

DATA ARTICLE OPEN ACCESS

Multi-Year Glaciological and Meteorological Observations on Debris-Covered Kennicott Glacier, Alaska, 2016–2023

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ABSTRACT

Despite increasing availability of satellite-derived products, in situ glacier observations are pivotal to accurately monitor glacier change and to calibrate and validate glacier models. However, comprehensive multi-variable field observations are especially rare on large glaciers and on debris-covered glaciers. Here we present extensive field observations from Kennicott Glacier, a heavily debris-covered glacier in central Alaska covering more than 400 km². The multi-year data set includes point glacier mass balances, meteorological data from several weather stations on and off the glacier, debris thickness and temperature, ice cliff back wasting derived from time-lapse photography of horizontal stakes drilled into several cliffs, and bathymetry, water temperature, and water level of proglacial and supraglacial lakes. Cumulated summer melt of more than 8 m was observed at the lowest clean-ice sites. Melt rates over clean ice correlate well with elevation, while the rates over debris-covered ice lack any strong elevation dependence. Melt rates drop exponentially with increasing debris thickness and tend to be much lower than for clean ice at similar elevations. Melt rates determined for ice cliffs in areas of otherwise continuous debris cover were up to 10× those for debris-covered ice, and even exceeded standard clean ice melt rates. Debris-cover thickness measurements at 150 sites vary from <1 to 69 cm with an average of 17 ± 11 cm ($\pm$ standard deviation). Debris thickens down-glacier, but with high spatial variability—thickness was observed to vary by tens of cm within a ~15 m radius. Depth-averaged thermal heat conductivity derived from supraglacial debris temperature profiles at 12 sites ranges from 0.53 to 1.86 W m⁻¹ K⁻¹. Interconnected proglacial lakes covered 1.61 km² in 2018 with observed water depths of more than 60 m in the two largest lakes. The dataset can be downloaded at <https://doi.org/10.5281/zenodo.14625691> (Petersen, Hock, Loso, Guo, et al., 2024) and will be useful for glaciological and glacier meteorological studies.

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1 | Dataset

The dataset is available in a public online repository at Zenodo, DOI <https://doi.org/10.5281/zenodo.14625691>. Link to download at <https://doi.org/10.5281/zenodo.14625691> (Petersen, Hock, Loso, Guo, et al. 2024). Correspondence regarding the dataset should be directed to the corresponding author, Eric Petersen.

2 | Introduction

The roughly 275,000 glaciers outside the ice sheets of Greenland and Antarctica, collectively covering an area of ~482,830 km² (RGI Consortium 2023), have undergone a widespread and globally largely coherent trend of mass loss, thinning, and retreat in recent decades (Hugonnet et al. 2021) concurrent with atmospheric warming. These changes have major implications on global sea-level change, downglacier hydrology, hazards, and landscape evolution (IPCC 2022). Thus, a robust understanding of glacier mass changes is critical to make reliable projections of future glacier evolution and its impacts and to adapt to these changes.

While new remote sensing techniques and sensors have revolutionised our ability to observe the state and changes of glaciers on a global scale (e.g., Millan et al. (2022); Hugonnet et al. (2021)), direct in situ observations remain pivotal for ground-truthing remote sensing data, enhancing the understanding of glacier processes as well as calibrating and evaluating glacier models. Yet in situ monitoring programs are scarce and, in some cases, have even been discontinued in recent years (Gärtner-Roer et al. 2023). Moreover, for logistical reasons, in situ monitoring programs tend to target smaller glaciers in the mid-latitudes, although glaciers greater than 100 km² (less than 0.4% of the global glacier population) make up more than 55% of global glacier area with larger ice masses concentrated at higher latitudes. Thus, many highly glacierized high-latitude regions are undersampled.

This scarcity of in situ observations is particularly problematic in Alaska, one of the largest regional contributors to the global sea-level contribution from glaciers (Hugonnet et al. 2021). There are more than 27,500 glaciers in Alaska (including neighbouring glaciers in Canada) covering an area of 86,000 km² (circa 2010, RGI Consortium (2023)). Multiple regional-scale mass change assessments have been performed for all Alaska (e.g., Arendt et al. 2002; Hugonnet et al. 2021; Berthier et al. 2010) or selected subregions (e.g., Das et al. 2014; Geck et al. 2013; Melkonian et al. 2014; Yang et al. 2020; VanLooy et al. 2006) relying entirely on remote sensing analyses, however, multi-year in situ monitoring programs are scarce. Long-term glacier mass-balance programs have been maintained on two benchmark glaciers, Gulkana Glacier (17.6 km²) and Wolverine Glacier (16.5 km²), since 1966 by the United States Geological Service (van Beusekom et al. 2010; Cox and March 2004; O'Neel et al. 2019), including meteorological and geodetic volume change observations. The longest annual surface mass balance records going back to 1946 are from Lemon Creek Glacier (~12 km²) and Taku Glacier (~671 km²), collected by the Juneau Icefield Research Program (Pelto et al. 2013; McNeil et al. 2020).

A number of additional glaciers have been monitored for mass change as part of short-term targeted research projects, but typically data collection only spanned over a few years (e.g., Trüssel et al. 2013; Sass et al. 2017; Young et al. 2018; Nolan et al. 2005; Bliss et al. 2020). In addition, Alaska is one of the regions with the highest portion of supraglacial debris cover globally (8.6%–14.3% of glacier area compared to 4.4%–7.3% globally for glaciers outside the ice sheets (Scherler et al. 2018; Herreid and Pellicciotti 2020)); however, existing monitoring programs and measurements have mostly been conducted on clean-ice glaciers (Gärtner-Roer et al. 2023), exacerbating the paucity of in situ observations for debris-covered glaciers in particular.

Supraglacial debris strongly modulates glacier melt as a function of its thickness; this effect is described by the Østrem curve (Østrem 1959). Thin debris cover produces increased melt relative to a bare ice surface, but sufficiently thick debris (on the order of a few centimetres) reduces melt significantly in a non-linear fashion—the exact shape of the curve being dependent upon debris properties and local climatic conditions (Østrem 1959; Khodakov 1972; Dolgushin 1972; Bozhinskiy et al. 1986; Mattson et al. 1993). Debris-covered glaciers develop a continuous debris cover across much of their ablation zone (Cogley et al. 2011), with debris thick enough to significantly reduce ablation and produce a stagnant tongue of ice with a delayed response to climatic forcing (Benn et al. 2012; Bolch et al. 2012; Mölg et al. 2020; Anderson and Anderson 2016).

