Collection and Analysis of Shear Strain Data of Polythermal Ice from Jarvis Glacier, Alaska

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Abstract

We seek to calibrate the flow law for polythermal ice through shear strain analysis. In a warming climate, increased melting of glaciers and ice caps play a big role in sea level rise. Approximately 60% of the current contribution to sea level rise from ice loss is attributed to glaciers and ice caps, raising the urgency of sharpening mass balance change predictions in regions of streaming flow. Polythermal glaciers constitute a significant portion of these contributing glaciers, though our knowledge of their flow dynamics is incomplete. Thermally complex polythermal glaciers have both warm and cold ice which lead to weak wet-based beds, with significant amounts of basal sliding and deformable till. Consequently, polythermal glaciers experience significant shear strain as their lateral shear margins sustain the majority of the resisting stress. Most in-situ and in-lab studies of natural ice over recent years have focused on bodies of ice with frozen beds that experience minimal shear strain downglacier and across vertical planes (with depth) relative to the bed. The lack of studies on wet-based polythermal glaciers causes uncertainties in the flow law, as differences in flow law factors between polythermal ice and bodies of ice with frozen beds have the potential to induce more than an order of magnitude difference in ice velocity. To improve calibration of the flow law for polythermal ice, we seek to improve our understanding of their shear strain regimes. We developed and deployed tilt sensor systems on the polythermal Jarvis Glacier in Alaska, where we drilled multiple boreholes close to Jarvis' shear margin and installed three boreholes with our tilt sensor systems. The tilt sensors measure gravity, magnetic and temperature data, and each system consists of multiple sensors connected along a cable and serially communicating along a common data bus with a datalogger. We have recently retrieved a year of Jarvis tilt sensor data and calculated the at-depth shear strain rates in the boreholes, allowing evaluation of the at-depth shear strain rate regimes of polythermal ice against theoretical models developed using Glen's flow law. We present the development of our data collection methodology and the results of our shear strain analysis, with suggestions for potential calibrations of the flow law for polythermal ice.

Flow Dynamics of Streaming Ice: Borehole Deformation Investigations with Self-Developed Tilt Sensors

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Abstract

We seek to investigate the flow dynamics of streaming ice, which is characterized by weak wet-based beds that results in significant shearing as the shear margins sustain most of the driving stress. We measured glacier flow in streaming ice in terms of borehole deformation tilt. We developed tilt sensors to measure accelerometer and magnetometer data and deployed them in two boreholes drilled close to the shear margin of Jarvis Glacier in Alaska. The observed deformation in each borehole is evaluated against theoretical flow dynamics parameters including shear strain and velocity, derived from Glen's exponential flow law. We tune the stress exponent n to compare with values from lab deformation experiments on ice that correlate the n-values with creep mechanisms. We find that though our research site is in a low-stress region, the high total strains coupled with potential dynamic recrystallization experienced by the ice lead to strong anisotropy that results in higher than expected n-values particularly at the shear margins. Regions of streaming flow are responsible for draining the major ice sheets and alpine regions and occurs in two major groups of glaciers: polythermal and temperate.

Flow Law for Ice

Most glaciologist use the conventional Glen's exponential flow law, which relates strain rate $\dot{\varepsilon}$ to stress σ:

