BEDSAT:Antarctica

random writings

Ana Fabela Hinojosa[1]

Supervisors:
Dr. Felicity McCormack
Dr Jason Roberts
Dr Richard Jones

MONASH University

School of Earth, Atmosphere and Environment

October, 2024

[1]ana.fabelah@gmail.com

Abstract

Antarctica has been losing ice mass over recent decades, contributing to rising sea levels (SLR). There is significant uncertainty regarding the extent and timing of this ice loss. One key factor influencing ice flow and loss is bed topography, typically derived from sparse airborne radar surveys. The uncertainty in the data can impact simulations of the Antarctic Ice Sheet (AIS) evolution under climate change. We need alternative approaches to surveying Antarctica and given the logistical challenges we plan on modelling the bed topography. Our model's accuracy (surely?) depends on the spacing of ice thickness measurements and uncertainties in ice velocity (SOMETHING I AM WORKING ON understanding rn) and surface mass balance. BedSAT, aims to leverage the mathematical relationship between ice surface elevation (data we have?) and bed topography to estimate the actual bed topography of a surrounding spatial region (in 2D?).

Ana's plan

I've asked ChatGPT to build me a syllabus:

1. Fluid Mechanics: Conservation of mass, momentum (Navier-Stokes equations), incompressible flows.

2. Rheology and Non-Newtonian Fluids

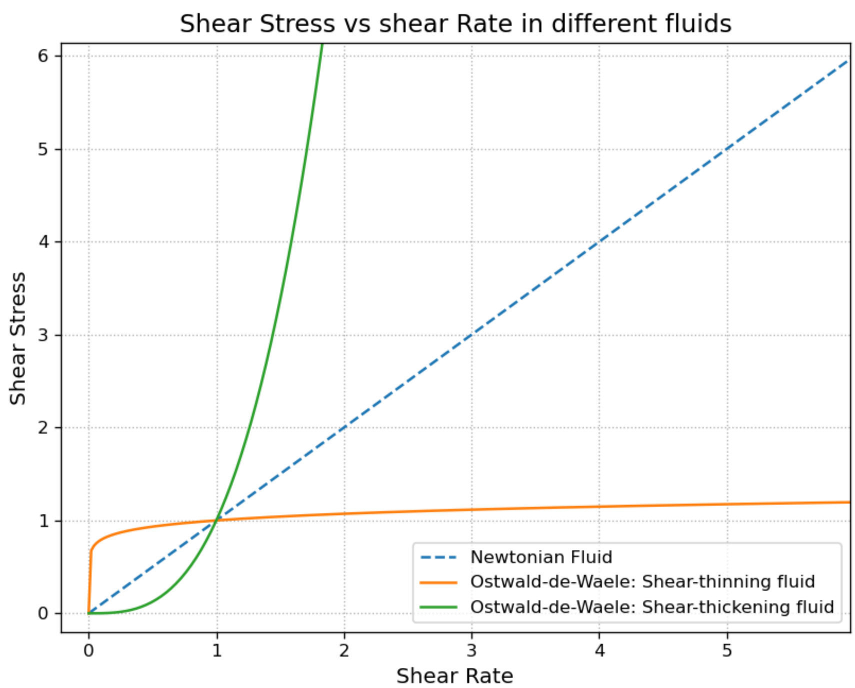

Figure 1.1: Newtonian vs. non-Newtonian behaviour, Shear Stress and shear Rate relationships.

3. Stokes' equations. Methods for solving PDEs, boundary conditions, numerical methods.

4. Glaciology Key Topics: Ice deformation, creep processes, thermal effects.

5. Numerical Methods for solving the Stokes equations can help since these equations often don't have analytical solutions.

76 words in this section.

Why Understanding Antarctica's Landscape Matters: Climate Impacts and Global Significance

The polar regions are losing ice, and their oceans are changing rapidly [1]. The consequences of this polar transition extend to the whole planet and it is crucial for us to understand them and plan for changes.

