Snow4Flow:

Concept Paper for a NASA Earth Venture Suborbital-4 Investigation

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1. *Mission Overview*

Snow4Flow was proposed as a large ($30M cost cap) Earth Venture Suborbital (EVS-4) mission in April 2023 and selected as such in April 2024. It will commence pending an Investigation Confirmation Review in 2025. Its airborne and ground campaigns are presently expected to occur in March–May 2027–2029.

Quantifying the ongoing retreat of glaciers and ice sheets – and projecting their futures – are major societal concerns due to their contribution to sea-level rise and influence on water resources, natural hazards, and associated socioeconomic impacts. The ability to confidently project glacier and ice-sheet mass change is limited by a severe lack of observations that reliably constrain both their input (*Snow*) and output (*Flow*) mass fluxes. *Snow4Flow* will capture the spatial variability in snow accumulation and ice volume across *4* Northern Hemisphere (*NH*) regions containing hundreds of rapidly changing glaciers to deliver more reliable, societally relevant projections of land-ice change. This major advance requires spatially extensive radar-sounding surveys that are not possible from orbit (**Fig. 1**). This EVS-4 mission will drive foundational improvements to NH land-ice boundary conditions and forcing data – including orographic precipitation patterns in alpine environments, ice thickness and subglacial topography – and directly leverages them into state-of-the-art models and projections. Our key science questions are:

1. How will NH glaciers respond to climate change through the end of the 21st century?
2. How does snow accumulation vary in regions of high topographic relief?

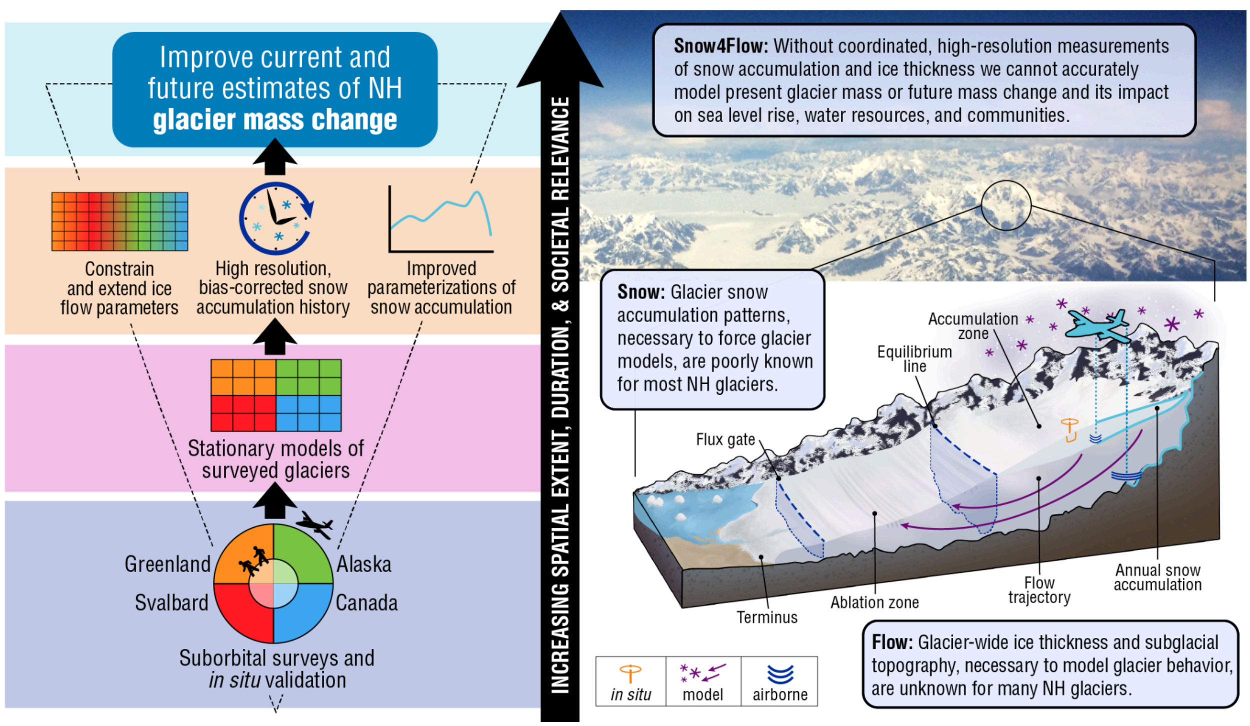


***Fig. 1.** Snow4Flow will directly improve projections of 21st century NH glacier mass change through airborne and in situ observations and associated modeling.*

Snow4Flow was conceived as a vertically integrated mission that includes airborne observations, *in situ* calibration/validation, and modeling. New data acquisition focuses on four major, fast-changing NH glacierized regions: Alaska (including far western Canada), southeastern Greenland, the Canadian High Arctic, and Svalbard. *Snow4Flow* will systematically measure the input (winter snow-accumulation rates) and output (the product of ice thickness and depth-averaged velocity) ice fluxes of NH glaciers. This will be achieved by large-scale springtime airborne microwave and high-frequency radar-sounding measurements of snow accumulation and ice thickness, respectively. The gradients in snow accumulation measured by *Snow4Flow* in regions with strong topographic relief permit the assessment of – and bias-correction for – snow accumulation in regional and global reanalyses and projections. They also provide a much-needed basis for improvements to parameterizations of orographic precipitation and its accumulation on mountain and glacier surfaces. *Snow4Flow* ice-thickness observations are assimilated into ice-flow models for each targeted glacier, then forced using historic and projected climate to improve assessment and quantification of present and future NH ice mass change, respectively.

2. Introduction: Why This Mission? Why Now?

Global mean sea-level rise (*SLR*) now exceeds 3 mm yr^{-1}, of which >50% is attributed to mass loss from land ice [1]. Even under the most optimistic anthropogenic emissions scenarios, rising oceans are guaranteed from land-ice wasting for several decades to come [2], [3]. Establishing how high sea levels will rise along our Nation's coasts in the 21st century – and how quickly they will rise – is essential to prepare for the far-reaching national and global socioeconomic impacts of this primary consequence of anthropogenic climate change [4]. Increased land ice mass loss and associated decreases in snow accumulation across the NH – both on ice and off – are already having a profound impact on downstream marine and terrestrial ecosystems, and water supply and availability [5]–[7]. Anticipated future impacts include population displacement and the loss of property, infrastructure, and habitats [8]. Improving our ability to interpret and project changes to snow accumulation and land-ice mass balance are thus an imperative to support humanity's adaptation to a warming planet [9].

The acceleration of mass loss from glaciers and ice sheets over the past few decades is now abundantly clear in the satellite record. We know *where* land ice is losing mass, often *when* this mass loss becomes significant and *sometimes* we understand *why* this mass loss was initiated (e.g., warming oceans, atmosphere, or both) [10]–[14]. NH mountain glaciers from Alaska to Svalbard and the Greenland Ice Sheet (*GrIS*) are particularly vulnerable due to both Arctic amplification of atmospheric warming and their numerous marine termini [15]. Although glaciers (not including the ice sheets) are ≤1% of total land-ice volume, their net mass loss exceeds 250 Gt yr^{-1} – 20% of present SLR – and they are experiencing very high area-averaged rates of mass loss: nearly one meter water-equivalent *per year* in Alaska [11], [16], [17]. While the future of the Antarctic Ice Sheet is highly uncertain, some projections indicate it might even *gain* mass [18]. In marked contrast, the mass-loss rates of Earth's glaciers could *triple* by 2100 depending on global policy decisions, and their SLR contribution could easily exceed 2 mm yr^{-1} for higher emissions scenarios [2], [19], with similar rates probable for the GrIS [20]–[22]. While every temperature increase matters to glacier futures on a *global* scale [2], a simple thermostat prediction is insufficient. Many individual glaciers and regional systems can be dynamically unstable, with the potential for rapid retreat that can only be meaningfully projected by *well-constrained* models, which are presently rare [23]–[27]. Due to their regional and global impacts, improved projections for these rapidly evolving systems are urgently needed.

Sustained investments by NASA and international partners have enabled important strides in quantifying recent land-ice changes and their impacts. Satellite altimetry and gravimetry provide invaluable estimates of past glacier and ice-sheet mass change [10], [28]–[31], but these methods require significant and uncertain assumptions regarding vertical flow [32], land uplift, and surface snow density [33] – nor can they foretell the future for such dynamic systems. This is because current state-of-the-art models of land-ice dynamics still rely on inadequate simplifications to both initial and boundary conditions to generate their projections. Critically, these models cannot yet accurately reproduce either the rate of present land-ice mass loss nor its acceleration this past decade [2], [34]. This deficiency is in large part due to a dearth of available calibration data and observational constraints.

Snow4Flow will target the two biggest modeling deficiencies that we can presently only measure *sub*orbitally: the seasonal snow input to these glaciers (snow depth ✕ density) and the ice thickness that constrains their output mass flux (thickness ✕ speed ✕ density) into the oceans. NASA's Operation IceBridge mission refined the technologies and survey methods needed to close these gaps, but that mission's focus was primarily on repeat laser altimetry of land and sea ice, with snow accumulation and ice thickness of harder-to-sound glaciers much lower priorities [35]. We exploit and scale up these new capabilities to address a pressing societal need while leveraging numerous existing NASA orbital assets and modeling efforts.

2.1. Why snow?

Glacier surface mass balance combines snow accumulation and surface melting. Unlike snow accumulation, near-surface air temperature and surface melting are relatively well-parameterized and resolved in reanalyses (syntheses of models and observations) [36]–[38], and satellite products capture their magnitude, extent and variability [39], [40]. In stark contrast, satellite retrievals, reanalyses, and sparse *in situ* data do not currently resolve the influence of alpine and glacierized terrain on snow accumulation. Precipitation observations from high-elevation, high-relief, and often ice-covered terrain, remain rare globally – especially for snow. Snow depth and density can vary substantially over relatively short length scales (≤100 m) – especially in complex alpine terrain and across glaciers – challenging extrapolation of point measurements across mountain ranges and resulting in high uncertainty in snow-water equivalent (*SWE*, a direct measurement of snow mass) [41] (**Fig. 2**). As such, sparse snow depth or SWE observations from small-scale field campaigns cannot necessarily improve reanalysis representation of terrain-dependent snow properties [42]. Further, the lack of observational constraints and the assumptions required still substantially limit satellite retrievals of SWE in mountainous regions, despite recent advances [43], [44].