Meanwhile, melt hot spots such as ice cliffs and supraglacial ponds contribute significantly to melt on otherwise debris covered glacier surfaces (Sakai et al. 2002; Buri et al. 2021; Anderson, Armstrong, Anderson, and Buri 2021). Miles et al. (2022) measured melt rates on ice cliffs 2–3× melt rates on clean glacier ice under similar conditions. As a result, ice cliffs covering ~10% of a debris-covered glacier tongue contribute ~20%–25% of the melt over the same area. This holds for observations in Alaska (Anderson, Armstrong, Anderson, and Buri (2021): 12% coverage, 26% melt rates on Kennicott Glacier) and Nepal (Brun et al. (2018), 7%–8% area coverage, 24% ± 5% melt rates on Changri Nup Glacier). Ice cliff melt is also significant on glacier and catchment-wide scales; Buri et al. (2021) found in a modelling study that ice cliffs account for 17% ± 4% of total glacier melt across the Langtang Glacier catchment.

As distributed glacier melt models seek to more accurately capture the effects of supraglacial debris cover (Rounce et al. 2015; Steiner et al. 2018; Miles et al. 2017; Fyffe et al. 2014; Carenzo et al. 2016; Collier et al. 2014; Reid et al. 2012; Nicholson and Benn 2012) and melt hot spots such as ice cliffs (Kneib et al. 2023; Buri et al. 2016; Steiner et al. 2015; Reid and Brock 2014), in situ observations will be needed to guide, constrain, and calibrate those models.

In this paper, we report multi-year glaciological, meteorological, and other related observations from Kennicott Glacier, a large heavily debris-covered glacier in central Alaska. Comprehensive data were collected as part of long-term monitoring programmes by the National Park Service (started by the NPS Inventory and Monitoring Program's Central Alaska Network in 2016) and the Chinese Academy of Sciences (started in 2018) as well as a targeted research project by the University of Alaska Fairbanks (2020 through 2023). The

overall common goal of these efforts is to enhance understanding of the mass changes of a large debris-covered glacier in Alaska and also to investigate the impact of debris cover on mass change. Observations include point glacier mass balances at 28 sites, ice-cliff back wasting observations based on horizontally drilled ablation stakes and time-lapse imagery, debris thickness measurements at 150 sites and debris temperature profiles at 12 sites, meteorological variables at several stations on and off the glacier including from a full energy balance station on debris-covered ice, proglacial lake extent, bathymetry, and water level fluctuations as well as an updated glacier outline for 2018. We also derive relationships between melt rate and debris thickness and calculate thermal diffusivities and conductivities for several debris-covered locations.

3 | Study Site

Kennicott Glacier is a 43 km long valley glacier located in Wrangell-St. Elias National Park, south-central Alaska (Figure 1; 61.58°N, 143.04°W; GLIMS Glacier ID G216957E61573N (RGI Consortium 2023)). The glacier (~400 km², including its tributaries Gates, Root and LaChapelle glaciers) is part of the >4700 km² ice complex straddling the volcanic massif of the Wrangell Mountains. The glacier's main trunk flows from the southern flank of Mount Blackburn at 4996 m a.s.l. to its terminus at ~450 m a.s.l. (RGI Consortium 2023). Modelled estimates of mean thickness are slightly above 200 m (Farinotti et al. 2019; Millan et al. 2022) and recent radar-derived measurements show thicknesses up to 600 m in the most downstream 12 km portion of the glacier (Wells et al. 2025). The glacier terminates into an expanding proglacial lake but an active calving front is lacking. The glacier dams several ice-marginal lakes including Hidden Creek Lake which drains catastrophically beneath the glacier each year (Anderson et al. 2005; Anderson, Walder, et al. 2003).

Nine medial moraines grow and merge downglacier, causing the formation of a continuous supraglacial debris layer ~7 km from the terminus. Debris covers ~20% (as of 2015) of the glacier surface (Anderson, Armstrong, Anderson, and Buri 2021) including largely metamorphosed basalt and andesite, marine limestones, and sedimentary deposits (MacKevett 1978). Much of the debris-covered portion of the glacier is characterised by a chaotic hummocky surface with hummocks reaching several tens of meter in elevation, numerous dynamic surface ponds and abundant ice cliffs. Ice cliffs covered 12% of the glacier's terminus region (lowermost 8.5 km) and were responsible for 26% of estimated melt over the debris-covered tongue in summer 2011 (Anderson, Armstrong, Anderson, and Buri 2021).

The glacier reached the latest maximum extent between 1860 and 1909 followed by steady retreat at an average rate of 7 m a⁻¹ between 1909 and 1995 (Rickman and Rosenkrans 1997). Based on repeat altimetry derived elevation changes Das et al. (2014) found an average mass-balance rate of -0.21 ± 0.06 m w.e. a⁻¹ over the period 1957–2007, and a 2.5× more negative rate for 2000–2007 revealing a substantial increase in mass wastage. The equilibrium-line altitude is at about 1500 m a.s.l. (Armstrong et al. 2017). Located ~150 km from the Gulf of Alaska and shielded by the more than ~2000 m a.s.l. Chugach

Mountain Range, climatologically, the area lies between the wet coastal region and the continental interior of Alaska (Anderson, Longacre, and Kraal 2003).

Owing to relatively easy access, Kennicott Glacier has been subject to numerous scientific investigations focused in particular on the interplay between glacier outburst floods, glacial hydrology, and ice dynamics. Several studies have focused on the Hidden Creek Lake outburst floods and their impact on ice dynamics (Rickman and Rosenkrans 1997; Anderson et al. 2005; Armstrong et al. 2016; Bartholomaeus et al. 2008, 2011; Brinkerhoff et al. 2016; Armstrong and Anderson 2020; Anderson, Walder, et al. 2003; Anderson, Longacre, and Kraal 2003). Some studies have investigated the glacier's debris cover and its impact on glacier mass balance and thinning (Anderson, Armstrong, Anderson, and Buri 2021; Anderson, Armstrong, Anderson, Scherler, and Petersen 2021; Petersen et al. 2022; Petersen, Hock, and Loso 2024).