- Climate-induced changes in seasonal ice extent and thickness are affecting sea ice and ocean layers, which impacts marine plant growth (highly likely). This alters ecosystems (moderately likely). The timing and amount of plant growth have changed in both polar oceans, varying by location (highly likely). In Antarctica, these changes relate to retreating glaciers and sea ice change (moderately likely). In the Arctic, they've affected the types, locations, and numbers of marine species, changing ecosystem structure (moderately likely) [1].
- The rapid ice loss from the Greenland and Antarctic ice sheets during the early 21st century has increased into the near present day, adding to the ice sheet contribution to global sea level rise (SLR)(extremely likely) [1].
- Both polar oceans will be increasingly affected by CO_2 uptake, causing conditions corrosive for calcium carbonate shell-producing organisms (high confidence), with associated impacts on marine organisms and ecosystems (medium confidence) [1].
- Thermohaline circulation changes: a large-scale system of ocean currents driven by differences in water temperature (thermo) and salinity (haline), these factors affect the density of seawater. Thermohaline circulation plays a critical role in regulating Earth's climate and distributing heat and nutrients across the globe. Warm surface waters flow from the tropics toward the poles, where they cool and sink, forming deep-water currents. These deep waters then travel along the ocean floor toward the equator, eventually rising to the surface through a process called upwelling, bringing cold, nutrient-rich waters to the surface [2]. Altering the salt concentration in the Antarctic ocean due to the melting of the ice sheet could result in disruptions to this circulation and could have significant consequences for global weather systems.

Unlike the Arctic, which has seen uniform warming, Antarctica's temperature changes have been less consistent. West Antarctica has warmed in some parts. East Antarctica hasn't shown significant overall change. in the past 3-5 decades. There's low confidence in these observations due to limited data and high variability [1].

Atmospheric factors influencing Antarctic climate:

- Southern Annular Mode (SAM)
  Recent changes in the Southern Annular Mode (SAM): The SAM has been mostly positive in recent decades during summer. This means stronger westerly winds around Antarctica. This positive phase is unprecedented in at least 600 years. It's associated with cooler conditions over Antarctica [1].
  Causes of SAM changes: Ozone depletion was likely the main driver of SAM changes from the late 1970s to late 1990s. Since 2000, tropical sea surface temperatures have played a stronger role in influencing SAM [1].
  Other influences on Antarctic climate: Tropical sea surface temperatures can affect Antarctic temperatures and Southern Hemisphere mid-latitude circulation [2].

- Pacific South American mode

- Zonal-wave 3

Other factors influencing Antarctic climate:

- Antarctica isn't warming as much as the Arctic because the Southern Ocean surrounding Antarctica absorbs and mixes heat deep into the ocean [3].

487 words in this section.

Topographic Models of Antarctica: A Review

Numerical modelling and sedimentary sequence interpretation suggest cyclical periods of ice-sheet expansion and retreat [4]. Using ice-penetrating radar data to generate a new basal bed topography of the Aurora Subglacial Basin (ASB) in east Antarctica is characterised by a fjord landscape (this land is under $\sim$ under $2 - 4.5$ km of ice). The ASB has a potentially significant influence on the east Antarctic ice-sheet (EAIS), however there is high uncertainty in estimates of past and present global sea level changes due to the scarcity of bed data [4]. This uncertainty also limits the accuracy of models used to predict future ice sheet growth or decay.

Methods in [4]

1. A ski-equipped airplane (DC-3T) carried a radar system (HiCARS), which can see through ice. HiCARS sends signals that bounce back to show the thickness of the ice and the shape of the land beneath it.

2. The plane flew back and forth over a large area, covering distances of around 1,000 km. The flights took place over two different periods in 2008–2009 and 2009–2010.