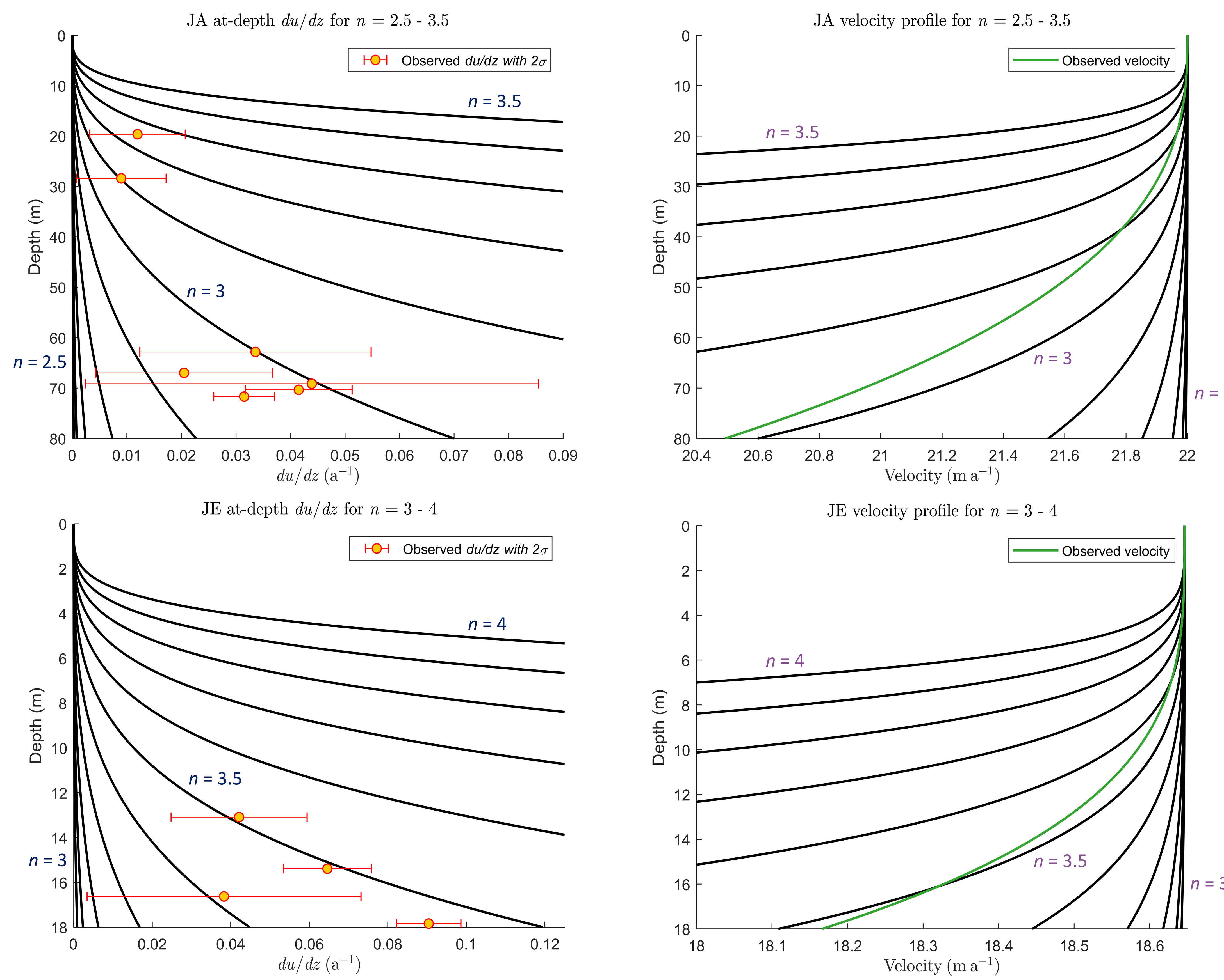
$$\dot{\varepsilon}_{ij} = \mathrm{E} A \sigma_{ij}^{n}$$

where i and j are any of the coordinates variables x, y, or z indicating the direction of applied strain/stress. E is an enhancement factor to account for crystallographic fabric, A is the temperature-dependent rate-factor and n is the stress exponent.

Most glaciologist use a stress exponent of n = 3, though experimental studies of ice mechanics have shown significant variation in n. We are interested in tuning the flow law for streaming ice as the strong shearing in these regions results in strong anisotropy. The development of preferred orientations in the ice crystal fabric creates planes of weakness which speeds up ice flow and leads to an increase in the stress exponent n and enhancement factor E.