4 | Glacier and Proglacial Lake Outlines

We created new outlines of the Kennicott Glacier and of several interconnected proglacial lakes at the glacier terminus. Both the glacier and the lake outlines were created through manual digitising of feature boundaries visible on cloud-free Maxar Worldview-1 panchromatic satellite image collected on 12 September 2018. The image has 0.5 m spatial resolution and we typically digitised at a scale of 1:500. Uncertainties in glacier mapping projects can be categorised as resulting from glaciological misinterpretation, digitising errors, and georeferencing errors. Based on the authors' direct and extensive field experience in the Kennicott Valley, we suggest that the uncertainties in our new glacier and proglacial lake outlines are dominated by the latter two items. We follow Fountain et al. (2023) in assuming that georeferencing errors would primarily affect the location of the outlines rather than total areas, and that digitising errors add uncertainties of up to 1% to our calculated glacier and lake areas (Fountain et al. 2023).

Our work updates and improves the existing Kennicott glacier outlines in RGI 7.0 (RGI Consortium 2023) which are the same as in version 6.0 (RGI Consortium 2017). The RGI splits the Kennicott glacier complex into two discrete entities: Kennicott Glacier (RGI2000-v7.0-G-01-05740) and its major tributary, Root Glacier (RGI2000-v7.0-G-01-05749). Those RGI outlines were derived from Landsat 7 ETM+ satellite imagery collected 29 July–7 August 2008 with a 15 m spatial resolution (Loso et al. 2014), and erroneously include a substantial amount of ice-free terrain southeast of the glacier terminus (Figure 2). Because we exclude that ice-free terrain, and also because the true glacier boundary shrank between 2010 and 2018, our estimate of glacier area for 2018 (384.7 km²) is only 97.4% as large as the combined RGI glacier area from 2008.

We include in our lake polygon the boundaries of all lakes that share a subaerial or inferred subglacial hydraulic connection—this was determined by identifying a common lake surface elevation in a photogrammetry-derived digital terrain model acquired September 2018 (presented in Petersen, Hock, and Loso (2024))—but exclude isolated supraglacial lakes perched on the glacier surface further upvalley. The total digitised area of

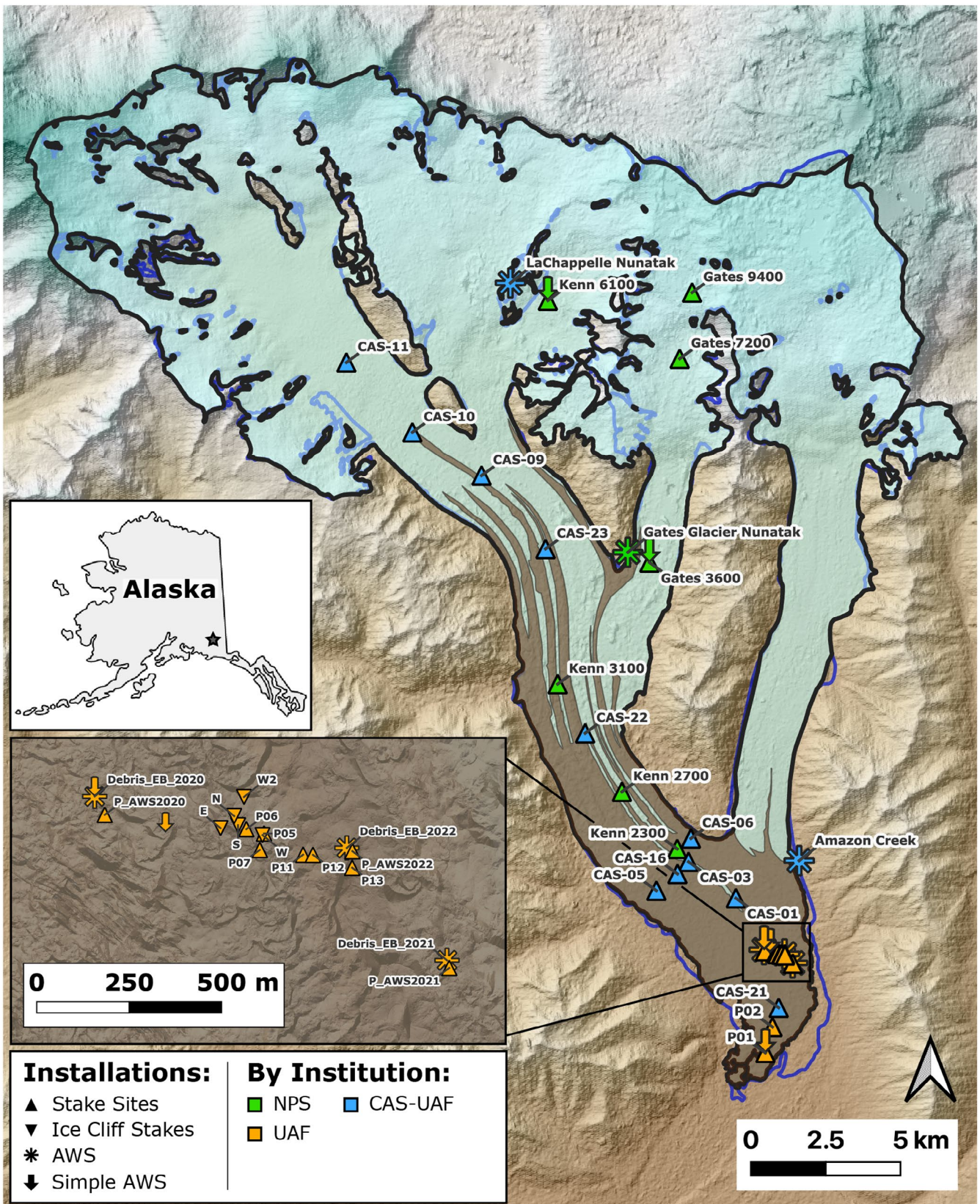


FIGURE 1 | Map of Kennicott Glacier with locations of ablation stake sites, automatic weather stations (AWS), and simple AWS (air temperature/relative humidity only). RGI 7.0 outline from 2008 is mapped with blue outline; updated 2018 glacier outline is shown with a black border (Section 4). Debris-covered area is marked in brown. 200m elevation contours are mapped over a hillshade rendered from 30m resolution ASTER DEM. Insets show location of Kennicott Glacier in Alaska as well as detail of a set of installations on the debris cover. The background images are composed of a 30m ASTER DEM hillshade and an 2019 orthophoto obtained by the National Park Service (inset).