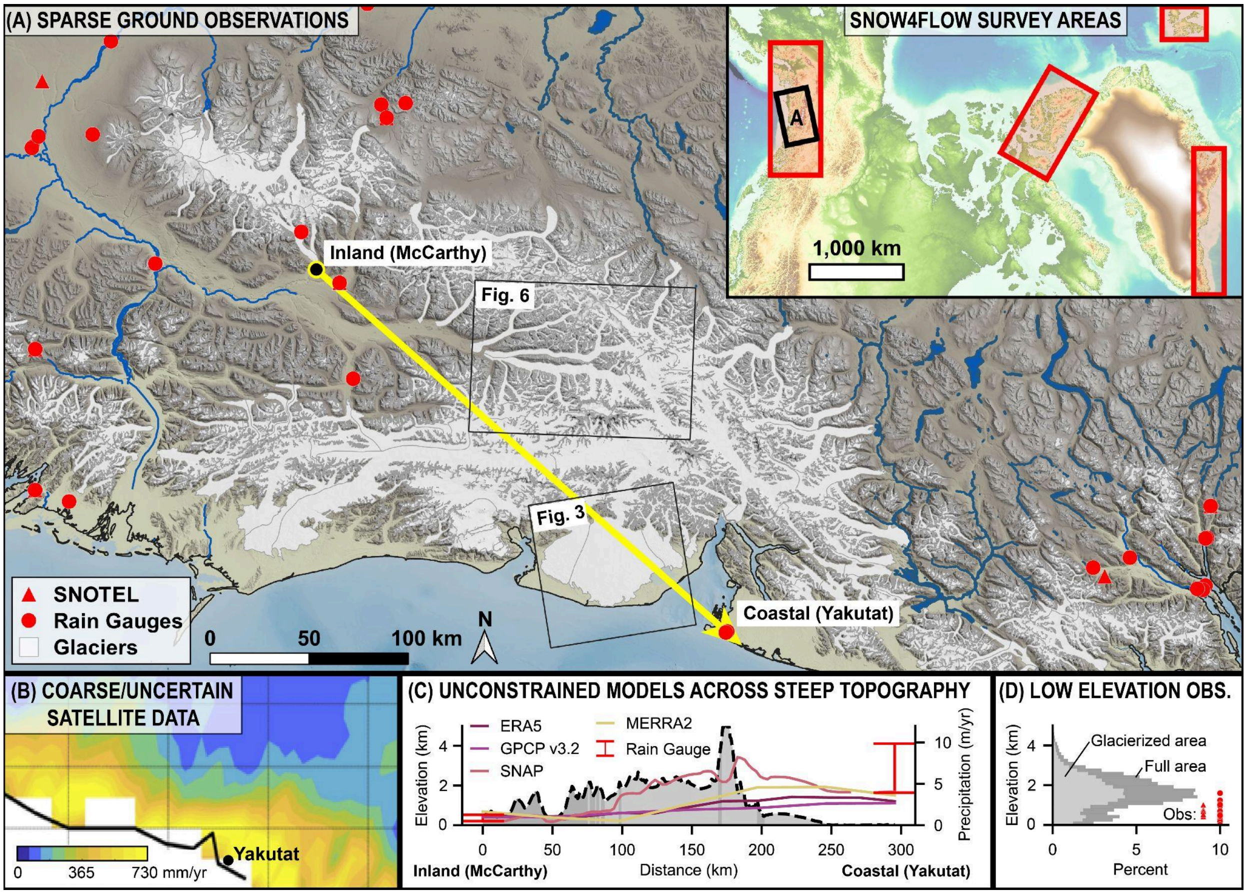


Fig. 2. *We know very little about snow in glacierized mountain ranges. Alaska's coastal ranges exhibit some of the steepest elevation gradients on Earth and its glaciers currently are the largest SLR contributor outside of Antarctica and Greenland [2], but there are few well-placed monitoring stations to constrain precipitation, hampering mass-loss projections.* ***(A)*** *Glaciated terrain and precipitation stations.* ***(B)*** *Standard deviation of recent satellite-based precipitation from 6 passive microwave and radar products, where larger values are associated with topographic relief; same region as A but at 0.5º resolution (including coastline).* ***(C)*** *McCarthy–Yakutat elevation transect (yellow line) with 1985–2014 mean annual precipitation from 4 data products + rain gauges.* ***(D)*** *Regional, glacier, and precipitation station hypsometry.*

The combination of observational sparsity and inherent complexity means that no well-validated, glacier-focused, fine-resolution snow reanalysis exists – even for Alaska, whose glaciers are a major SLR contributor (0.2 mm yr^{-1}) [45]. Glacier and ice-sheet surfaces and non-seasonal snow are often omitted in current snow reanalyses [46], [47]. These factors require well-distributed airborne observations and model integration to provide viable, spatiotemporally appropriate forcing data for land-ice models. Further, steep, rough surfaces and vegetation often challenge seasonal (winter) SWE retrieval in mountainous terrain. In contrast, glaciers are generally vegetation-free, smooth, and gently sloped. Airborne SWE retrievals across them can provide substantially more information across alpine terrain – precisely where observations are most lacking (**Fig. 2**). Snow4Flow exploits previously unexplored avenues for large-scale SWE retrieval by targeting glaciers flowing through data-poor high-relief terrain and across the High Arctic.

2.2. Why flow?

The horizontal component of flow is poorly constrained. Ice *surface velocities* can be obtained from orbit, but ice *flux* is poorly known for most of Earth's glaciers mostly due to a dearth of ice-thickness observations. We can currently measure the *volume change* of glaciers much better than we know their *actual volumes*. Despite the recent development of global ice-thickness models, these models are severely lacking when compared to measurements for the few glaciers where detailed observations exist [48]–[50] (**Fig. 3**). This issue prohibits realistic representations of ice flux and is of particular concern for credible projections of the ocean-driven response of marine-terminating glaciers, which are often thickest near their termini [51]. These thickness models also problematically assume stationary and poorly constrained climatic mass-balance gradients. Thus, they are poorly suited for capturing the dynamic response of many present-day glaciers, especially marine-terminating glaciers [51], and especially so given the rate of modern climate change. A similar situation persists even for the better-surveyed GrIS [52]. There, 38% of its 239 major outlet glaciers have essentially no ice-thickness data within 20 km of their terminus, most of which are in southeastern (*SE*) Greenland, forcing reliance on physically-based interpolations exactly where these glaciers are most vulnerable to ocean warming [53]–[55].

The vertical component of flow is also mostly unconstrained. Snow input and ice flow are intimately connected. Repeat-altimetry data (e.g., ICESat-2) are insufficient to resolve vertical flow because the surface on which the snow is deposited is also moving (downward in the upper glacier where snow accumulates, upward where it melts; **Fig. 1**) [32], [56]. This vertical flow can only be estimated with a combination of surface-elevation change, horizontal velocity, snow-accumulation *and* ice-thickness data.

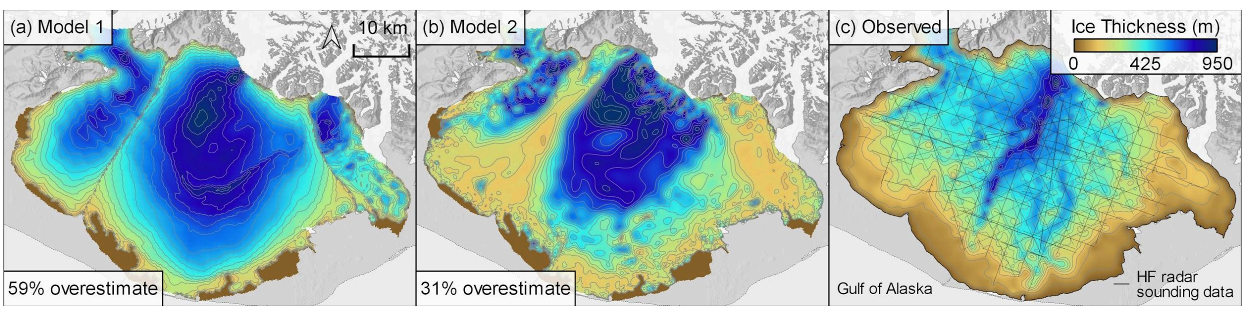


Fig. 3. *We rarely know how much ice there is until we measure it. (a, b) Modeled ice thickness from two recent global compilations [48] [49] differ significantly from that measured by (c) a modern airborne radar-sounder campaign [50]. This major Alaskan glacier (Sít' Tlein / Malaspina) alone contains ten times as much ice as the Swiss Alps.*

3. Science Goals and Objectives

Previous and ongoing NASA and international investments have provided invaluable insight into NH glacier mass change but still fall short of pressing societal needs. Beyond the measurement paucity discussed above, they also suffer from several structural shortcomings: 1. Sparse ground validation with limited coordination; 2. Significant disagreement between satellite observations confounded by unobserved variables (e.g., vertical ice flow and snow density [56], [57]); 3. Limited integration of glacier systems within Earth system models and reanalyses and climate models [46], [47], [58]. Collectively, this situation results in projections of 21st century NH glacier mass change with large relative uncertainty (~50–70% depending on emission scenario) [19] and for which the path toward further model improvement is unclear in the absence of substantially better validation. A large-scale airborne measurement campaign directly integrated with state-of-the-art modeling is clearly warranted. *Snow4Flow*'s science questions and objectives will directly address these challenges (**Table 1**).

Table 1. *Science questions (**SQ**), sub-questions, and objectives (**SO**).*

SQ1	**How will NH glaciers respond to climate change through the end of the 21st century?**	**1.1**	What is the snow accumulation across NH glacier catchments?
		1.2	What is their present volume?
		1.3	What is their output flux?
		1.4	What is the projected timing and magnitude of changes in mass and flux?
SQ2	**How does snow accumulation vary in regions of high topographic relief?**	**2.1**	How well do precipitation models match measurements?
		2.2	How can we improve precipitation models for high-relief regions?
SO1	Measure seasonal snow accumulation across major NH glaciers and climatic regions.		
SO2	Validate and calibrate precipitation models across glacierized NH mountain ranges.		
SO3	Measure ice thickness of major NH glaciers at strategic locations, including their equilibrium lines and termini.		
SO4	Project location, timing and magnitude of future regional mass changes of NH glacierized systems and their downstream impacts on communities.		

Concentrating on glacierized areas will enable measurement of solid precipitation accumulated over the entire winter, simplifying measurement of precipitation rates in alpine environments. Getting snow "right" on a diverse set of NH glaciers is not only required for accurate quantification of key variables on those surveyed glaciers, but also improves our ability to regionally predict those key variables on *unsurveyed* glaciers. It also helps improve representation of snow on non-glacierized, high-relief terrain closer to NH population centers, because of the nature of parameterizations in Earth system and regional models. We know that satellite observations, models, and reanalyses are presently inadequate in these regions (**Fig. 2**), that improved bias corrections and model parameterizations require better data, and that where such data are available model biases can be reduced significantly (**Fig. 4**).

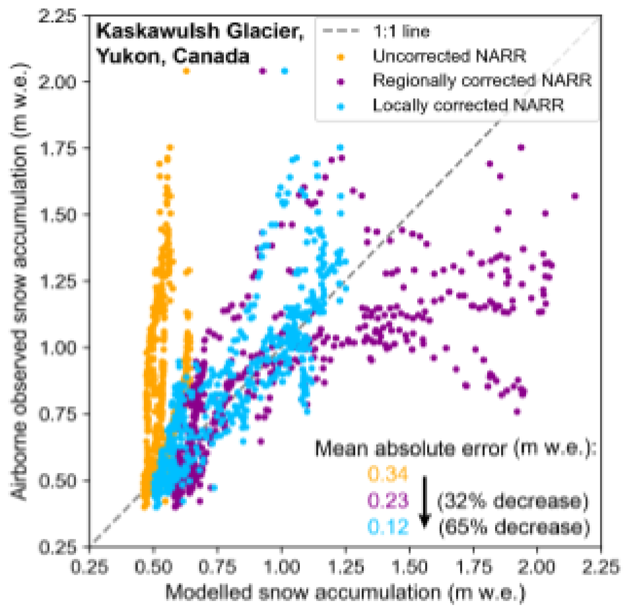


Fig. 4. *Catchment-specific observations of snow accumulation significantly decrease bias in modeled snow accumulation [35], [37]. Downscaled North American Regional Reanalysis (NARR) output is much higher than airborne shallow radar-sounding observations. Correcting with nearby (≤30 km) or local observations improves the match significantly.*

Without new, extensive and strategically targeted measurements of recent seasonal snow accumulation across multiple alpine, subpolar and polar environments, we cannot reliably assess and improve models in these complex, remote regions. The gradients in snow accumulation we will measure will be used to assess and bias-correct snow-accumulation estimates in multiple regional and global reanalyses and projections. They also provide the basis for improved parameterization of orographic precipitation and snow accumulation on mountain and glacier surfaces.

