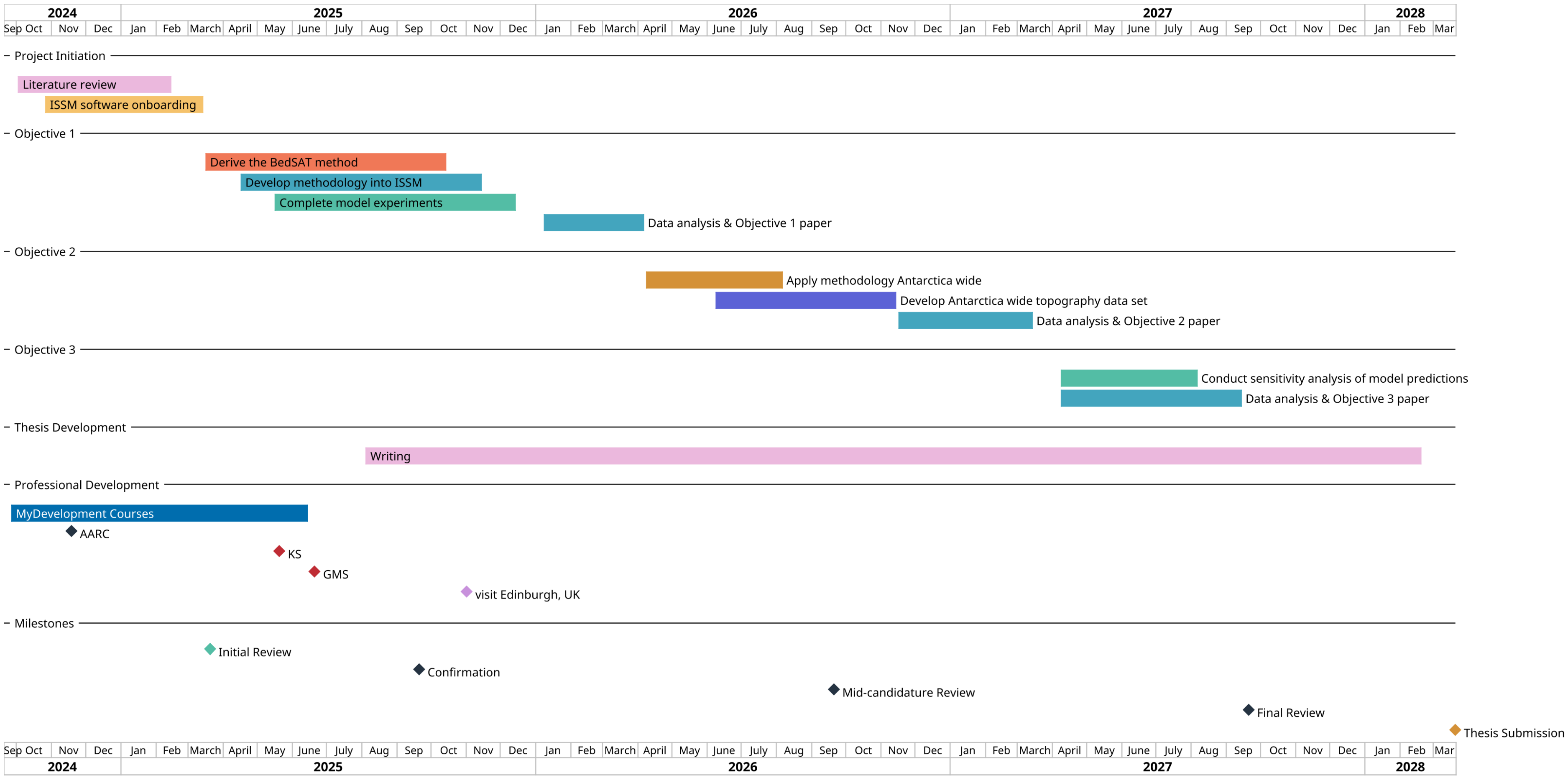
Project timeline



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