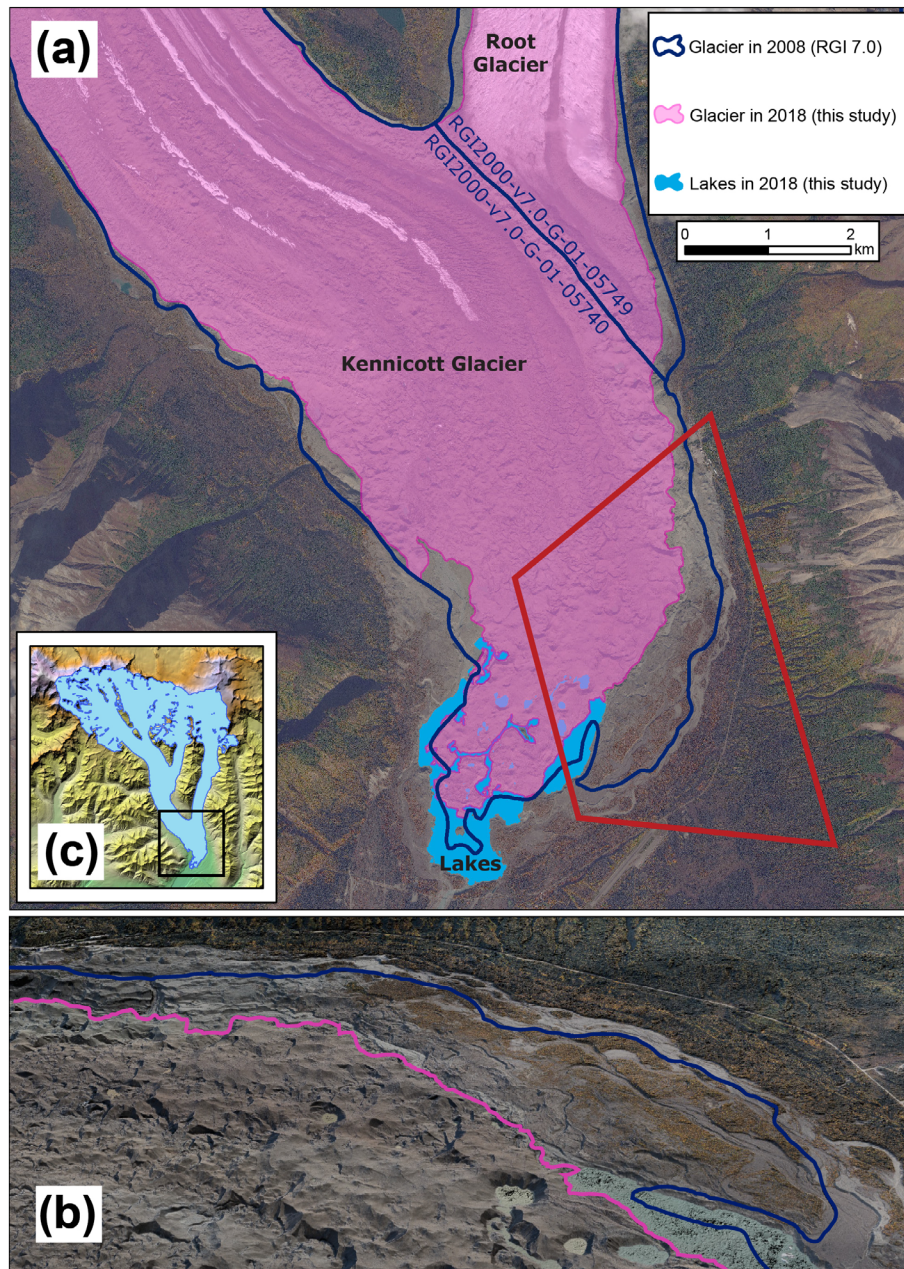


FIGURE 2 | (a) Comparison of Randolph Glacier Inventory (RGI 7.0) outline from 2008 and this paper's new 2018 glacier outline for the lower reaches of Kennicott Glacier and its tributary Root Glacier. Also shown are outlines of proglacial and large hydraulically-connected supraglacial lakes at terminus from 2018. Background is true colour Worldview satellite image from 17 September 2017. (b) Oblique view of the eastern portion of the glacier terminus generated from a DEM and orthophoto collected on 13 September 2018. Approximate ground coverage of the view in (b) is outlined in red in (a), emphasising the non-glacierized terrain erroneously included in the RGI 7.0 glacier boundary. (c) Overview of Kennicott Glacier with location of panel (a).

these interconnected proglacial lakes is 1.61 km², of which the large eastern lake comprises 0.34 km² and the large southwestern lake comprises 0.76 km².

5 | Meteorological Measurements

5.1 | Overview

We compile data here from eleven automatic weather stations (AWSs) operated by four different institutions (Table 1,

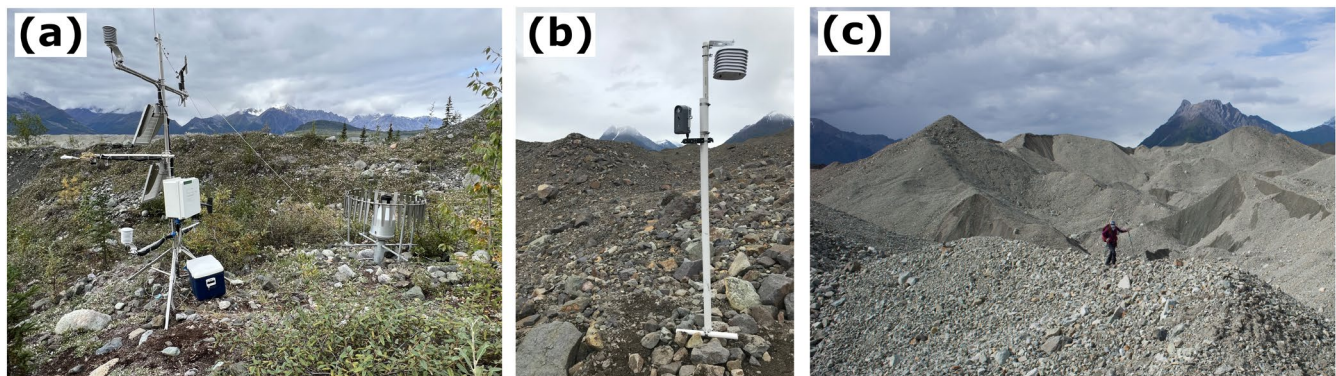
Figure 3). Eight stations are located on the glacier, while three are located close to the glacier margin (within less than 500 m). Elevations range from 585 to 2200 m a.s.l. A full energy-balance AWS (including temperature/relative humidity, windspeed, air pressure, short wave and long wave radiation) was operated on the debris-covered glacier tongue during the melt seasons 2020 to 2022, representing the first published meteorological record over debris-covered ice in Alaska. Three additional stations over debris measured air temperature and humidity, and two AWS at higher elevations over clean ice recorded air temperature only (Figure 3c). Measured variables of all stations are listed