Treatment of the Flow Law for Streaming Ice

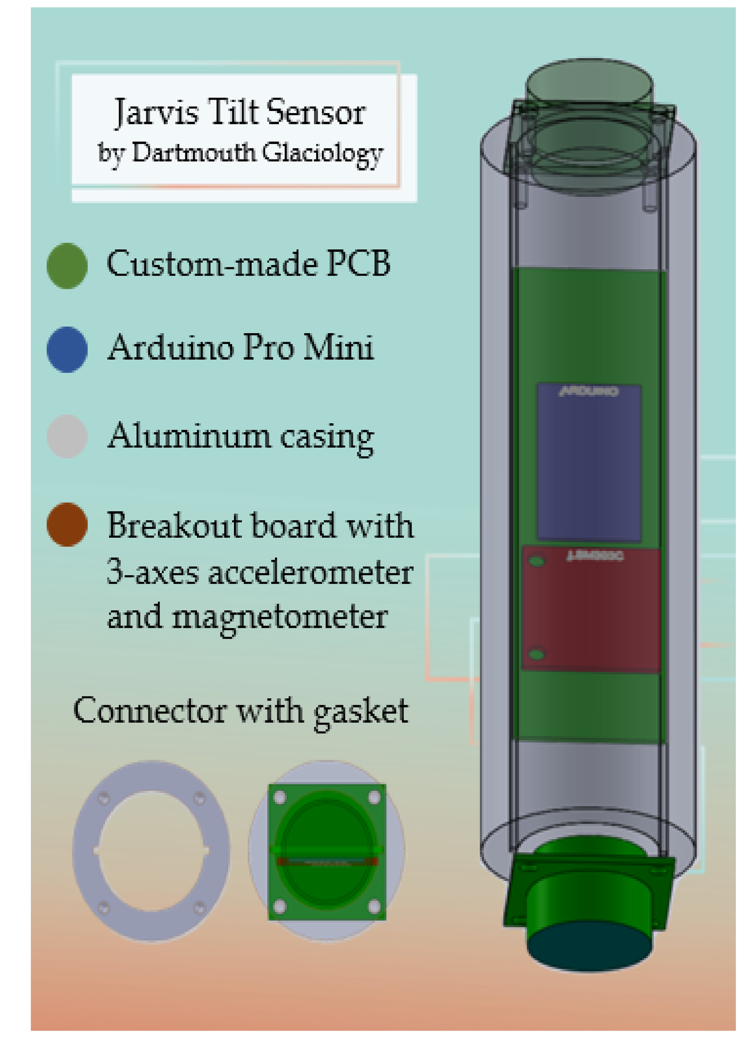
We installed our tilt sensor system in two boreholes and retrieved our data in Aug. 2018, collecting 16 months of uninterrupted data from JA (close to the centerline) and JE (at the shear margin). We calculated observed flow dynamic parameters including shear strain and velocity and evaluated them against theoretical models derived from Glen's exponential flow law, with a range of n-values to compare with experimentally-derived n-values and stages of creep.



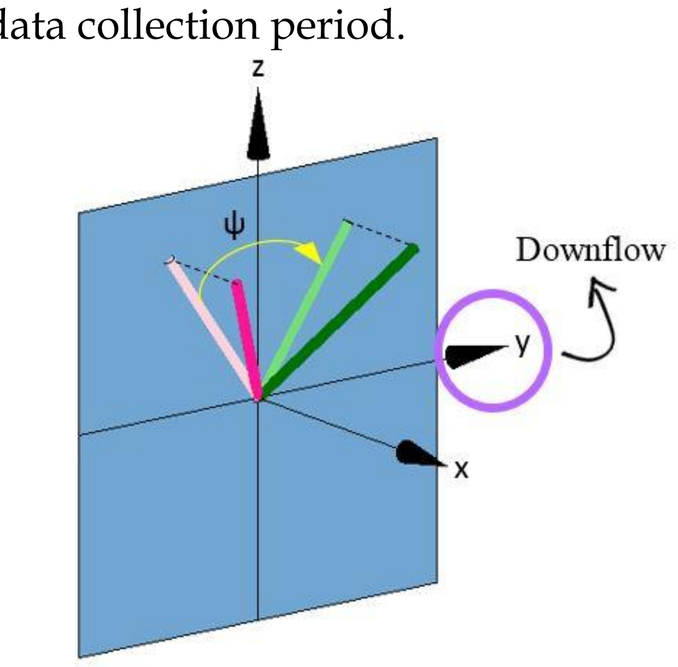
JA fits well around n = 3 and JE fits well around n = 3.5. From *Goldsby and Kohlstedt (2001)*, our observed n-values lie between basal slip creep (n = 2.4) and dislocation creep (n = 4). JA's n-value is typical for glacier ice as used by glaciologists applying Glen's flow law with n = 3 (Glen's data lies in the vicinity of the transition from dislocation creep to superplastic flow, which is characterized by large strains >>100% and n = 1.8) and JE's n-value falls just short of dislocation creep.