3. The radar data was cleaned up (processed) to improve accuracy, and they used a special radar system that helps reduce distortions (errors) in the measurements. [**HOW?**]

4. Thickness of the ice was measured using the time it took for the radar signals to travel through the ice and back, assuming the radar signals move through the ice at a specific speed (169 meters per microsecond).

5. The height of the land below the ice was calculated by looking at the radar-determined surface of the ice. [**WHAT?**]

6. The radar data was combined with other existing datasets (BEDMAP) to improve the overall picture. They used a computer algorithm to fill in gaps where they didn't have direct measurements. [**WHICH?**]

7. Determining how rough or uneven the land under the ice was, by using a statistical measure called the "root mean squared (rms) deviation."

In short, Young et al. used advanced radar technology on an airplane to map the ice thickness and the landscape beneath it in a region of Antarctica, combining this data with previous maps for a better overall picture.

345 words in this section.

Ice is weird

A Newtonian fluid (like water) has a constant viscosity regardless of the flow conditions, while a non-Newtonian fluid's viscosity changes based on factors like strain-rate. The viscosity of ice is not constant.depends on how much it is deforming (shear rate). Ice is a slow, shear-thinning fluid. "shear-thinning" means that the viscosity of ice decreases with increasing strain rate. This means that under more strain forces ice becomes "softer" and flows more easily."Slow" means that the flow of ice occurs at very low velocities

$$\rho(\vec{u_t} + \vec{u} \cdot \nabla\vec{u}) = 0, \tag{4.1}$$

i.e. the change in flow velocity (time dependent and convective) is approximately zero. This assumption greatly simplifies the Navier-Stokes equations for ice flow. The equations we use to are the incompressibility condition

$$\nabla\vec{u} = 0, \tag{4.2}$$

i.e. the divergence of the velocity field is zero. The force balance equation

$$-\nabla p + \nabla \cdot \tau_{ij} + \rho g, = 0 \tag{4.3}$$

i.e. the pressure gradient, the divergence of the stress tensor (viscous forces within the ice) and the gravitational body force acting on the ice all cancel out, dnd finally Glen's flow law

$$D_{ij} = A\tau^n \tau_{ij}, \tag{4.4}$$

where the strain rate tensor D_{ij}, which describes how fast the ice is deforming is proportional to the deviatoric stress tensor τ_{ij} and it's magnitude τ, which accounts for the stress caused by deformation (as opposed to isotropic stress like pressure). The flow law exponent n determines how strongly the flow rate depends on stress. For ice, Glen's law uses $n = 3$, which implies a nonlinear relationship between stress and strain rate, meaning the flow rate accelerates rapidly with increased stress [5].

This model does not have time derivatives anymore, this means that a time-stepping ice sheet program recomputes the full velocity field at every time step and does not require velocity information from the previous time step.

Shallow Ice Approximation

(Bons et al 2018) Glen's law exponent n can range from 1 to 5???woah!?
low driving stresses make SIA fail?

293 words in this section.

Numerics

Ice-sheet models (ISM) essentially focus in modelling the change in mass from snow fall and snow melt onto the glacier (the glacier's mass balance). This is usually calculated through degree day or energy balance models. Secondly, ISMs must compute the flow of ice downslope under its own weight [6]. For now I have two modelling missions, in the diagram in figure 6.1 represents two simulations. The simulations are in 2D and 1D. The idea in these simulations is to recreate the ice bed flow given some bedrock profile.