TABLE 1 | Summary of meteorological stations for which data are presented in this paper.

Station	Latitude°	Longitude°	Elev. m a.s.l.	Institution	Locale	Variables
<i>Off-glacier stations</i>						
LaChappelle Nunatak	61.68302	−143.08995	2200	CAS/UAF	Bare ground	T, RH, u, p
Gates Glacier Nunatak	61.60280	−143.01310	1238	NPS	Bare ground	T, RH, u, SW↓, p, Prec, SD
Amazon Creek	61.51100	−142.90250	682	CAS/UAF	Vegetated ground	T, RH, u, SW↓, SW↑, LW, p, Prec
<i>On-glacier stations</i>						
Kenn6100_T	61.6779	−143.0661	1835	NPS	Clean ice	T
Gates3600_T	61.5998	−142.9994	1078	NPS	Clean ice	T
Debris_EB_2020	61.48414	−142.92372	585	UAF	Debris-covered ice	T, RH, SW↓, SW↑, LW, p
Debris_EB_2021	61.48029	−142.90572	546	UAF	Debris-covered ice	T, RH, u, SW↓, SW↑, LW, p, Debris ^a
Debris_EB_2022	61.48298	−142.91088	559	UAF	Debris-covered ice	T, RH, u, SW↓, SW↑, LW, p, Debris ^a
Debris_T1	61.4532	−142.92200	418	UAF	Debris-covered ice	T, RH
Debris_T2	61.4833	−142.92010	574	UAF	Debris-covered ice	T, RH
Debris_T3	61.48414	−142.92372	585	UAF	Debris-covered ice	T, RH

Abbreviations: CAS, Chinese Academy of Sciences; *Debris*, refers to debris properties; LW, longwave incoming and outgoing radiation; NPS, National Park Service; p, air pressure; Prec, precipitation; RH, relative humidity; SD, snow depth; SW↓ and SW↑, incoming and reflected shortwave radiation, respectively; T, near-surface air temperature; u, wind speed and direction; UAF, University of Alaska Fairbanks.

^aDebris heat flux (2021 and 2022) and debris temperatures and moisture content (2022).

**FIGURE 3** | Photos of weather stations: (a) Energy-balance station “Amazon Creek” located off-glacier, (b) example of on-glacier station with air temperature and humidity sensor only “Debris_T1”, and (c) an example of debris-covered glacier surface with rough, hummocky terrain.

in Table 1 and periods of operation/available data are shown in Figure 4.

Sensor types and heights varied between stations and are detailed in each station's metadata. All stations recorded at least hourly data. Stations were typically visited twice a year when the mass-balance measurements were also performed. Data gaps occurred at most stations due to power loss and sensor malfunctioning.

The on-glacier energy balance AWS was operated in the debris-covered terminus region, being installed at the beginning and

dismantled at the end of each summer. Great care was taken to select locations with relatively flat local topography and consistent debris thickness to reduce local destabilisation via differential melt. This helped to keep the mast upright and relatively vertical, with sensors at a consistent height above the debris surface. Tilt meters installed on the radiometer provided real-time measurement of the deviations from vertical. These were not used to correct the data presented, but are provided with the data for reference and future use. The station tilted to a maximum of 16° from vertical in 2021; typical deviations are 10° or less. During mid-season visits, the station was righted to vertical. The mast footing was also stabilised by strategic rock placement to withstand high

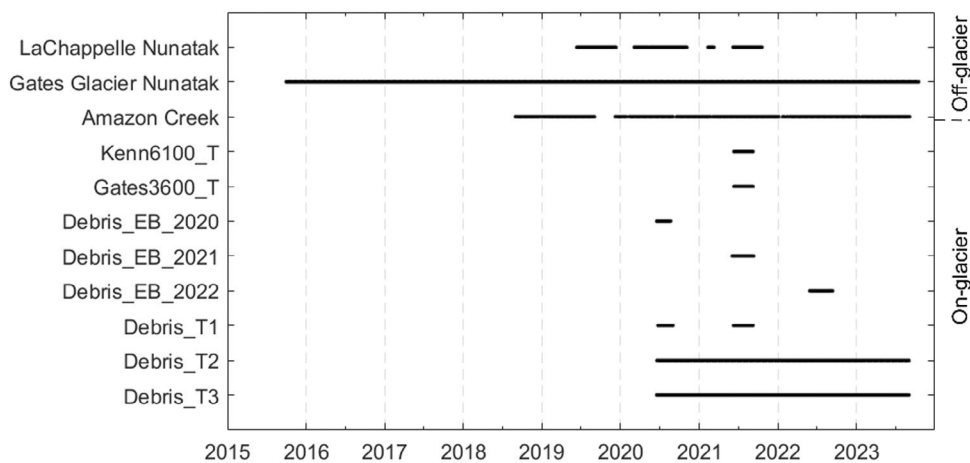


FIGURE 4 | Periods of available data for at least one meteorological variable for 11 automatic weather stations in the study area (Table 1).

winds. The debris surface was snow-free throughout the period of operation. The simple debris AWSs (Debris_T1, Debris_T2, Debris_T3) consisted of sensors in radiation shields mounted to a pipe installed loosely around an inner mast drilled into the ice (Figure 3b). In this design, the pipe sheathing slides down the static inner mast as the ice surface melts and deflates, thus ensuring that sensor height remains constant.