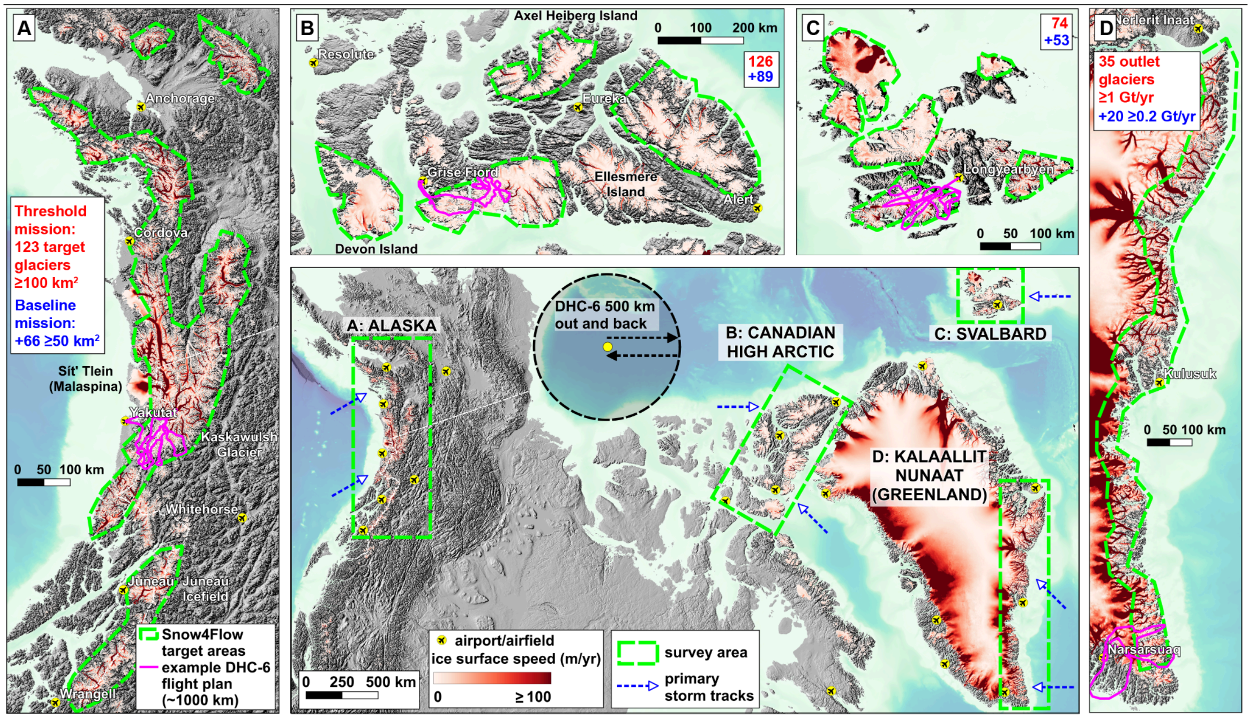


Fig. 5. *Large, fast-flowing, rapidly wasting and NASA-accessible glacier systems across the western NH. Survey areas capture diverse climatic zones and elevation gradients. Example DHC-6 flight plans (**§5.3.1**) (magenta) address multiple mission science requirements (**R2,3,8,9**; **Table 2**). Target areas based on storm tracks, established in situ survey sites [56], existing ice-thickness data [54], apparent frontal ablation rate [59], and present rate of ice thinning [16].*

Because the gravitational stress that drives ice flow depends strongly on ice thickness, measuring this thickness is fundamental to any ice-flow or glacier-evolution model (collectively *dynamic ice models)*. We will integrate ice-thickness data into such models for each targeted glacier to constrain thickness and subglacial topography across the entire glacier. These models will be forced using historical climate to quantify the resulting improvement in our understanding of present NH ice-mass change. These results are limited not by model-parameterization complexity but by uncertain boundary conditions and forcing data [60].

Snow4Flow will focus on four major glacierized regions in the western NH that were identified as both critical for projections and tractable for an EVS-4 mission: Alaska, the Canadian High Arctic, SE Greenland, and Svalbard (**Fig. 5**). From the extreme precipitation rates in the maritime coastal climate of Alaska to the much drier high polar climate of Svalbard, we focus on NH glaciers that are critical to understanding present regional mass loss (i.e., rapidly thinning), vulnerable to future retreat (e.g., terminating in water), and difficult to model (e.g., flanked by steep mountains). Our survey areas include hundreds of such glaciers whose present snow accumulation and ice-mass flux – and potential changes therein – are poorly constrained.

The paucity of snow-accumulation and ice-thickness data for model validation and projection in glacierized alpine environments is not limited to our study regions. EVS-4 precluded direct access to the Russian Arctic or High-Mountain Asia, while South American and Antarctic Peninsula glaciers reside in environments similar to Alaska and Svalbard, respectively. The NH regions we will target contain both substantial and sufficient variability in topography, regional climate, and glacier systems to enable development of a significantly improved understanding of snow accumulation and ice thickness in similar environments. This will result in improved parameterizations and bias corrections that enhance our ability to quantify snow accumulation and distribution, ice thickness, and uncertainty therein in alpine environments.

4. Baseline and Threshold Science Requirements

Snow4Flow mission science requirements must balance its scientific objectives, instrument technical maturity, operational feasibility, limitations of existing data and models, and independently identified foci of NH ice mass loss (**Table 2**; **Fig. 5**). Both the threshold and baseline outcomes generate unprecedented datasets and model advances. These requirements are as regionally uniform as possible to simplify intercomparison and evaluation, but for Alaska and Greenland we adjust them to accommodate logistical and physiographic constraints. In Alaska, there are more logistically straightforward opportunities for *in situ* calibration of airborne SWE retrievals by a NASA-led mission (**R14**). In SE Greenland, we focus on output ice flux along a single sector that contains >50 dynamic, marine-terminating outlet glaciers (**R9**, [14]) and less on snow accumulation (**R2, R3, R13**), which is somewhat better constrained for the GrIS [67]. We will rely on established international *in situ* networks for validation there [68] (**R13**). Requirements that specify reductions in model error or uncertainty (**Table 2**) will be further refined prior to the Snow4Flow Investigation Confirmation Review.

Table 2. *Baseline and threshold science requirements that Snow4Flow shall meet.*

Measurement or model (SO)	**Baseline and threshold science requirements**
Snow accumulation (SO1,2)	**R1.** **≥50** (**≥25**) **% mean successful retrieval rate for past winter snow layer** of each region's total length of surveys across glaciers **R2.** **≥5** (**≥2**) **sea-to-summit surveys** (not including Greenland) **R3.** **≥5** (**≥2**) **high-elevation col surveys** ≥2 km long with ≥10 yr snow-accumulation record (not including Greenland) **R4.** **≥5** (**≥2**) **surveys over *in situ* sites** per survey year **R5.** **≥50** (**≥25**) **% decrease in mean absolute error** between observations and bias-corrected, downscaled, stationary modeled snow-accumulation pattern **R6.** **≥20** (**≥10**) **% decrease in mean absolute error** between observations and bias-corrected total snow accumulation in a suite of current model projections
Ice thickness (SO3)	**R7.** **≥50** (**≥25**) **% mean retrieval rate** for ice ≥200 m thick **R8.** **≥1 survey ≥10 km long for all glaciers** **≥50** (**≥100**) **km^2** that intersects their equilibrium line **R9.** **≥1 cross-flow surveys within** **≤5** (**≤10**) **km of terminus** (marine-terminating glaciers); for Greenland all glaciers with apparent discharge of **≥0.2** (**1**) **Gt yr^{-1}** **R10.** **≥3** (**≥1**) **surveys over glaciers with *in situ* sites** **R11.** **≤100** (**≤200**) **m mean absolute error** between modeled ice thickness and observations
Ice elevation (SO3)	**R12.** **≥90** (**≥75**) **% mean retrieval rate** for all surveys
***In situ* snow properties (SO1,2)**	**R13.** **Seasonal snow depth, density and water content** (snow properties) at ≥1 lower-elevation and ≥1 higher-elevation site for **≥5** (**≥2**) glaciers within ≤1 month of overflight (**Alaska only**, **all regions**) **R14.** **Snow properties at** **≥2** (**≥1**) glaciers with **≥5** (**≥5**) topographically diverse sites (**Alaska only**, **all regions**)
Ice surface velocity (SO4)	**R15.** **≥95** (**≥90**) **% mean retrieval rate** within 5 km of all cross-flow surveys **R16.** **≥20** (**≥10**) **% decrease in mean uncertainty of output ice flux** for all surveyed marine-terminating glaciers and **≥40** (**≥20**)% decrease for previously unsurveyed ones
Glacier projections (SO4)	**R17.** **≥10** (**≥5**) **yr observation-validated model hindcast with** **≤25** (**≤50**) **% mean absolute error** vs. observed elevation change **R18.** **≥20** (**≥10**) **% decrease in flow-attributable ensemble spread for total mass loss at 2100** relative to current state-of-the-art projections

Snow4Flow's baseline mission will significantly advance knowledge of snow accumulation in glacierized alpine environments, ice thickness of regionally representative glaciers at their most vulnerable points, and capacity to quantify the consequences of these boundary conditions upon NH glaciers. Multiple requirements can be met simultaneously by individual sorties. Based on the requirements partly met by the example flight plans (**Fig. 5**), the baseline mission requires ~90–120 total survey sorties across the four survey regions and three survey years, depending on the selected platform (**§5.3.1**).

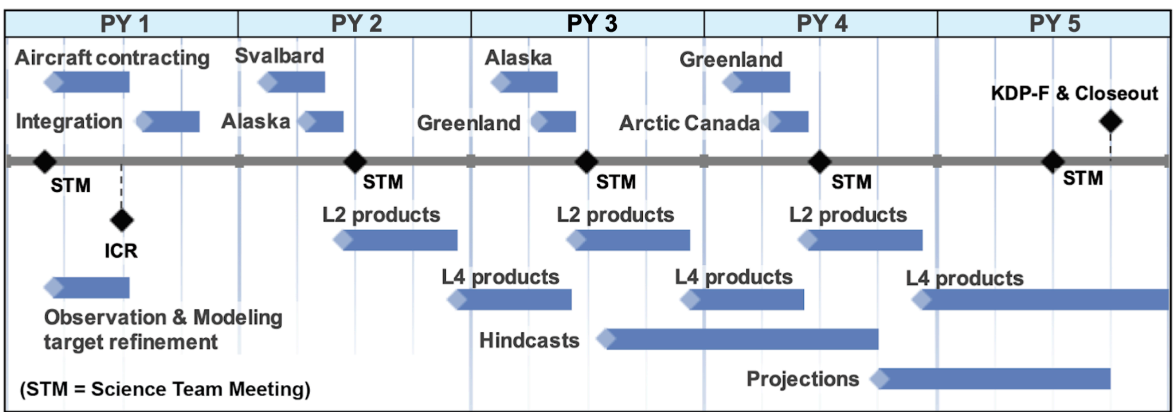
5. Science Implementation

For each project year (*PY*; **Table 3**), we target one primary (longer survey period) and one secondary region (shorter period), with existing observations and pre-campaign modeling guiding survey design. While repeat surveys may occur, they are not a priority of Snow4Flow. Data processing and targeted modeling follows these surveys to provide glacier-wide SWE and ice thickness.

5.1. Science measurement requirements

Snow4Flow will focus on acquiring the needed observations to constrain seasonal snow accumulation, ice thickness and flux. **Table B1** describes science measurement requirements for these observations, which are informed by our scientific objectives (**Table 1**; **SO1,2,3**), the mission science requirements to address those objectives (**Table 2**), knowledge of the precision, accuracy and heritage of existing TRL ≥ 6 instruments, and the inputs needed for existing models.

Table 3. *Notional timeline of major investigation milestones.*



5.1.1. Snow accumulation

Airborne, microwave-frequency radar sounding consistently measures recent (years to decades) seasonal snow accumulation rates across polar ice sheets, which tend to be flat, cold, and dry [69]. Recent surveys have established that such records are also readily retrievable across steeper, warmer, and wetter mountain glaciers (**Fig. 6**) [70], [71].

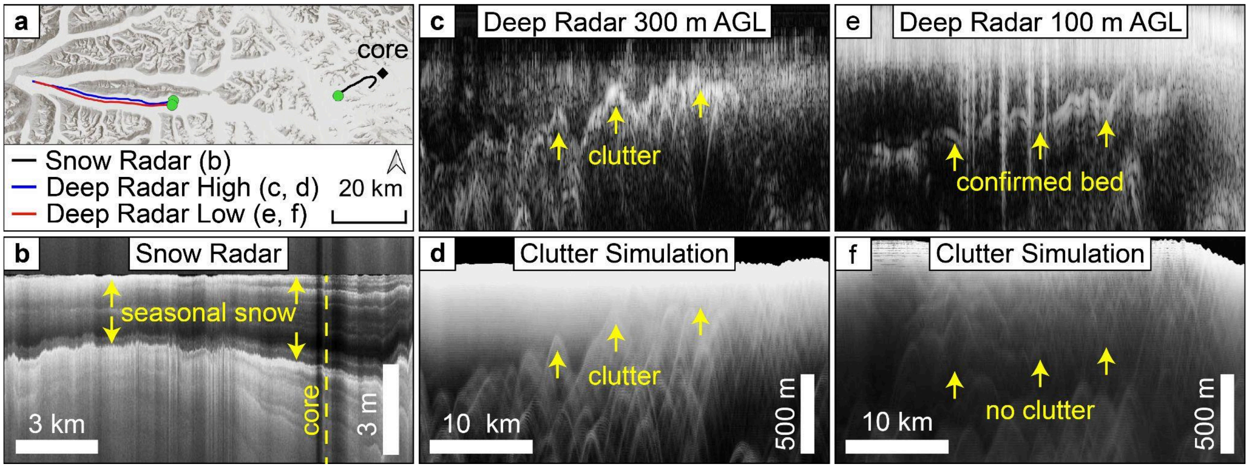


Fig. 6. *Example shallow (microwave) radar sounding across upper Kaskawulsh Glacier (Canada) and deep (HF) radar-sounding data across Logan Glacier (Alaska). (a) Map view; profiles begin at green circles. (b) Example shallow radar sounding detects seasonal snow layer [71] verified by nearby firn core [72]. (c-f) Deep radar sounding from 300 m and 100 m altitude and associated clutter simulations. Lower altitudes reduce surface clutter, improving bed detection.*

We will use this shallow radar-sounding technology to measure recent seasonal snow accumulation over glaciers across our target areas, prioritizing sparsely sampled areas, glaciers for which models suggest unrealistic or unvalidated patterns of snow accumulation (**Figs. 2,4**), sea-to-summit surveys that capture the as much of the elevation gradient in snow accumulation as possible between the ocean and mountain peaks, and surveys across summit cols (saddles) where longer records may exist [71]. We will also collect ground-based *in situ* measurements of snow depth and density targeted to sample a range of relevant topographic parameters (e.g., elevation, roughness) along key airborne radar surveys in each major snow climate (maritime, subarctic, arctic). These observations are required to calibrate and validate SWE retrieval from airborne data and meet two science objectives (**SO1,2**). As needed, small-scale and co-located ground-based radar sounding surveys may be performed to aid in further interpretation of the larger-scale airborne data and *in situ* direct observations of snow properties. Contemporaneous ground-based and airborne campaigns minimize interpretation uncertainty and are coordinated with international partners (Geological Survey of Denmark and Greenland, Norwegian Polar Institute, Polar Continental Shelf Program). For Alaska and Greenland only, which are investigated in two years, a small number (≤5 anticipated) of selected surveys are repeated for high-priority glaciers to capture the interannual variability in snow accumulation. Where possible and appropriate, we may perform surveys that underfly contemporaneous orbital assets to permit intercomparison of measurements from multiple sensors (e.g., ICESat-2, NISAR).