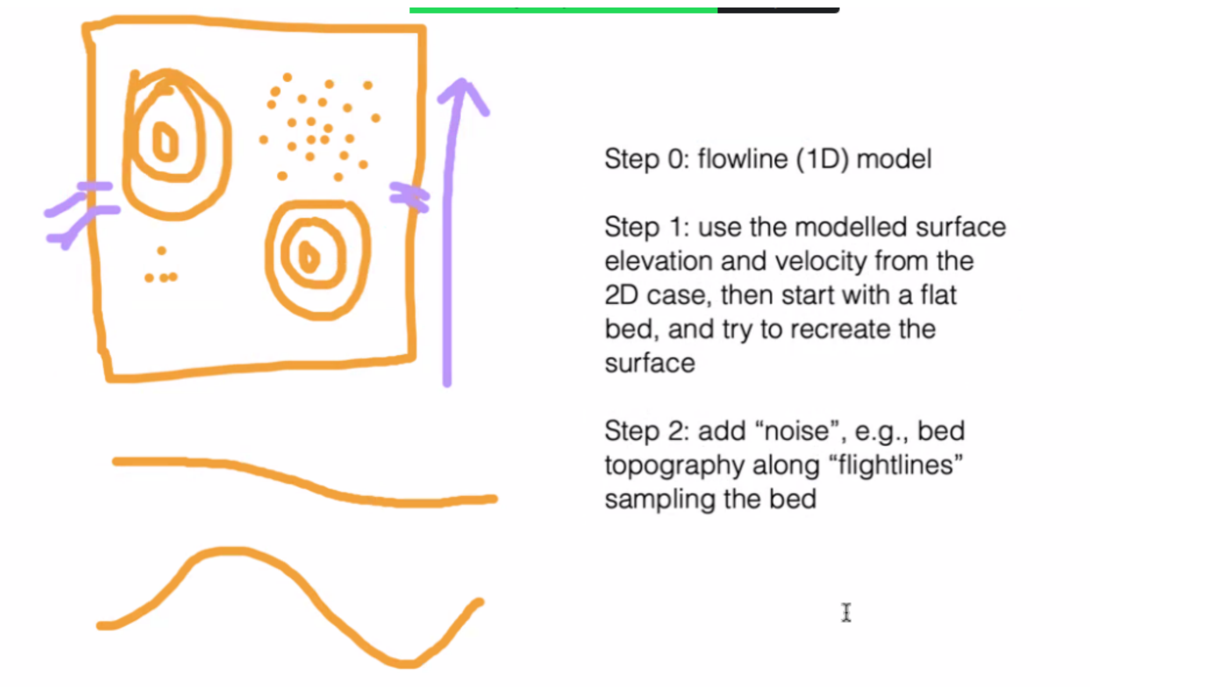

Figure 6.1: TODO

The simulations in figure 6.1 should use the Shallow ice approximation (SIA). There are pros and cons for each approximation used to model the full Stokes equations of flow (FS). SIA neglects horizontal stress gradients and is unsuitable for fast flow, while FS accounts for all stress components, making it highly accurate, but its computational expense poses a challenge for large-scale applications.

while SSA ignores vertical shear, limiting accuracy near grounding lines.