All meteorological data were carefully quality-controlled and physically implausible values were removed or corrected as described below. The most notable correction involved records when reflective short-wave radiation exceeded shortwave incoming radiation—these occurred during the subarctic night when solar angle was low and absolute shortwave radiation values were close to zero. For these values, reflected shortwave radiation was adjusted using an albedo calculated from daytime values. Data were also removed in cases when data or field observations indicated that the mast had fallen over.

The time series of the on-glacier debris stations and the station with the longest continuous record (Gates Glacier Nunatak) is shown in Figures 5 and 6, respectively (See Appendix for other stations).

5.2 | Off-Glacier to On-Glacier Air Temperature Extrapolation and Lapse Rates

Two of the off-glacier stations are located on nunataks: the Gates Glacier Nunatak station (Sousanes et al. 2023), and the higher elevation LaChappelle Nunatak station. To compare temperatures at these stations with on-glacier temperatures relevant to melt modelling, we measured air temperatures at 2 m above the glacier surface using radiation-shielded sensors at two glacier stakes (Gates 3600 and Kennicott 6100, so named after their respective approximate elevations in feet above sea level) adjacent to their respective nunatak weather stations during the 2021 melt season (11 June to 8 September). Gates 3600 and Kennicott 6100 are 160 m and 365 m lower than their respective adjacent off-glacier nunatak stations. Off-glacier temperatures were consistently higher than their on-ice counterparts on warm days, but as air temperatures dropped, they were closer to those on

the nearby glacier surface. We developed linear regressions to predict the on-ice temperatures from these observed relationships, and found that the Gates Glacier station provided the best prediction ($r^2 = 0.88$) of melt-season temperatures at its adjacent on-glacier site: Gates 3600 (Figure 7). For this reason, and because Gates 3600 is the longest-running and most consistently maintained AWS in the Kennicott Valley, we selected that station as our primary long-term air temperature record and used the linear regression

$$y = 0.57(x) + 1.78$$

to predict melt season on-glacier air temperatures at the adjacent on-glacier site (Gates 3600, 1078 m a.s.l.).

To determine the appropriate lapse rate for calculation of on-glacier temperatures at other clean ice locations on the middle and upper glacier, we compared the directly-measured air temperatures at Gates3600_T and Kenn6100_T over the entire 2021 melt season. The mean difference between those records was 2.83°C over an elevation range of 760 m, yielding a melt season clean ice lapse rate of 3.72°C km⁻¹. Direct concurrent measurements of air temperatures on the debris-covered lower glacier at AWS Debris 2021 suggest that a stronger lapse rate (yielding comparatively higher temperatures on the lower debris-covered glacier) provides the best reconstruction for debris-covered ice. From the reference on-glacier temperatures at Gates3600_T, we used a lapse rate of 4.86°C km⁻¹ to reconstruct air temperatures over the debris-covered portions of the glacier (see Figure 8). This value is lower than the free-air moist adiabatic lapse rate (approximately -6 to -7°C km⁻¹), primarily due to the cooling effects of a thermal boundary layer above the ice surface and the influence of katabatic winds (Marshall et al. 2007; Wheler et al. 2014).

6 | Glaciological Data

6.1 | Point Measurements of Mass Change

Glaciological monitoring programs by the National Park Service (NPS), Chinese Academy of Sciences (CAS), and University of Alaska Fairbanks (UAF) began in May 2016, August 2018, and