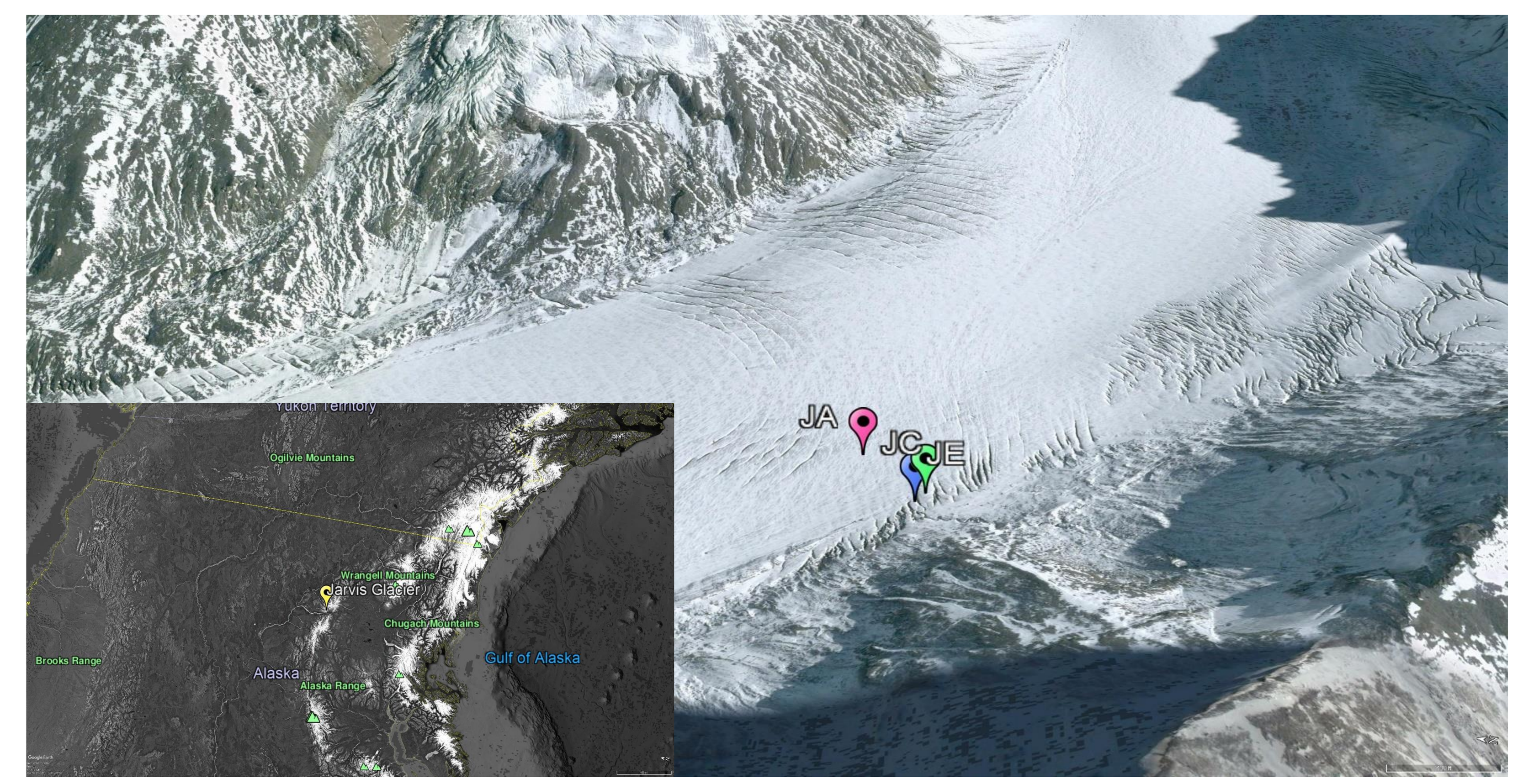
From *Goldsby and Kohlstedt (1997a)*, in regions of low stress n experimentally approaches 2.4 or even ≤ 2 (*Goldsby and Kohlstedt (2001)*), and approaches n = 4.5 at the highest stress levels. JA and JE are in regions of low stress ($\sigma \leq 0.1$ MPa) with large strains (up to ~1300% for JA and ~16% for JE), though we observe higher than expected n-values due to the high total strains that are tough to account for on the basis of the strain history at JA and JE being unknown. High total strains lead to higher strain rates over time and when coupled with potential dynamic recrystallization, lead to strong anisotropy in the ice crystal fabric that can result in higher than expected values of n and E. We are interested in further exploring the parameter space of varying n and E, as tuning n alone increases the curvature while tuning E can shift the curves.

Study Area and Methods



From the raw sensor outputs of gravity **A** and magnetism **M**, we calculated inclination θ and azimuth ϕ. The real-world orientation of the sensors are recreated within a unit cube model and the angle of rotation ψ of each sensor in the 2-dimensional downflow plane is cumulatively summed (ψ_{total}) over the data collection period.





Jarvis Glacier is located in the Eastern Alaskan range (inset), and has streaming ice coupled with a simple geometry which makes it an ideal natural laboratory.

Significance

- Developed an inexpensive tilt sensor easily modified for a wide range of uses
- Support calibration efforts of the flow law for streaming ice
- The future of machine learning applications to glaciology

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