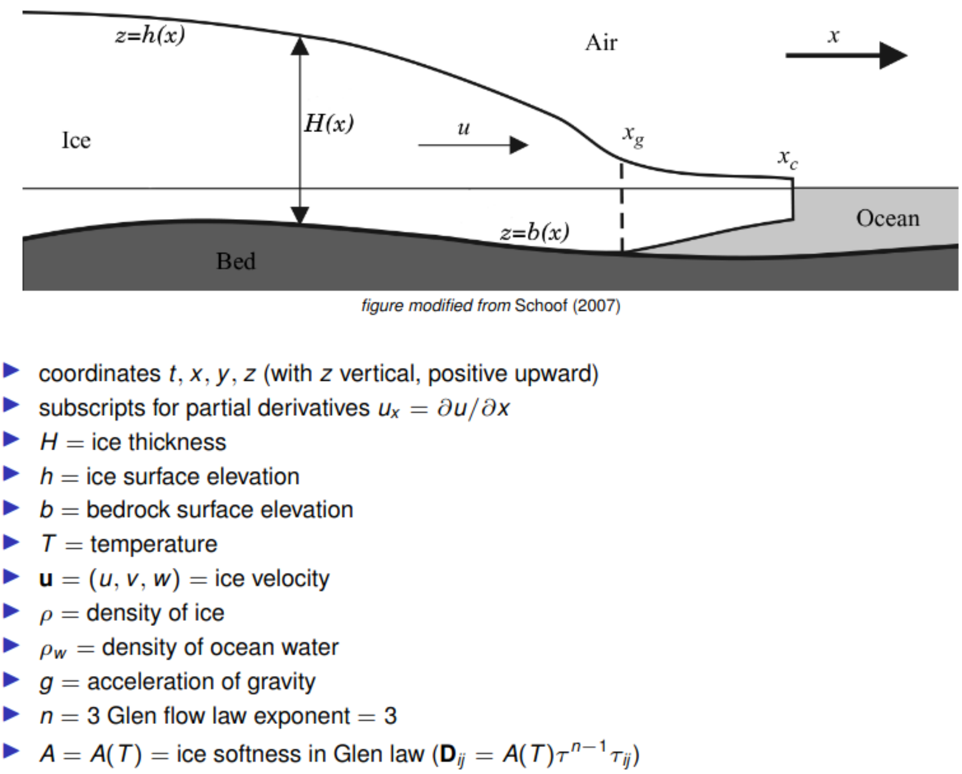

Figure 6.2: figure taken from [5]

6.1 ISSM: Continental-Scale Ice Sheet Modelling

The Ice Sheet System Model (ISSM) was developed and is used for simulating ice sheet flow at continental scales. ISSM, a finite element, thermomechanical model, incorporates high-order stresses and high spatial resolution capabilities [7]. The Larour et al. (2012) ISSM paper discusses the different ice flow models within the software, including the full-Stokes, Blatter-Pattyn, Shallow-Shelf, and Shallow Ice Approximations, highlighting their individual strengths and limitations. It also explores numerical methods employed, such as static adaptive mesh refinement and inverse methods for parameter estimation. Finally, the study showcases the application of ISSM to the Greenland Ice Sheet, demonstrating its capacity to model the ice flow velocity with high accuracy, using data assimilation techniques to infer the basal drag coefficient.

281 words in this section.

Glossary of Key Terms

1. Temperate ice: Ice at or near its pressure-melting point.
2. Sliding: The movement of a glacier over its bed by sliding rather than internal deformation.
3. Basal sliding: Sliding occurring at the base of a glacier.
4. Normal stress (N):The force acting perpendicular to a surface, per unit area. In the context of glaciers, it is primarily the weight of the overlying ice.
5. Shear stress (T): The force acting parallel to a surface, per unit area. In the context of glaciers, it is the force driving glacier motion.
6. Limiting static shear stress (TS): The minimum shear stress required to initiate sliding from a resting position.
7. Coefficient of static friction (μs): The ratio of the limiting static shear stress to the normal stress, indicating the resistance to sliding from rest.
8. Steady-state velocity (Vb): The constant velocity reached by a glacier or ice block when the driving shear stress is balanced by resisting forces.
9. Limiting dynamic shear stress (Tm): The shear stress at which a glacier or ice block transitions from steady-state sliding to accelerated sliding.
10. Coefficient of sliding friction (μ): The ratio of the shear stress to the normal stress during steady-state sliding.
11. Regelation: The process of melting under pressure and refreezing at lower pressure, potentially contributing to ice sliding.
12. Asperity: A protrusion or bump on a surface.RoughnessThe unevenness of a surface, characterized by the size and distribution of asperities.
13. Shallow Ice Approximation (SIA): A simplified ice flow model that considers only vertical shear stresses and neglects horizontal stress gradients. Suitable for slow-moving ice in the interior of ice sheets.
14. Shallow Shelf Approximation (SSA): A simplified ice flow model that neglects vertical shear stresses and assumes depth-independent horizontal velocity. Appropriate for modelling floating ice shelves and fast-flowing ice streams