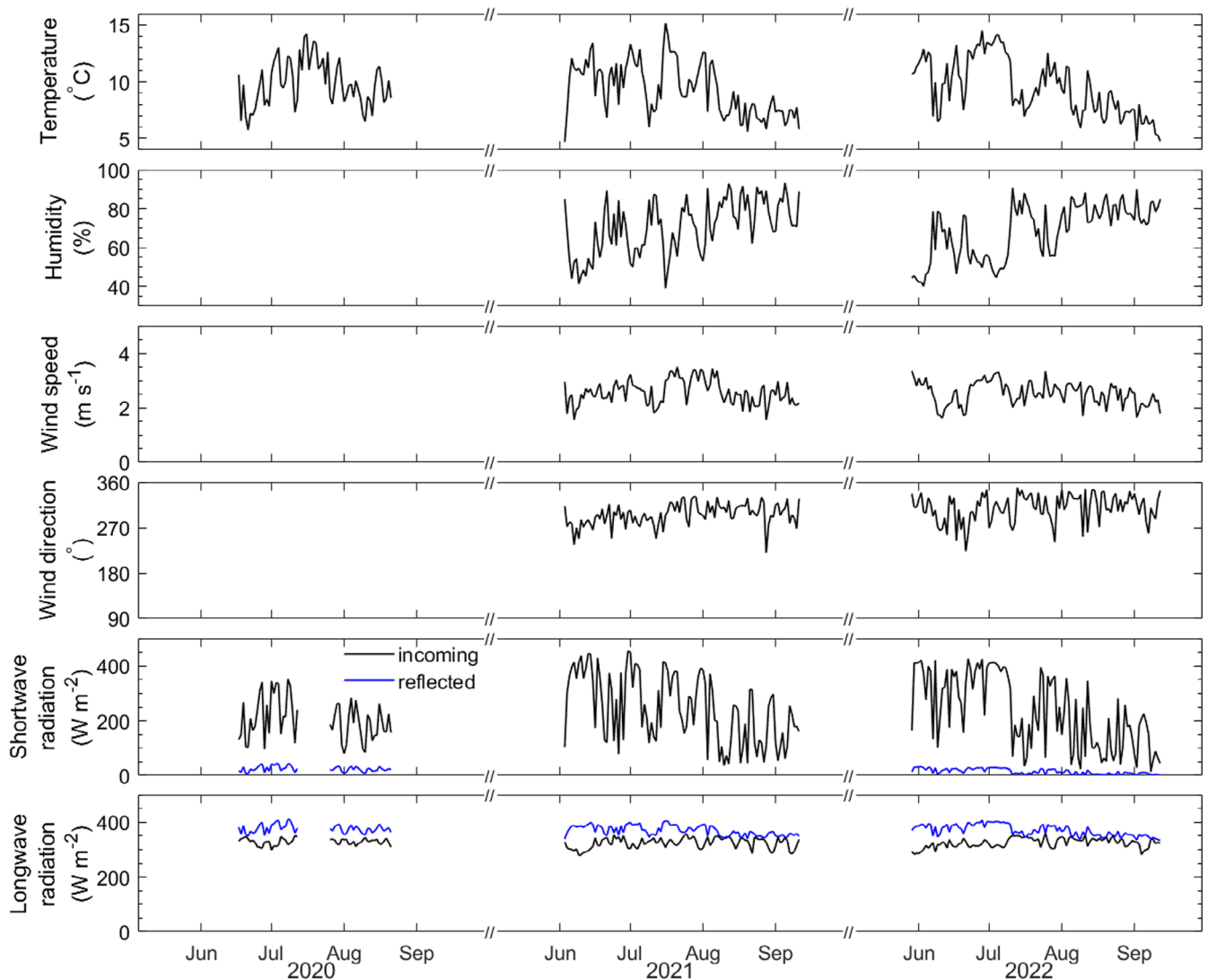


FIGURE 5 | Daily meteorological data from the AWS operated on debris during the melt seasons 2020–2022 (Debris_EB_2020, Debris_EB_2021, and Debris_EB_2022).

June 2020, respectively, with each continuing through August/September 2023. Glaciological measurements were conducted at a network of 5 to 27 sites (dependent on survey year) ranging in elevation from 417 to 2180 m a.s.l.

Sites include two located in the accumulation zone (although the lower of these two, ‘Kenn 6100’, is close enough to the equilibrium line altitude (ELA) to sometimes exhibit a negative annual balance), six located on bare ice, fifteen located on debris-covered ice, and four “twin” sites which each include one stake on bare ice and one stake on debris-covered ice within a few tens of metres.

Sites were visited for measurement 2 to 3 times per year, typically early (‘spring,’ May–June) and late (‘fall,’ August–September) in each melt season, with mid-season measurements (mid-July) made for a number of UAF/CAS stake sites during the 2020 to 2021 seasons. There is substantial variability in the timing of these measurements caused primarily by weather contingencies. In practice, spring measurements typically occur after the mass maximum for all sites, while fall measurements usually precede the mass minimum at lower elevation sites but are sometimes

after the mass minimum, especially at higher elevations. For this reason, point balances are reported here in the floating date system (Cogley et al. 2011) and do not correlate exactly to seasonal balances in the stratigraphic system.

Each measurement site is marked by an ablation stake that is drilled into the snow/firn/ice surface with a portable Heucke steam drill (Heucke 1999). Two different stake constructions were used. UAF and CAS-UAF stakes generally are constructed of 8 segments of 1.5 m long 0.5" diameter PVC segments strung together with paracord such that 12 m of stake material installed in the ice folds in place as it melts out. NPS program stakes and CAS-UAF stakes above 1100 m a.s.l. consist of thin-walled 1" aluminium conduit cut into 2–3 m segments. The bottom segment is fitted with a rubber stopper to prevent melt-subsidence of the stake, and segments are connected using steel or PVC pipe nipples with retaining rings. We typically drill and emplace a new stake at each site every spring or as needed, removing older stakes in the fall of the following year after they flow downstream for ~1.5 years. NPS stake locations are surveyed during every visit using a Trimble GeoXH receiver with external Zephyr antenna. Positions are later post-processed to yield reported errors < 15

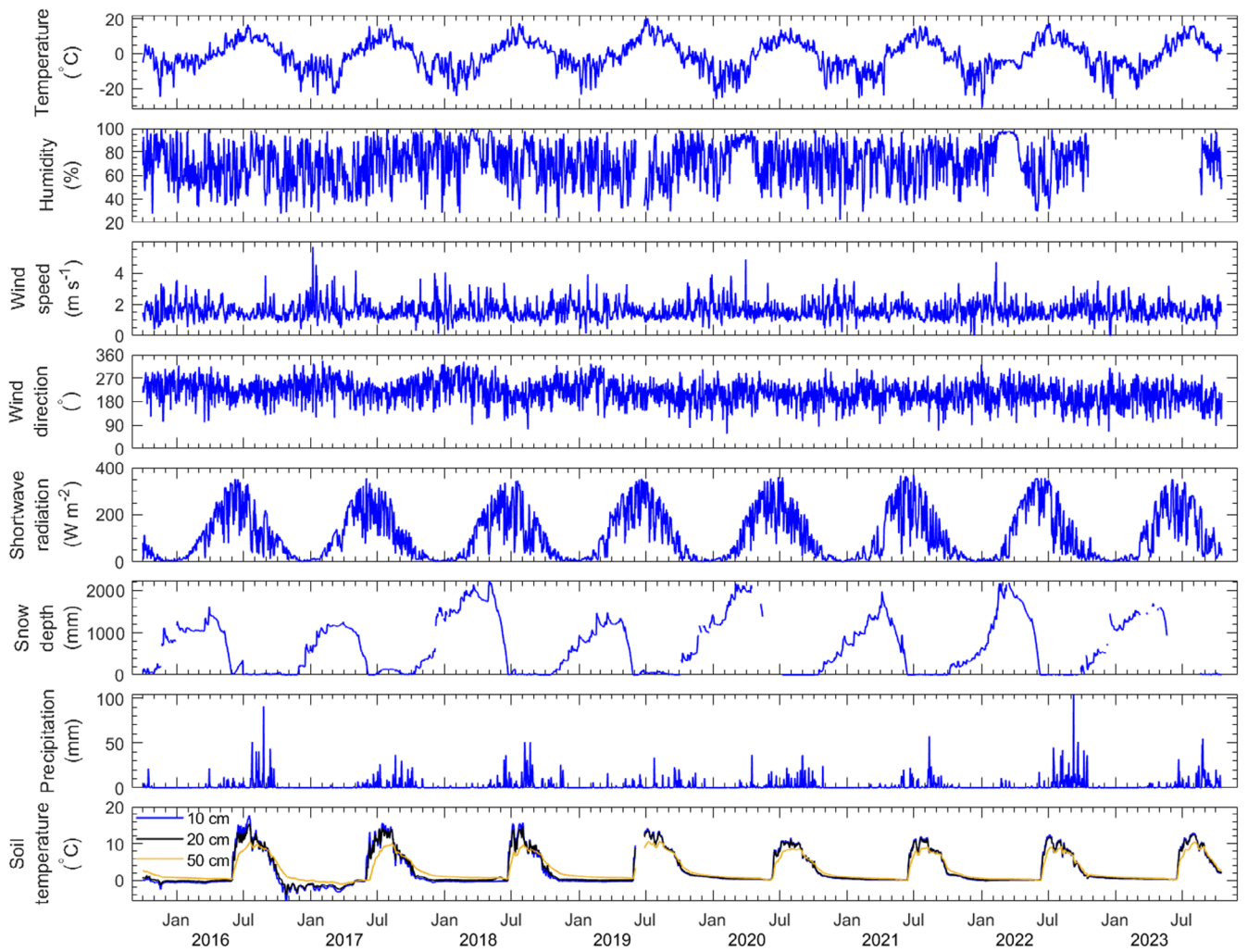


FIGURE 6 | Daily meteorological data from the automatic weather station Gates Glacier Nunatak.