5.1.2. Ice thickness and flux

To constrain both glacier volume and ice-mass flux (**SO3**), we will measure ice thickness, surface elevation and velocity near both the equilibrium lines and termini of targeted glaciers within our survey areas. Simultaneous elevation measurements from laser altimetry tie radar-measured ice thickness to a reliable datum and simplify determination of subglacial topography [50]. Surface velocities are necessary to estimate the output ice flux but are readily derived from a constellation of satellites. Contemporaneous imagery of surveyed surfaces simplifies interpretation of these datasets.

Crevassed, temperate or polythermal ice is common in our survey regions, including Greenlandic outlet glaciers. This ice exhibits higher dielectric attenuation, surface and volume scattering losses [73]. Measuring the thickness of such ice often requires long-wavelength (≥ 10 m, equivalent to High Frequency, *HF*) airborne radar sounders that are less sensitive to volume scattering (englacial water) [35]. This necessitates the use of longer dipole antennas whose broad radiation patterns generate more off-nadir echoes (*clutter*) from steep proximal topography (generally valley walls) that can confound thickness measurements (**Fig. 6**). Clutter simulations using subaerial topography are thus also critical for flight planning and data interpretation [74]. When flight paths are optimized for radar sounding rather than repeat laser altimetry (lower altitudes and paths that minimize clutter sources) [35], retrieval rates improve and depths over 1 km have been sounded in Alaska (**Fig. 6**). We will acquire cross-flow thickness profiles of a glacier to establish flux gates and along-flow profiles to further constrain dynamical models.

5.2. Science modeling requirements

Snow4Flow modeling will ensure that the sum of its observations efficiently reduces uncertainty in initial and boundary conditions required by dynamic ice models (**Figs. 1**,**7**; **Table B2**; **SO2,4**), while using these observations to improve precipitation estimates across alpine terrain (**SO2**).

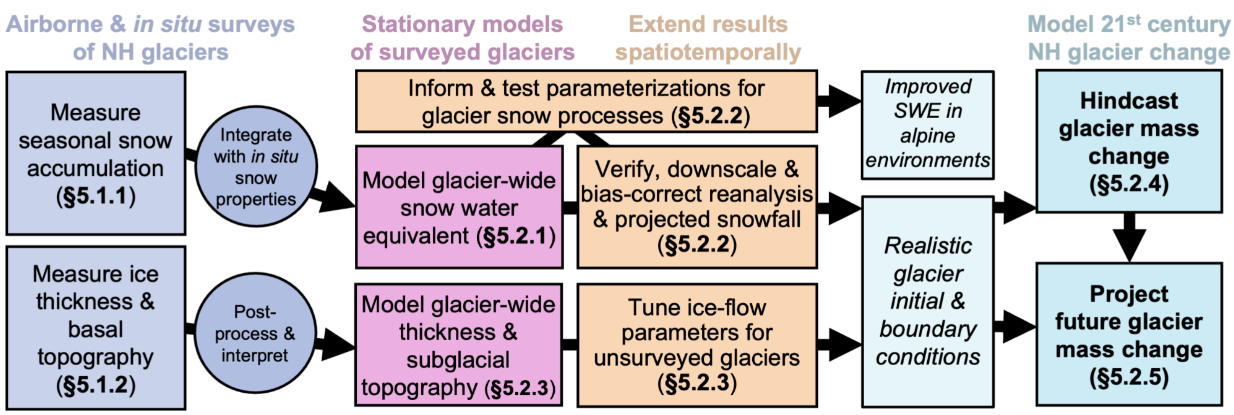


Fig. 7. *Snow4Flow modeling flowchart.*

We will incorporate validated airborne observations into spatial models of glacier snow accumulation and ice thickness. We will downscale, assess, and bias-correct current reanalysis and satellite data and climate projections to produce spatiotemporally distributed snow-accumulation forcing datasets. These datasets will improve quantification of orographic precipitation and snow-accumulation biases within Earth system models (*ESMs*). We will apply established methods to simplify production of the datasets required for dynamic ice models to hindcast NH glacier mass and evolution during the satellite era. Finally, we will project 21st century NH glacier mass change.

5.2.1. Modeling stationary SWE patterns

Coarse-resolution satellite-derived and modeled precipitation estimates are presently deficient relative to what is required to assess and project local to regional-scale glacier evolution [25]. These deficiencies arise because the processes controlling the spatial distribution of accumulated SWE – a critical component of any glacier's surface mass balance (*SMB*) – are virtually unconstrained at the scales needed to capture the accumulation distribution that drives ice flow. Despite recent efforts to address this challenge regionally and globally [75], [76], observational calibration and validation remains limited. Combined

Snow4Flow measurements and modeling address these challenges by characterizing the spatial patterns of glacier SWE distribution and identifying the most significant terrain and climate predictors of these patterns.

We will generate a stationary (*stable over time*) seasonal SWE accumulation pattern for each surveyed glacier using statistical models that extend radar-derived SWE observations using climate and terrain properties as predictors for snowfall modification by local conditions. These may include – but are not limited to – *elevation*, which impacts the orographic precipitation gradient, *slope and topographic shadowing*, which influence the wind redistribution of snow; and *aspect*, which affects incoming solar radiation and exposure to prevailing winds. While elevation is expected to be the dominant predictor, these characteristics are important at the catchment scale [70], [77].

Multiple statistical models can extrapolate SWE distribution across an entire glacier, but their accuracy depends on sufficiently extensive observations to capture the range of SWE values [70], [78], [79]. We will assess the effectiveness of both traditional statistical and machine learning techniques. Both methods have successfully extrapolated SWE across glaciers and predicted SWE from snow-cover fraction [70], [76], [80]. While machine learning techniques can overfit SWE using selected predictors, reducing their value over time and across unsampled glaciers, we can mitigate this issue by ensuring that training datasets span the range of predictors [81] by integrating modeling requirements into the flight planning process.

Snow4Flow will provide an unprecedented opportunity to assess the stationarity of glacier SWE distributions over multiple years and climatic regimes, by leveraging detection of multiple seasonal snow layers in low-accumulation regions, by comparing our surveys against previous radar-derived SWE datasets (**Fig. 6**), and by collecting select repeat surveys. Glacier-wide SWE distribution may be robust to interannual variability, but this has only been tested on a handful of relatively low-elevation glaciers with small accumulation zones that do not represent regional climatic gradients [79], [82].

5.2.2. Improving glacier surface-mass-balance forcing and model processes

Stationary SWE patterns cannot reveal temporal variability in precipitation. To provide the necessary input precipitation data at appropriate spatiotemporal scales to force dynamic ice models, we must downscale reanalysis or satellite data and then bias-correct these models using derived stationary SWE patterns (**§5.2.1**). The resolution (~10–100 km) and biases of current reanalysis and satellite products used to provide long-term, spatially distributed precipitation records are unsuitable for forcing dynamic ice models. These deficiencies are currently addressed *ad hoc* using several downscaling and bias-correction approaches [83]: prescribed rain–snow temperature thresholds or fixed temperature and precipitation lapse rates [23]. However, these approaches lack generality and spatial transferability, and improvements therein have been hindered by the dearth of validation data.

Snow4Flow will mitigate the resolution challenge by downscaling reanalysis products using methods that reproduce the distribution and characteristics of the collected airborne data. Several techniques exist to downscale reanalyses [83]–[87]. We will again assess two approaches: 1. Standard statistical downscaling that includes the above-mentioned terrain properties with a prescribed temperature for the rain–snow threshold [83]; 2. A nonparametric statistical precipitation downscaling scheme using machine learning algorithms combined with atmospheric, terrain, and satellite-derived predictors [85], [88]. Through this process, we will also produce a downscaled surface melting estimate using similar machine learning techniques as in **§5.2.1**, but which leverages different atmospheric, terrain (also debris cover), and satellite-derived predictors [40]. Surface melt volumes and distributions are generally much better constrained than snow accumulation patterns; however, deriving both components of surface mass balance using similar techniques ensures both physical consistency and ensures ease of integration into ice dynamical models.

Bias-corrected estimates of precipitation will then be generated using the downscaled precipitation and stationary maps of glacier-wide SWE distribution. These techniques can improve seasonal SWE estimates and gradients compared to on-glacier observations [37] (**Fig. 4**) and have successfully downscaled the MERRA-2 reanalysis across High Mountain Asia [85]. These downscaling and bias-correction techniques are not unique to *Snow4Flow*, but the scale and value of the results will be. Radar-derived SWE observations across many glaciers will permit better characterization of model and satellite bias in different climate regimes.

Snow4Flow surveys of glaciers across multiple climatic zones provide a unique opportunity to characterize large-scale biases in reanalysis products. While spatial resolution and its impact on topographic representation critically influence SWE distribution and SMB gradients [89], other model characteristics are also important: wind direction and orographic blocking [90]; land cover type [91], supraglacial debris cover, and snow accumulation and densification parameterizations [92] – all of which are often tuned globally [92], [93]. By assessing glacier SWE biases across models and global reanalyses against direct observations, our data–model integration directly benefits model development at a time when the representation of fine-resolution, high-elevation solid precipitation and glaciers within the Arctic system are becoming both more feasible and more critical [65].

Downscaling and bias-correcting reanalysis and satellite-precipitation data provide accurate, fine-resolution forcing data to hindcast recent glacier mass and flow (**§5.2.4**). To project precipitation and SMB through the end of the 21st century, we will downscale and bias-correct a subset of CMIP6 projections using the same methods described above [94]. Downscaling precipitation from relatively unbounded models is challenging because they can fail to represent precipitation intensity or variability accurately, or lack the necessary parameterizations to reproduce the impact of emissions on precipitation [95]. However, CMIP6 model representation of snow cover and precipitation intensity is improving [96], [97], and free-running climate models tend to better reproduce winter precipitation. For projections of glacier flow and mass change, capturing interannual accumulation variability is likely more important than individual storm intensity [95], because of the longer time scales of ice flow.

5.2.3. Modeling glacier-wide ice thickness

Knowledge of subglacial topography is critical to projecting glacier flow and mass change [98]. There are long-term efforts to both measure ice-sheet and glacier thickness and thus subglacial topography [35], [99], and to incorporate these measurements into gridded products using multiple techniques [48], [49], [52]. Despite these efforts, the overwhelming majority of NH glaciers have few or no thickness data [99].

Snow4Flow will use process-based mass-conservation and machine learning methods to extend our observations and generate glacier-wide thickness and subglacial topography, [48], [49], [100], including those methods that cast ice-thickness distribution as a minimization problem [101], [102]. These methods combine satellite-derived surface observations and ice-flow dynamics to invert for ice thickness and subglacial topography. Model accuracy depends on the quality and temporal alignment of the datasets used *and* direct observations of ice thickness to infer model parameters that govern the partitioning of ice flow between deformation and basal sliding. These parameters can vary substantially between glaciers and regions, so presently sparse ice-thickness observations often result in poorly constrained model parameters and substantial uncertainty in modeled ice thickness – even where glacier surface properties are well known (**Fig. 3**).