15. Blatter-Pattyn Approximation (BP): A higher-order ice flow model that incorporates longitudinal stresses, making it suitable for simulating fast-flowing ice streams and regions with significant vertical shear.
16. Full-Stokes (FS): The most comprehensive and computationally expensive ice flow model, accounting for all stress components. Essential for accurately simulating ice flow near grounding lines.
17. Ice Sheet System Model (ISSM): A finite element, thermomechanical ice flow model that incorporates SIA, SSA, BP, and FS formulations to simulate ice sheet behaviour at various complexities and spatial resolutions.
18. Finite Element Method (FEM): A numerical method for solving partial differential equations by dividing the domain into smaller elements and approximating the solution within each element.
19. Adaptive Mesh Refinement: A technique used to refine the mesh in regions of high variability or complexity, enhancing model accuracy and efficiency.
20. Data Assimilation: The process of incorporating observational data into a model to improve its accuracy and predictive capabilities.
21. Basal Drag Coefficient: A parameter representing the frictional resistance between the ice sheet base and the underlying bedrock.
22. Grounding Line: The boundary where the ice sheet transitions from grounded ice to floating ice (ice shelf).
23. Calving: The process by which icebergs break off from the edge of a glacier or ice sheet
24. InSAR: Interferometric Synthetic Aperture Radar, a remote sensing technique used to measure ice surface velocity.

WHAT ARE THESE

- Channel incision
- Alpine style glaciation

TOOLS

- ICECAP aero geophysical programme
- BEDMAP

MATHS

- Lagrangian interpolation
- natural-neighbour interpolation

Bibliography

[1] M. Meredith, M. Sommerkorn, S. Cassotta, C. Derksen, A. Ekaykin, A. Hollowed, G. Kofinas, A. Mackintosh, J. Melbourne-Thomas, M. M. C. Muelbert, G. Ottersen, H. Pritchard, and E. A. G. Schuur. *The Ocean and Cryosphere in a changing climate*, pages 203—-320. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA (2019). DOI: 10.1017/9781009157964.005. 5, 6

[2] S. S. JACOBS. *Bottom water production and its links with the thermohaline circulation*. Antarctic Science **16**, 427–437 (2004). DOI: 10.1017/S095410200400224X. 5, 6

[3] M. Collins, R. Knutti, J. Arblaster, J.-L. Dufresne, T. Fichefet, P. Friedlingstein, X. Gao, W. J. Gutowski, T. Johns, G. Krinner, M. Shongwe, C. Tebaldi, A. J. Weaver, M. F. Wehner, M. R. Allen, T. Andrews, U. Beyerle, C. M. Bitz, S. Bony, and B. B. B. Booth. *Long-term Climate Change: Projections, Commitments, and Irreversibility*, pages 1029–1136. Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, United Kingdom (2013). 6

[4] D. A. Young, A. P. Wright, J. L. Roberts, R. C. Warner, N. W. Young, J. S. Greenbaum, D. M. Schroeder, J. W. Holt, D. E. Sugden, D. D. Blankenship, and T. D. van Ommen. *A dynamic early East Antarctic Ice Sheet suggested by ice-covered fjord landscapes*. Nature **474**, 72 (2011). DOI: https://doi.org/10.1038/nature10114. 8

[5] E. Bueler. *Numerical modelling of glaciers, ice sheets, and ice shelves*, (2016). University of Alaska, Fairbanks. 10, 14

[6] B. Davies. *AntarcticGlaciers.org: East Antarctic Ice Sheet*, (2024). 13

[7] E. Larour, H. Seroussi, M. Morlighem, and E. Rignot. *Continental scale, high order, high spatial resolution, ice sheet modeling using the Ice Sheet System Model*, (2012). J. Geophys. Res., 117, F01022. DOI: https://doi:10.1029/2011JF002140. 14