Snow4Flow's airborne measurements of ice thickness will directly address this gap. We will model ice thickness at all surveyed glaciers using contemporaneous satellite-derived ice velocity, surface topography, and other relevant fields. Calibrated ice-flow parameters are then used to produce a glacier-wide estimate of ice thickness. In the absence of direct ice-thickness data, previous studies used regional calibrations or reference values for model parameters [49]. We will also consider glacier type (marine or land-terminating), topography, geology, and climatic zone (e.g., polar or temperate). For surveyed glaciers, our glacier-wide thickness products will be evaluated against existing global models. For the very few glaciers with existing extensive datasets, we will compare our methods against standard geostatistical interpolation (e.g., **Fig. 3**).

5.2.4. Hindcasting modern glacier mass and mass change

By increasing confidence in model initial conditions and forcing data (**§5.2.1–5.2.3**), we will directly improve our ability to reproduce modern NH glacier and ice-sheet mass and evolution by reducing uncertainties (e.g., **Fig. 8;** [103]). Despite differences in how they parameterize ice flow, all dynamic ice models require information about ice thickness and SMB [48], [52], [100]–[102]. Through integration of finer resolution and more accurate observations, *Snow4Flow* will facilitate glacier-mass hindcasts for 2000–2030 for all NH glaciers in our survey areas and 1980–2030 for surveyed glaciers with available altimetry data [10], [11], [28], [30].

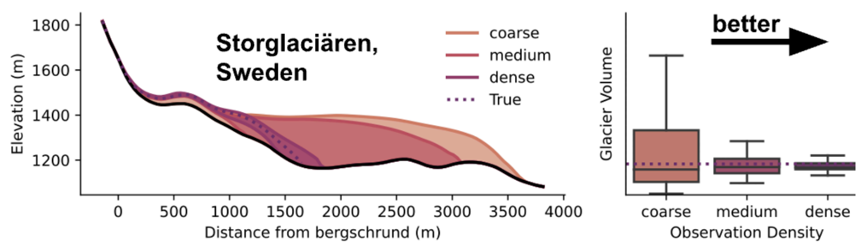


Fig. 8. *Denser snow-accumulation and ice-thickness data improve dynamic ice model hindcasts.*

To evaluate the effectiveness of Snow4Flow observations in improving modeled glacier mass balance, we will perform a series of 1980–2030 hindcasts for surveyed glaciers. The control experiment will use current subglacial topography and non-bias corrected accumulation data. The test experiments will use newly developed surface mass balance forcings (**§5.2.2**), improved ice flow parameters (**§5.2.3**) and basal topography information (**§5.2.3**), and alternatively withhold each newly developed dataset (SMB, ice-flow parameter, or subglacial topography). These hindcasts will be assessed against satellite-derived extent, surface elevation, and geodetic mass balance with the goal of assessing model biases and whether these biases are reduced by the improved datasets, and whether climatic regimes play a role in the relative importance of certain observations. To expand our results beyond Snow4Flow surveyed glaciers, we will produce 2000–2030 hindcasts of all NH glaciers in our survey areas using the bias-corrected, downscaled SMB forcings and improved ice-flow parameters and assess the models against both observations of geodetic mass balance and previous modeling efforts [48], [49].

Our two-fold approach will balance the availability and quality of reanalysis data driving the downscaled forcing datasets (**§5.2.1–5.2.2**) and satellite-altimetry data, while striving for longer hindcasts where data quality and quantity justify the effort. Geodetic mass balances are available at a range of time intervals for nearly all glaciers and ice sheets, making these data ideal validation targets [28], [30], [31], [104]. Longer hindcasts are favorable because we will generally prioritize larger glaciers with larger regional climatic impacts but often commensurately longer response times (**Table 2**). Because geodetic mass balance uses a combination of surface-elevation data and often ill-constrained density assumptions [57], we will also assess glacier mass and mass change for surveyed glaciers. This enables assessment of the density-induced uncertainty in geodetic mass change. Ultimately, well-calibrated modern glacier masses will improve accuracy of subsequent projections of glacier mass loss and potential demise.

5.2.5. Project 21st century NH glacier and ice-sheet evolution

Recent glacier and ice-sheet model intercomparisons have included dozens of models with distinct methods to conserve mass, momentum, and energy. Models focused on the evolution of individual mountain glaciers and ice caps (distinct from ice sheets) tend to focus on SMB (energy), which is the primary driver of present changes [16], whereas ice-sheet models tend to prioritize advances in ice dynamics (momentum) [21], [98]. However, dynamic ice models of intermediate sophistication with limited simplifications to the momentum balance are widely used to study ice sheets and are also beginning to be applied to individual glaciers [2], [105]. Similarly, mass-balance models that employ a physically-based surface energy-balance, rather than simple empirical relationships between temperature and melt, are becoming more useful due to more accurate, higher resolution forcing data [25].

Advances in the representation of snow accumulation and surface mass balance, including improved spatial resolution, reduce the number of parameters needed by both mass-balance and dynamic ice models of glacier change. When forcing data are improved, projections can be constrained based on model performance [22]; with better initial states from hindcasting (**§5.2.4**), individual model performance can be assessed and weighted more appropriately.

The observations collected during *Snow4Flow* will be leveraged to advance glacier mass and runoff projections. To do this, we will develop improved snow-accumulation projections to model future NH glacier mass change in our study regions. First, we will assess the pattern and magnitude of snow accumulation within a subset of CMIP models during the historical period against and the hindcast SMB datasets (**§5.2.4**), and when possible measured snow accumulation (**§5.1.1**). We will then develop a downscaled, bias corrected surface mass balance dataset following the methods detailed above (**§5.2.1–5.2.2**). This dataset, in conjunction with an improved understanding of ice flow characteristics (**§5.2.3**), will be used to project glacier mass, mass change, and runoff for the NH study area glaciers using at least one glacier mass model to 2100.

By improving and validating their initial and boundary conditions (**§5.2.4**) and providing improved forcing data, dynamic ice models improve both assessments of their performance and their projections of the total SLR contribution from NH glaciers in our survey areas. Further, an appropriate model spin-up (**§5.2.4**) improves calibration and projections by better capturing the system's transient state when projections begin. More reliable estimates of snow-accumulation and gradients therein reduce present overparameterization, enabling new forms of model calibration. Ultimately, we expect that Snow4Flow observations will provide higher fidelity projections of NH glacier mass change and runoff, while providing substantial insight into the uncertainty and biases in the models themselves.

5.3. Science observing profile

5.3.1. Measurement platforms and deployment locations

Snow4Flow will require airborne platforms that can fly *low and slow* in remote and cold polar environments *between* mountain ranges where many NH outlet glaciers reside. Low (≤300 m altitude) improves radar sounder performance by reducing surface clutter and geometric spreading loss (**Fig. 6**). Slow (≤100 m s^{-1} airspeed) improves the signal-to-noise ratio for radar sounding and minimizes platform roll (≤20º) during maneuvers in narrow mountain valleys, preserving GNSS signal lock. To maximize survey coverage, we will also require fixed-wing aircraft that can operate over-the-horizon across *and* between high-relief terrain from remote airfields. No active NASA aircraft meet all these requirements, but three crewed aircraft used regularly in polar airborne operations do: the DC-3T Basler, the DHC-6 Twin Otter and the DHC-8 Dash-8. All are available through CAS vendors with whom NASA has contracted in the past decade. The Basler and Dash-8 are larger and have greater range, but the Twin Otter's higher climb rate and maneuverability can be preferable for steeper terrain in Alaska and southeastern Greenland. All aircraft are easily modified and large enough to accommodate anticipated scientific payloads, as already demonstrated on the shorter-range DHC-3 Otter [35]. For some easily accessible glaciers in our target regions or to supplement *in situ* surveys, instrumented CAS helicopters or small, line-of-sight UAS may be suitable. **Fig. 5** shows example flight plans for each of our four survey areas. CAS helicopters or ski-equipped, fixed-wing aircraft deploy *in situ* survey teams.

Our survey areas can all be reached from airports where NASA has deployed suitable aircraft in the past two decades (**Fig. 5**). These include U.S. airports and airfields (e.g., ICAO airport code PAYA), overseas U.S. bases (e.g., BGTL), international commercial airports (e.g., BGSF) and international airfields (e.g., BGCO, CYEU, BGNO). We pursue partnerships with cognizant national and international government institutions to enable regional access, prioritize local science targets and potentially share operational costs. Partnerships with cognizant international government institutions and universities minimize mission risk associated with access and operation from international facilities. Snow4Flow's field campaigns will be subject to and abide by any permitting, notification or data access requirements required by local governments and Indigenous rightsholders.

5.3.2. Observing and data-analysis periods

February through April in PYs 2,3,4 will be the core observing period (**Table 3**). Scientifically, there are two major advantages to late winter / early spring surveys prior to the onset of significant surface melting. This period decreases both the potential negative bias for measurement of total winter snow accumulation and the deleterious impact of supraglacial and englacial water upon radar sounding for ice thickness. Operationally, during this period daylight hours in the Arctic are both increasing and sufficient for low-altitude flying, and weather patterns across our target regions tend to be less stormy or foggy than in later spring.

Following each survey period, all datasets will be processed from L0 to L1B prior to further analysis over several months (**Table 3**). For radar-sounder data, L2 products will be generated from the two-way traveltimes between the traced air–snow reflection and subsurface reflections, including the ice–rock reflection. The apparent surface elevation from the air–snow reflection will be compared against L1B laser-altimetry data. *In situ* snow properties will validate airborne radar identification of the seasonal snow horizon and enable conversion of snow-layer traveltimes to layer thickness and SWE. L1B full-thickness radargrams will be compared against cluttergrams that consider subaerial topography only to validate traced ice–rock reflections (**Fig. 6**). When a region's surveys are complete, L2 ice-thickness data will be combined with surface velocity and altimetry data, along with earlier surveys, to generate new L4 products that synthesize ice thickness and subglacial topography throughout the region.

Snow4Flow modeling efforts will be continuous, with punctuated modeling sprints following the final collection of L2 products for each survey region (**Table 3**). We will first ensure access to necessary topographic, satellite, and reanalysis datasets, and then synthesize these data to assess the range of glacier characteristics in each survey region and ensure that the airborne campaigns prioritize the glaciers and climate gradients most critical to subsequent modeling efforts. Following each airborne campaign, we will produce L4 data–model fusion maps of stationary glacier-wide SWE and ice thickness for both surveyed glaciers and un-surveyed glaciers in the survey region. These L4 products will be available for glacier hindcasts within six months of L2 product availability, with those hindcasts complete by the end of PY4. In PY5, we will develop and complete 21st century NH glacier mass projections.

6. Relevance to Earth Science and Applications Goals

Snow4Flow is responsive to multiple NASA, federal and community-identified scientific priorities. Its primary ESD focus area is Climate Variability and Change (addressing both *Cryospheric Sciences* and *Modeling, Analysis, and Prediction*), and the secondary focus is Weather and Atmospheric Dynamics (*Atmospheric Dynamics and Precipitation Science,* and *Satellite Data Assimilation)*. We directly address multiple high-priority Science and Applications Priorities of the 2017–2027 NAS Decadal Survey for Earth Science and Applications from Space [61]: Questions C-1 and C-1c, concerning quantification of, and uncertainty reduction in, future sea-level change due to glacier and ice-sheet mass balance; and Questions C-8 and C-8b, concerning the consequences of Arctic amplification of climate change for sea-level change and high-latitude weather. This mission is also directly responsive to NASA's 2023 Climate Strategy [62], addressing multiple elements of all four priorities by: "advanc[ing] climate and Earth science through novel observations" (1.1), "support[ing] communities and stakeholders in preparing for…climate change" (2.2), "help[ing] humanity understand and prepare for climate change" (3.1), and "facilitat[ing] coordination and partnerships with other federal agencies [and] international entities" (4.1).

Snow4Flow will fill a critical gap in NASA's observational and modeling needs to address these questions and priorities that cannot be achieved solely from space using current, planned or foreseeable assets. We will directly leverage and increase the value of several present and near-term NASA orbital assets (ICESat-2, Landsat-8/9, GRACE-FO, GPM, and NISAR), NASA atmospheric and dynamic ice models, reanalyses, and products, insights from other snow- and ice-focused NASA programs (SnowEx) and missions (Operation IceBridge), and *in situ* monitoring efforts by other federal agencies, U.S. universities, and international partners (**§5.3.1**). Mission outcomes are also directly applicable to applied scientific research about ongoing impacts of climate change, including proglacial lake evolution [63], deglaciated slope stability [64], and the timing and magnitude of freshwater discharge to downstream watersheds, ecosystems, and coastal zones.

Snow4Flow addresses broader federal needs identified by the Interagency Arctic Research Policy Committee's 2022–2026 Arctic Research Plan [65], especially within its Priority Area 2 (Arctic Systems Interactions) concerning the quantification and consequences of NH land ice retreat. Similarly, we will directly address three of the major challenges identified by the Future of Greenland Ice Sheet Science Workshop [66], including better integration of observations and models (#2), sustained observations (#4), and projecting the GrIS contribution to SLR (#5).

7. Earth Science to Action

Snow4Flow will address issues of global relevance, with immediate importance to communities living in the Arctic. Glaciers and their associated ecosystems have been an integral part of Arctic Indigenous cultures for thousands of years, so *Snow4Flow* is preceded by a long tradition of oral and written history that includes glacier and glacial environment changes. *Snow4Flow* will engage with both local and globally impacted communities from the start, sharing project plans and goals, seeking input, and ensuring that results are ultimately delivered in a form useful for planning and education (SHARE Principles for Conducting Research in the Arctic). As such *Snow4Flow* will address NASA's Earth Science to Action Strategy, including objectives to "Holistically Observe, Monitor, and Understand the Earth System" to "Deliver Trusted Information to Drive Earth Resilience Activities."

8. Appendix A: Glossary of Terms

Table A1. *Key scientific terms used in this document.*

Term	**Description**
Bias correction	A technique of adjusting model outputs based on calculated biases in specific variables; suitable methods may include Delta change and multiple linear regression.
Dynamic ice model	A model that simulates the flow of a glacier and its mass balance over time.
Earth system model (ESM)	A model that simulates the interactions of the Earth's atmosphere, ocean, land, ice, and biosphere; these are similar but generally more comprehensive than global climate models.
Hindcast	An analysis that uses models and historical data to simulate past events, in this case past climate or glacier conditions; alternatively, a 'retrospective forecast'.
Ice flow parameters	Ice and glacier properties that affect modeled ice flow, including the flow exponent, ice softness, enhancement factor, Glen's creep parameter, and basal sliding parameters.
Ice mass flux	The mass of ice that crosses a unit area per unit time; here a flow-orthogonal cross-section, typically near the terminus of an outlet glacier.
Snow-water equivalent (SWE)	The mass of liquid water (or equivalent) in a snow pack, which depends on snow depth, density, and liquid water content.
Surface clutter	Reflected radio waves from the off-nadir subaerial surface that "clutter" a radargram and are not associated with the subsurface signal of interest.
Stationary model	A stochastic model describing a field (here snow distribution on a glacier) that assumes there is no temporal trend in the underlying processes controlling this distribution.

9. Appendix B: Science Measurement and Modeling Requirement Matrices

Table B1. *Science Measurement Requirement Matrix (**PR**: Priority Rating, where 1 is highest priority and 3 is lowest; **T**: Threshold; **B**: Baseline).*

Scientific Measurement	PR	Measurement Requirements	SQs	SOs	Scope
Snow accumulation	**1**	A. Seasonal (winter) snow-layer thickness sampled every ≤10 m along-track with ≤5 cm vertical resolution in dry snow whose density is 450 kg m^{-3} and ≥40 m depth penetration in dry snow B. *In situ* snow-layer thickness and contemporaneous snow density with ≤25% accuracy and ≤20 cm vertical sampling resolution to ≥2 m or the winter-season snow depth, whichever is greater	**1.1, 1.4, 2.1, 2.2**	**1, 2, 4**	**T**
Ice thickness	**1**	Ice thickness sampled every ≤100 m along-track with ≥500 m depth penetration in temperate ice with ≤30 m vertical resolution in ice, and ≥800 m depth penetration with ≤50 m vertical resolution	**1.2, 1.3**	**3, 4**	**T**
Ice velocity	**1**	Annual mean ice-surface velocity at ≤150 m horizontal resolution and <5% accuracy or ≤20 m yr^{-1}, whichever is greater	**1.3, 1.4**	**3, 4**	**T**
Surface elevation	**2**	Surface elevation at sub-catchment scales along-track with ≤10 cm vertical accuracy across a ≥50 m swath	**1.2, 1.3, 1.4**	**1, 3, 4**	**T**
Natural color image	**3**	Surface color image with ≤1 m horizontal resolution	**1.1, 2.1, 2.2**	**1, 2, 4**	**B**

Table B2. *Science Modeling Requirement Matrix.*

Scientific Modeling Capability	PR	Measurement Requirements	SQs	SOs	Scope
Model spatially distributed seasonal snow accumulation patterns across NH glaciers	**1**	Seasonal snow accumulation across climatic gradients, and glacier / catchment topography, both at ≤150 m resolution	**1.1, 2.1, 2.2**	**1, 2, 4**	**T**
Assess, bias-correct, and downscale reanalysis, climate projection, and satellite estimates of snow accumulation (recent past and projections)	**1**	Spatially distributed snow accumulation patterns	**1.1, 2.1, 2.2**	**1, 4**	**T**
Propose and assess improved snowfall and snow process parameterizations for ESMs	**2**	Seasonal snow accumulation and *in situ* calibrated density across climatic gradients at ≤150 m resolution	**1.1, 2.1, 2.2**	**1,2**	**B**
Reduce uncertainty in models of current NH glacier thickness and basal topography	**1**	Ice thickness, surface elevation	**1.2**	**3**	**T**
Hindcast recent NH glacier change and validate against observations	**2**	Gridded, bias-reduced, downscaled SWE and temperature; gridded subglacial topography and ice thickness	**1.3**	**3, 4**	**B**
Project NH glacier evolution through the end of the 21st century	**1**	Bias-reduced, downscaled climate model snow accumulation and temperature; gridded subglacial topography and ice thickness	**1.4**	**3, 4**	**T**

10. Appendix C: Mission Milestones

The notional timeline for *Snow4Flow* operations is given in **Table 3**. Additional mission milestones, including likely time windows, are given in **Table C1**.

Table C1. *Approximate mission milestone timeline.*

Date(s)	**Milestone**
Late 2022 – Early 2023	Proposal development with community members
April 2023	Snow4Flow EVS-4 proposal submitted
April 2024	Snow4Flow selected
November 2024	Concept paper released publicly
2025	ROSES-25 is released, including the Announcement of Opportunity (AO) for Snow4Flow Science Team (ST)
	Snow4Flow ST proposals due 90 days after AO release
	Snow4Flow ST selected
2026	Snow4Flow IST funded (Official start of PY1) and the first in-person science team meeting held
	Airborne platform confirmed and contract in place
	Completion of Mission Investigation Implementation Plan, Mission Data Management and Inclusion Plans, NEPA Review
	Snow4Flow Investigation Confirmation Review
	Possible short prove-out airborne campaign in Alaska
2027	Snow4Flow campaign #1 ● All deployments require a Flight/Operational Readiness Review ● Annual Science Team meetings for planning, science updates, and data workshops
2028	Snow4Flow campaign #2
	Mid-Term Review (half way through data collection)
2029	Snow4Flow campaign #3
2030	Closeout Review and Key Decision Point - F demonstrating completion of Level 1 mission requirements and final report on spending, data archival, and science achievements

11. References

[1] T. Frederikse *et al.*, “The causes of sea-level rise since 1900,” *Nature*, vol. 584, no. 7821, pp. 393–397, Aug. 2020, doi: 10.1038/s41586-020-2591-3.

[2] D. R. Rounce *et al.*, “Global glacier change in the 21st century: Every increase in temperature matters,” *Science*, vol. 379, no. 6627, pp. 78–83, 2023, doi: 10.1126/science.abo1324.

[3] T. Moon, A. Ahlstrøm, H. Goelzer, W. Lipscomb, and S. Nowicki, “Rising Oceans Guaranteed: Arctic Land Ice Loss and Sea Level Rise,” *Curr Clim Change Rep*, vol. 4, no. 3, pp. 211–222, Sep. 2018, doi: 10.1007/s40641-018-0107-0.

[4] R. E. Kopp, E. A. Gilmore, C. M. Little, J. Lorenzo-Trueba, V. C. Ramenzoni, and W. V. Sweet, “Usable Science for Managing the Risks of Sea-Level Rise,” *Earth’s Future*, vol. 7, no. 12, pp. 1235–1269, 2019, doi: 10.1029/2018EF001145.

[5] H. D. Pritchard, “Asia’s shrinking glaciers protect large populations from drought stress,” *Nature*, vol. 569, no. 7758, pp. 649–654, May 2019, doi: 10.1038/s41586-019-1240-1.

[6] W. W. Immerzeel *et al.*, “Importance and vulnerability of the world’s water towers,” *Nature*, vol. 577, no. 7790, pp. 364–369, Jan. 2020, doi: 10.1038/s41586-019-1822-y.

[7] S. O’Neel *et al.*, “Icefield-to-Ocean Linkages across the Northern Pacific Coastal Temperate Rainforest Ecosystem,” *BioScience*, vol. 65, no. 5, pp. 499–512, May 2015, doi: 10.1093/biosci/biv027.

[8] Intergovernmental Panel on Climate Change (IPCC), *The Ocean and Cryosphere in a Changing Climate: Special Report of the Intergovernmental Panel on Climate Change*, 1st ed. Cambridge University Press, 2022. doi: 10.1017/9781009157964.

[9] T. Moon *et al.*, “Ending a Sea of Confusion: Insights and Opportunities in Sea-Level Change Communication,” *Environment: Science and Policy for Sustainable Development*, vol. 62, no. 5, pp. 4–15, Sep. 2020, doi: 10.1080/00139157.2020.1791627.

[10] B. Smith *et al.*, “Pervasive ice sheet mass loss reflects competing ocean and atmosphere processes,” *Science*, vol. 368, no. 6496, pp. 1239–1242, Jun. 2020, doi: 10.1126/science.aaz5845.

[11] R. Hugonnet *et al.*, “Accelerated global glacier mass loss in the early twenty-first century,” *Nature*, vol. 592, no. 7856, Art. no. 7856, Apr. 2021, doi: 10.1038/s41586-021-03436-z.

[12] The IMBIE team, “Mass balance of the Antarctic Ice Sheet from 1992 to 2017,” *Nature*, vol. 558, no. 7709, pp. 219–222, Jun. 2018, doi: 10.1038/s41586-018-0179-y.

[13] The IMBIE Team, “Mass balance of the Greenland Ice Sheet from 1992 to 2018,” *Nature*, vol. 579, no. 7798, pp. 233–239, Mar. 2020, doi: 10.1038/s41586-019-1855-2.

[14] M. Wood *et al.*, “Ocean forcing drives glacier retreat in Greenland,” *Sci. Adv.*, vol. 7, no. 1, p. eaba7282, Jan. 2021, doi: 10.1126/sciadv.aba7282.

[15] M. R. England, I. Eisenman, N. J. Lutsko, and T. J. W. Wagner, “The Recent Emergence of Arctic Amplification,” *Geophysical Research Letters*, vol. 48, no. 15, Aug. 2021, doi: 10.1029/2021GL094086.

[16] C. F. Larsen, E. Burgess, A. A. Arendt, S. O’Neel, A. J. Johnson, and C. Kienholz, “Surface melt dominates Alaska glacier mass balance,” *Geophysical Research Letters*, vol. 42, no. 14, pp. 5902–5908, Jul. 2015, doi: 10.1002/2015GL064349.

[17] M. F. Meier *et al.*, “Glaciers Dominate Eustatic Sea-Level Rise in the 21st Century,” *Science*, vol. 317, no. 5841, pp. 1064–1067, Aug. 2007, doi: 10.1126/science.1143906.

[18] T. L. Edwards *et al.*, “Projected land ice contributions to twenty-first-century sea level rise,” *Nature*, vol. 593, no. 7857, pp. 74–82, May 2021, doi: 10.1038/s41586-021-03302-y.

[19] B. Marzeion *et al.*, “Partitioning the Uncertainty of Ensemble Projections of Global Glacier Mass Change,” *Earth’s Future*, vol. 8, no. 7, Jul. 2020, doi: 10.1029/2019EF001470.

[20] A. Aschwanden *et al.*, “Contribution of the Greenland Ice Sheet to sea level over the next millennium,” *Sci. Adv.*, vol. 5, no. 6, Jun. 2019, doi: 10.1126/sciadv.aav9396.

[21] H. Goelzer *et al.*, “The future sea-level contribution of the Greenland ice sheet: a multi-model ensemble study of ISMIP6,” *The Cryosphere*, vol. 14, no. 9, pp. 3071–3096, Sep. 2020, doi: 10.5194/tc-14-3071-2020.

[22] A. Aschwanden and D. J. Brinkerhoff, “Calibrated Mass Loss Predictions for the Greenland Ice Sheet,” *Geophysical Research Letters*, vol. 49, no. 19, Oct. 2022, doi: 10.1029/2022GL099058.

[23] R. Hock, F. Maussion, B. Marzeion, and S. Nowicki, “What is the global glacier ice volume outside the ice sheets?,” *Journal of Glaciology*, vol. 69, no. 273, pp. 204–210, Feb. 2023, doi: 10.1017/jog.2023.1.

[24] S. O’Neel, “Evolving force balance at Columbia Glacier, Alaska, during its rapid retreat,” *J. Geophys. Res.*, vol. 110, no. F3, p. F03012, 2005, doi: 10.1029/2005JF000292.

[25] D. R. Rounce, T. Khurana, M. B. Short, R. Hock, D. E. Shean, and D. J. Brinkerhoff, “Quantifying parameter uncertainty in a large-scale glacier evolution model using Bayesian inference: application to High Mountain Asia,” *Journal of Glaciology*, vol. 66, no. 256, pp. 175–187, Apr. 2020, doi: 10.1017/jog.2019.91.

[26] H. Sevestre *et al.*, “Tidewater Glacier Surges Initiated at the Terminus,” *J. Geophys. Res. Earth Surf.*, vol. 123, no. 5, pp. 1035–1051, May 2018, doi: 10.1029/2017JF004358.

[27] I. M. Howat, I. Joughin, and T. A. Scambos, “Rapid Changes in Ice Discharge from Greenland Outlet Glaciers,” *Science*, vol. 315, no. 5818, pp. 1559–1561, Mar. 2007, doi: 10.1126/science.1138478.

[28] L. Sandberg Sørensen, S. B. Simonsen, R. Forsberg, K. Khvorostovsky, R. Meister, and M. E. Engdahl, "25 years of elevation changes of the Greenland Ice Sheet from ERS, Envisat, and CryoSat-2 radar altimetry," *Earth and Planetary Science Letters*, vol. 495, pp. 234–241, Aug. 2018, doi: 10.1016/j.epsl.2018.05.015.
[29] A. Bhattacharya *et al.*, "High Mountain Asian glacier response to climate revealed by multi-temporal satellite observations since the 1960s," *Nat Commun*, vol. 12, no. 1, Art. no. 1, Jul. 2021, doi: 10.1038/s41467-021-24180-y.
[30] E. Berthier, E. Schiefer, G. K. C. Clarke, B. Menounos, and F. Rémy, "Contribution of Alaskan glaciers to sea-level rise derived from satellite imagery," *Nature Geosci*, vol. 3, no. 2, Art. no. 2, Feb. 2010, doi: 10.1038/ngeo737.
[31] L. Jakob, N. Gourmelen, M. Ewart, and S. Plummer, "Spatially and temporally resolved ice loss in High Mountain Asia and the Gulf of Alaska observed by CryoSat-2 swath altimetry between 2010 and 2019," *The Cryosphere*, vol. 15, no. 4, pp. 1845–1862, Apr. 2021, doi: 10.5194/tc-15-1845-2021.
[32] C. J. Mcneil *et al.*, "Geodetic Data for USGS Benchmark Glaciers: Orthophotos, Digital Elevation Models, Glacier Boundaries and Surveyed Positions." U.S. Geological Survey, 2019. doi: 10.5066/P9R8BP3K.
[33] E. M. Enderlin *et al.*, "Uncertainty of ICESat-2 ATL06- and ATL08-derived snow depths for glacierized and vegetated mountain regions," *Remote Sensing of Environment*, vol. 283, p. 113307, Dec. 2022, doi: 10.1016/j.rse.2022.113307.
[34] A. Aschwanden, T. C. Bartholomaus, D. J. Brinkerhoff, and M. Truffer, "Brief communication: A roadmap towards credible projections of ice sheet contribution to sea level," *The Cryosphere*, vol. 15, no. 12, pp. 5705–5715, Dec. 2021, doi: 10.5194/tc-15-5705-2021.
[35] J. A. MacGregor *et al.*, "The Scientific Legacy of NASA's Operation IceBridge," *Reviews of Geophysics*, vol. 59, no. 2, p. e2020RG000712, 2021, doi: 10.1029/2020RG000712.
[36] J. P. Beamer, D. F. Hill, A. Arendt, and G. E. Liston, "High-resolution modeling of coastal freshwater discharge and glacier mass balance in the Gulf of Alaska watershed," *Water Resources Research*, vol. 52, no. 5, pp. 3888–3909, 2016, doi: 10.1002/2015WR018457.
[37] G. Flowers, K. Robinson, and E. Young, "Assessing Sources of Uncertainty in Runoff Partitioning From a Highly Glacierized Catchment in Northern Canada," vol. 2021, pp. C44B-08, Dec. 2021.
[38] Y. He, C. Chen, B. Li, and Z. Zhang, "Prediction of near-surface air temperature in glacier regions using ERA5 data and the random forest regression method," *Remote Sensing Applications: Society and Environment*, vol. 28, p. 100824, Nov. 2022, doi: 10.1016/j.rsase.2022.100824.
[39] L. Zheng, X. Cheng, X. Shang, Z. Chen, Q. Liang, and K. Wang, "Greenland Ice Sheet Daily Surface Melt Flux Observed From Space," *Geophysical Research Letters*, vol. 49, no. 6, p. e2021GL096690, 2022, doi: 10.1029/2021GL096690.
[40] Z. Hu, P. Kuipers Munneke, S. Lhermitte, M. Izeboud, and M. van den Broeke, "Improving surface melt estimation over the Antarctic Ice Sheet using deep learning: a proof of concept over the Larsen Ice Shelf," *The Cryosphere*, vol. 15, no. 12, pp. 5639–5658, Dec. 2021, doi: 10.5194/tc-15-5639-2021.
[41] R. S. Kim *et al.*, "Snow Ensemble Uncertainty Project (SEUP): quantification of snow water equivalent uncertainty across North America via ensemble land surface modeling," *The Cryosphere*, vol. 15, no. 2, pp. 771–791, Feb. 2021, doi: 10.5194/tc-15-771-2021.
[42] A. G. Slater and M. P. Clark, "Snow Data Assimilation via an Ensemble Kalman Filter," *Journal of Hydrometeorology*, vol. 7, no. 3, pp. 478–493, Jun. 2006, doi: 10.1175/JHM505.1.
[43] L. Tsang *et al.*, "Review article: Global monitoring of snow water equivalent using high-frequency radar remote sensing," *The Cryosphere*, vol. 16, no. 9, pp. 3531–3573, Sep. 2022, doi: 10.5194/tc-16-3531-2022.
[44] H. Lievens, I. Brangers, H.-P. Marshall, T. Jonas, M. Olefs, and G. De Lannoy, "Sentinel-1 snow depth retrieval at sub-kilometer resolution over the European Alps," *The Cryosphere*, vol. 16, no. 1, pp. 159–177, Jan. 2022, doi: 10.5194/tc-16-159-2022.
[45] J. S. Littell, S. A. McAfee, and G. D. Hayward, "Alaska Snowpack Response to Climate Change: Statewide Snowfall Equivalent and Snowpack Water Scenarios," *Water*, vol. 10, no. 5, Art. no. 5, May 2018, doi: 10.3390/w10050668.
[46] Y. Fang, Y. Liu, and S. A. Margulis, "A western United States snow reanalysis dataset over the Landsat era from water years 1985 to 2021," *Sci Data*, vol. 9, no. 1, Art. no. 1, Nov. 2022, doi: 10.1038/s41597-022-01768-7.
[47] Y. Liu, Y. Fang, and S. A. Margulis, "Spatiotemporal distribution of seasonal snow water equivalent in High Mountain Asia from an 18-year Landsat–MODIS era snow reanalysis dataset," *The Cryosphere*, vol. 15, no. 11, pp. 5261–5280, Nov. 2021, doi: 10.5194/tc-15-5261-2021.
[48] D. Farinotti *et al.*, "A consensus estimate for the ice thickness distribution of all glaciers on Earth," *Nat. Geosci.*, vol. 12, no. 3, Art. no. 3, Mar. 2019, doi: 10.1038/s41561-019-0300-3.
[49] R. Millan, J. Mouginot, A. Rabatel, and M. Morlighem, "Ice velocity and thickness of the world's glaciers," *Nat. Geosci.*, vol. 15, no. 2, Art. no. 2, Feb. 2022, doi: 10.1038/s41561-021-00885-z.
[50] B. S. Tober *et al.*, "Comprehensive Radar Mapping of Malaspina Glacier (Sít' Tlein), Alaska – the World's Largest Piedmont Glacier – Reveals Potential for Instability," *Journal of Geophysical Research: Earth Surface*, vol. 128, no. 3, p. e2022JF006898, 2023, doi: 10.1029/2022JF006898.
[51] M. Möller, F. Navarro, M. Huss, and B. Marzeion, "Projected sea-level contributions from tidewater glaciers are

highly sensitive to chosen bedrock topography: a case study at Hansbreen, Svalbard," *J. Glaciol.*, pp. 1–15, Jan. 2023, doi: 10.1017/jog.2022.117.
[52] M. Morlighem *et al.*, "BedMachine v3: Complete Bed Topography and Ocean Bathymetry Mapping of Greenland From Multibeam Echo Sounding Combined With Mass Conservation," *Geophysical Research Letters*, vol. 44, no. 21, Nov. 2017, doi: 10.1002/2017GL074954.
[53] G. A. Catania *et al.*, "Geometric Controls on Tidewater Glacier Retreat in Central Western Greenland," *JGR Earth Surface*, vol. 123, no. 8, pp. 2024–2038, Aug. 2018, doi: 10.1029/2017JF004499.
[54] M. Morlighem, "IceBridge BedMachine Greenland, Version 5." NASA National Snow and Ice Data Center DAAC, 2022. doi: 10.5067/GMEVBWFLWA7X.
[55] D. Felikson, G. A. Catania, T. C. Bartholomaus, M. Morlighem, and B. P. Y. Noël, "Steep Glacier Bed Knickpoints Mitigate Inland Thinning in Greenland," *Geophysical Research Letters*, vol. 48, no. 2, Jan. 2021, doi: 10.1029/2020GL090112.
[56] L. Zeller, D. McGrath, L. Sass, S. O'Neel, C. McNeil, and E. Baker, "Beyond glacier-wide mass balances: parsing seasonal elevation change into spatially resolved patterns of accumulation and ablation at Wolverine Glacier, Alaska," *Journal of Glaciology*, vol. 69, no. 273, pp. 87–102, 2023, doi: 10.1017/jog.2022.46.
[57] M. Huss, "Density assumptions for converting geodetic glacier volume change to mass change," *The Cryosphere*, vol. 7, no. 3, pp. 877–887, May 2013, doi: 10.5194/tc-7-877-2013.
[58] V. Eyring *et al.*, "Overview of the Coupled Model Intercomparison Project Phase 6 (CMIP6) experimental design and organization," *Geoscientific Model Development*, vol. 9, no. 5, pp. 1937–1958, May 2016, doi: 10.5194/gmd-9-1937-2016.
[59] W. Kochtitzky *et al.*, "The unquantified mass loss of Northern Hemisphere marine-terminating glaciers from 2000–2020," *Nat Commun*, vol. 13, no. 1, p. 5835, Oct. 2022, doi: 10.1038/s41467-022-33231-x.
[60] A. Morin, G. E. Flowers, A. Nolan, D. Brinkerhoff, and E. Berthier, "Exploiting high-slip flow regimes to improve inference of glacier bed topography," *J. Glaciol.*, pp. 1–7, Jan. 2023, doi: 10.1017/jog.2022.121.
[61] Committee on the Decadal Survey for Earth Science and Applications from Space, Space Studies Board, Division on Engineering and Physical Sciences, and National Academies of Sciences, Engineering, and Medicine, *Thriving on Our Changing Planet: A Decadal Strategy for Earth Observation from Space*. Washington, D.C.: National Academies Press, 2018, p. 24938. doi: 10.17226/24938.
[62] "Advancing NASA's Climate Strategy," NP-2023-03-3112-HQ. [Online]. Available: https://www.nasa.gov/sites/default/files/atoms/files/advancing_nasas_climate_strategy_2023.pdf
[63] M. G. Loso *et al.*, "Quo vadis, Alsek? Climate-driven glacier retreat may change the course of a major river outlet in southern Alaska," *Geomorphology*, vol. 384, p. 107701, Jul. 2021, doi: 10.1016/j.geomorph.2021.107701.
[64] B. Higman *et al.*, "The 2015 landslide and tsunami in Taan Fiord, Alaska," *Sci Rep*, vol. 8, no. 1, p. 12993, Sep. 2018, doi: 10.1038/s41598-018-30475-w.
[65] Interagency Arctic Research Policy Committee of the National Science and Technology Council, "Arctic Research Plan 2022 - 2026," 2021. [Online]. Available: https://www.iarpccollaborations.org/uploads/cms/documents/final-arp-2022-2026-20211214.pdf
[66] W. Chu, T. Bartholomaus, J. MacGregor, M. Morlighem, and V. Walden, "Future of Greenland Ice Sheet Science (FOGSS) Workshop 2022: Summary report." NSF Arctic Data Center, 2022. doi: 10.18739/A2SN0157W.
[67] E. W. Burgess *et al.*, "A spatially calibrated model of annual accumulation rate on the Greenland Ice Sheet (1958-2007)," *J. Geophys. Res.*, vol. 115, no. F2, Jun. 2010, doi: 10.1029/2009JF001293.
[68] R. S. Fausto *et al.*, "Programme for Monitoring of the Greenland Ice Sheet (PROMICE) automatic weather station data," *Earth Syst. Sci. Data*, vol. 13, no. 8, pp. 3819–3845, Aug. 2021, doi: 10.5194/essd-13-3819-2021.
[69] B. Medley *et al.*, "Constraining the recent mass balance of Pine Island and Thwaites glaciers, West Antarctica, with airborne observations of snow accumulation," *The Cryosphere*, vol. 8, no. 4, pp. 1375–1392, Jul. 2014, doi: 10.5194/tc-8-1375-2014.
[70] D. McGrath *et al.*, "End-of-winter snow depth variability on glaciers in Alaska," *Journal of Geophysical Research: Earth Surface*, vol. 120, no. 8, pp. 1530–1550, 2015, doi: 10.1002/2015JF003539.
[71] J. Li *et al.*, "Snow stratigraphy observations from Operation IceBridge surveys in Alaska using S and C band airborne ultra-wideband FMCW (frequency-modulated continuous wave) radar," *The Cryosphere*, vol. 17, no. 1, pp. 175–193, Jan. 2023, doi: 10.5194/tc-17-175-2023.
[72] N. E. Ochwat, S. J. Marshall, B. J. Moorman, A. S. Criscitiello, and L. Copland, "Evolution of the firn pack of Kaskawulsh Glacier, Yukon: meltwater effects, densification, and the development of a perennial firn aquifer," *The Cryosphere*, vol. 15, no. 4, pp. 2021–2040, Apr. 2021, doi: 10.5194/tc-15-2021-2021.
[73] J. A. MacGregor, M. Studinger, E. Arnold, C. J. Leuschen, F. Rodríguez-Morales, and J. D. Paden, "Brief communication: An empirical relation between center frequency and measured thickness for radar sounding of temperate glaciers," *The Cryosphere*, vol. 15, no. 6, pp. 2569–2574, Jun. 2021, doi: 10.5194/tc-15-2569-2021.
[74] J. W. Holt, M. E. Peters, S. D. Kempf, D. L. Morse, and D. D. Blankenship, "Echo source discrimination in single-pass airborne radar sounding data from the Dry Valleys, Antarctica: Implications for orbital sounding of Mars," *J. Geophys. Res.*, vol. 111, no. E6, p. E06S24, 2006, doi: 10.1029/2005JE002525.
[75] R. Hock *et al.*, "GlacierMIP – A model intercomparison of global-scale glacier mass-balance models and projections," *J. Glaciol.*, vol. 65, no. 251, pp. 453–467, Jun. 2019, doi: 10.1017/jog.2019.22.

[76] M. Guidicelli, M. Huss, M. Gabella, and N. Salzmann, “Spatio-temporal reconstruction of winter glacier mass balance in the Alps, Scandinavia, Central Asia and western Canada (1981–2019) using climate reanalyses and machine learning,” *The Cryosphere*, vol. 17, no. 2, pp. 977–1002, Mar. 2023, doi: 10.5194/tc-17-977-2023.
[77] A. Pulwicki, G. E. Flowers, V. Radić, and D. Bingham, “Estimating winter balance and its uncertainty from direct measurements of snow depth and density on alpine glaciers,” *J. Glaciol.*, vol. 64, no. 247, pp. 781–795, Oct. 2018, doi: 10.1017/jog.2018.68.
[78] L. Sold *et al.*, “Mass Balance Re-analysis of Findelengletscher, Switzerland; Benefits of Extensive Snow Accumulation Measurements,” *Frontiers in Earth Science*, vol. 4, 2016, doi: doi.org/10.3389/feart.2016.00018.
[79] J. Revuelto, J. I. López-Moreno, C. Azorin-Molina, and S. M. Vicente-Serrano, “Topographic control of snowpack distribution in a small catchment in the central Spanish Pyrenees: intra- and inter-annual persistence,” *The Cryosphere*, vol. 8, no. 5, pp. 1989–2006, Oct. 2014, doi: 10.5194/tc-8-1989-2014.
[80] E. H. Bair, A. Abreu Calfa, K. Rittger, and J. Dozier, “Using machine learning for real-time estimates of snow water equivalent in the watersheds of Afghanistan,” *The Cryosphere*, vol. 12, no. 5, pp. 1579–1594, May 2018, doi: 10.5194/tc-12-1579-2018.
[81] Y. Gu *et al.*, “An Optimal Sample Data Usage Strategy to Minimize Overfitting and Underfitting Effects in Regression Tree Models Based on Remotely-Sensed Data,” *Remote Sensing*, vol. 8, no. 11, Art. no. 11, Nov. 2016, doi: 10.3390/rs8110943.
[82] D. McGrath *et al.*, “Interannual snow accumulation variability on glaciers derived from repeat, spatially extensive ground-penetrating radar surveys,” *The Cryosphere*, vol. 12, no. 11, pp. 3617–3633, Nov. 2018, doi: 10.5194/tc-12-3617-2018.
[83] E. M. Young, G. E. Flowers, E. Berthier, and R. Latto, “An imbalancing act: the delayed dynamic response of the Kaskawulsh Glacier to sustained mass loss,” *Journal of Glaciology*, vol. 67, no. 262, pp. 313–330, Apr. 2021, doi: 10.1017/jog.2020.107.
[84] M. Hofer, J. Nemec, N. J. Cullen, and M. Weber, “Evaluating Predictor Strategies for Regression-Based Downscaling with a Focus on Glacierized Mountain Environments,” *Journal of Applied Meteorology and Climatology*, vol. 56, no. 6, pp. 1707–1729, Jun. 2017, doi: 10.1175/JAMC-D-16-0215.1.
[85] Y. Mei, V. Maggioni, P. Houser, Y. Xue, and T. Rouf, “A Nonparametric Statistical Technique for Spatial Downscaling of Precipitation Over High Mountain Asia,” *Water Resources Research*, vol. 56, no. 11, p. e2020WR027472, 2020, doi: 10.1029/2020WR027472.
[86] H. Guan, J. L. Wilson, and H. Xie, “A cluster-optimizing regression-based approach for precipitation spatial downscaling in mountainous terrain,” *Journal of Hydrology*, vol. 375, no. 3–4, pp. 578–588, Sep. 2009, doi: 10.1016/j.jhydrol.2009.07.007.
[87] H. Guan, J. L. Wilson, and O. Makhnin, “Geostatistical Mapping of Mountain Precipitation Incorporating Autosearched Effects of Terrain and Climatic Characteristics,” *Journal of Hydrometeorology*, vol. 6, no. 6, pp. 1018–1031, Dec. 2005, doi: 10.1175/JHM448.1.
[88] V. Maggioni and C. Massari, “On the performance of satellite precipitation products in riverine flood modeling: A review,” *Journal of Hydrology*, vol. 558, pp. 214–224, Mar. 2018, doi: 10.1016/j.jhydrol.2018.01.039.
[89] L. A. Rasmussen and L. M. Andreassen, “Seasonal mass-balance gradients in Norway,” *Journal of Glaciology*, vol. 51, no. 175, pp. 601–606, ed 2005, doi: 10.3189/172756505781828990.
[90] M. Hughes, A. Hall, and R. G. Fovell, “Blocking in Areas of Complex Topography, and Its Influence on Rainfall Distribution,” *Journal of the Atmospheric Sciences*, vol. 66, no. 2, pp. 508–518, Feb. 2009, doi: 10.1175/2008JAS2689.1.
[91] L. R. Leung and S. J. Ghan, “Parameterizing Subgrid Orographic Precipitation and Surface Cover in Climate Models,” *Monthly Weather Review*, vol. 126, no. 12, pp. 3271–3291, Dec. 1998, doi: 10.1175/1520-0493(1998)126<3271:PSOPAS>2.0.CO;2.
[92] M. Stieglitz, A. Ducharne, R. Koster, and M. Suarez, “The Impact of Detailed Snow Physics on the Simulation of Snow Cover and Subsurface Thermodynamics at Continental Scales,” *J. Hydrometeor.*, vol. 2, no. 3, pp. 228–242, Jun. 2001, doi: 10.1175/1525-7541(2001)002<0228:TIODSP>2.0.CO;2.
[93] R. I. Cullather, S. M. J. Nowicki, B. Zhao, and M. J. Suarez, “Evaluation of the Surface Representation of the Greenland Ice Sheet in a General Circulation Model,” *Journal of Climate*, vol. 27, no. 13, pp. 4835–4856, Jul. 2014, doi: 10.1175/JCLI-D-13-00635.1.
[94] B. Thrasher, W. Wang, A. Michaelis, F. Melton, T. Lee, and R. Nemani, “NASA Global Daily Downscaled Projections, CMIP6,” *Sci Data*, vol. 9, p. 262, Jun. 2022, doi: 10.1038/s41597-022-01393-4.
[95] D. Maraun *et al.*, “Precipitation downscaling under climate change: Recent developments to bridge the gap between dynamical models and the end user,” *Reviews of Geophysics*, vol. 48, no. 3, 2010, doi: 10.1029/2009RG000314.
[96] L. Mudryk *et al.*, “Historical Northern Hemisphere snow cover trends and projected changes in the CMIP6 multi-model ensemble,” *The Cryosphere*, vol. 14, no. 7, pp. 2495–2514, Jul. 2020, doi: 10.5194/tc-14-2495-2020.
[97] E. Scoccimarro and S. Gualdi, “Heavy Daily Precipitation Events in the CMIP6 Worst-Case Scenario: Projected Twenty-First-Century Changes,” *Journal of Climate*, vol. 33, no. 17, pp. 7631–7642, Sep. 2020, doi: 10.1175/JCLI-D-19-0940.1.

[98] A. Aschwanden, M. A. Fahnestock, and M. Truffer, "Complex Greenland outlet glacier flow captured," *Nat Commun*, vol. 7, no. 1, p. 10524, Feb. 2016, doi: 10.1038/ncomms10524.
[99] E. Welty *et al.*, "Worldwide version-controlled database of glacier thickness observations," *Earth Syst. Sci. Data*, vol. 12, no. 4, pp. 3039–3055, Nov. 2020, doi: 10.5194/essd-12-3039-2020.
[100] D. Farinotti *et al.*, "How accurate are estimates of glacier ice thickness? Results from ITMIX, the Ice Thickness Models Intercomparison eXperiment," *The Cryosphere*, vol. 11, no. 2, pp. 949–970, Apr. 2017, doi: 10.5194/tc-11-949-2017.
[101] D. J. Brinkerhoff, A. Aschwanden, and M. Truffer, "Bayesian Inference of Subglacial Topography Using Mass Conservation," *Front. Earth Sci.*, vol. 4, Feb. 2016, doi: 10.3389/feart.2016.00008.
[102] M. A. Werder, M. Huss, F. Paul, A. Dehecq, and D. Farinotti, "A Bayesian ice thickness estimation model for large-scale applications," *Journal of Glaciology*, vol. 66, no. 255, pp. 137–152, Feb. 2020, doi: 10.1017/jog.2019.93.
[103] A. Aschwanden, C. Khroulev, and E. Bueler, "The parallel ice sheet model (PISM) as a flow-line model," vol. 2010, pp. C21C-0546, Dec. 2010.
[104] A. A. Arendt, K. A. Echelmeyer, W. D. Harrison, C. S. Lingle, and V. B. Valentine, "Rapid Wastage of Alaska Glaciers and Their Contribution to Rising Sea Level," *Science*, vol. 297, no. 5580, pp. 382–386, Jul. 2002, doi: 10.1126/science.1072497.
[105] F. Maussion *et al.*, "The Open Global Glacier Model (OGGM) v1.1," *Geoscientific Model Development*, vol. 12, no. 3, pp. 909–931, Mar. 2019, doi: 10.5194/gmd-12-909-2019.