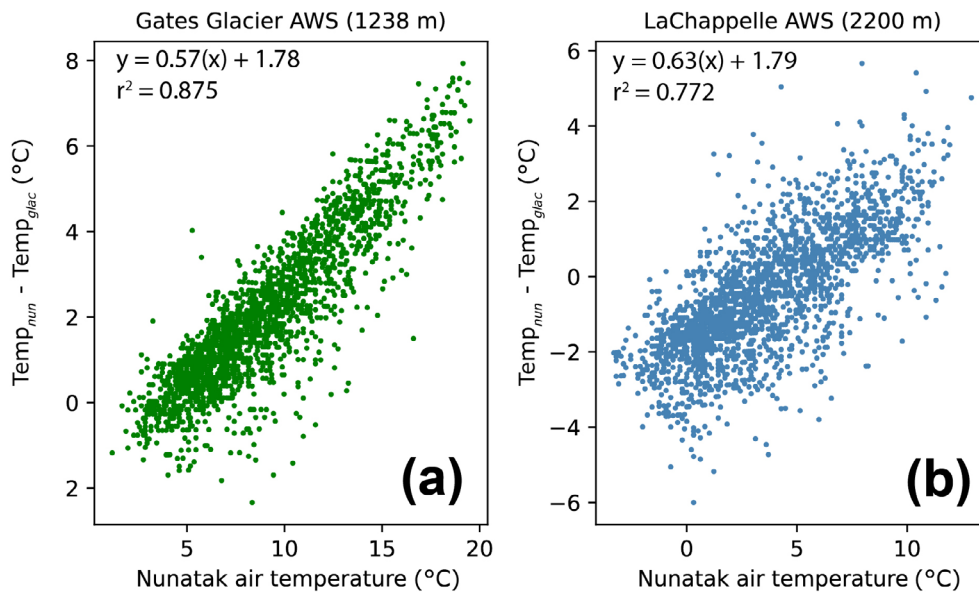


FIGURE 7 | Hourly air temperature differences between off-glacier ('nunatak', $Temp_{nun}$) and adjacent on-glacier sites ($Temp_{glac}$) during the 2021 melt season, plotted as functions of nunatak air temperatures. Panels show relationships between paired temperatures at the Gates Glacier and LaChappelle sites. In both cases, nunatak air temperatures are notably warmer than on-glacier temperatures during the warmest hours. Equations shown are not for the plotted temperature differences, but for the direct regressions of glacier temperatures against nunatak temperatures.

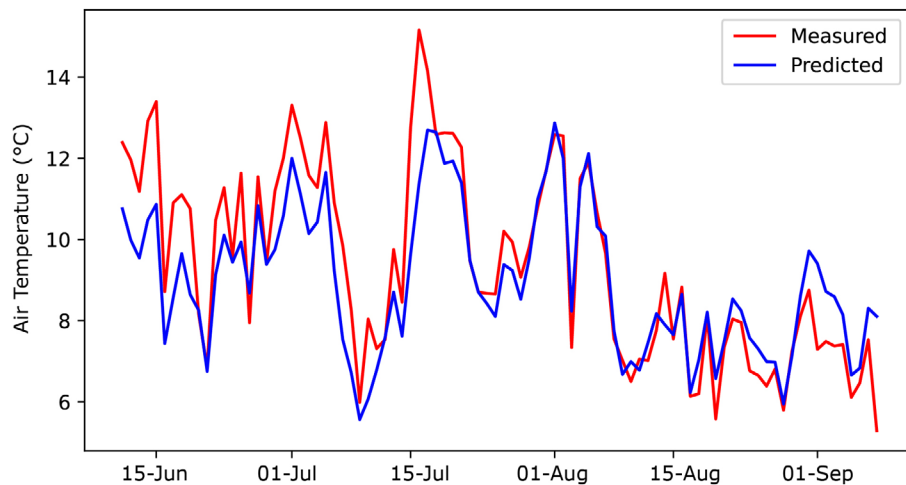


FIGURE 8 | Comparison of measured and predicted daily air temperatures at the Debris_EB_2021 site (Figure 1), a debris-covered portion of the lower glacier. The predicted temperatures are reconstructed from the predicted air temperatures at Gates 3600 using a lapse rate of $4.86^{\circ}\text{C km}^{-1}$. The predicted and measured temperatures have a correlation coefficient (r) of 0.88.

cm. CAS and CAS-UAF stake locations were surveyed using the waypoint averaging feature on a Garmin 64st, resulting in positioning error of ~ 3 m.

Exposed lengths of stakes were measured to the nearest centimetre to derive rates of local seasonal surface lowering or raising (independent of flow dynamics), and stake sections were added or removed at each visit as needed. Stake exposure is not corrected for typically modest amounts of lean, but in rare cases we have trigonometrically corrected elevation changes for stakes leaning > 15 degrees from vertical. At debris-covered sites, debris cover is first removed (see Section 8), the stake installed in the ice, and debris cover reconstructed as faithfully as possible. Debris thickness is measured using the installed ablation stake as reference. Great care is taken to choose relatively stable locations, indicated by flat local topography, low local debris thickness variability, and no nearby ice cliffs. In spite of this, ablation stakes may at times be affected by ice cliff back-wasting, or by shifting debris resulting in significant change in debris thickness over the measurement period. Stake measurements affected by ice cliff passage are discarded. Debris thickness at stake locations is periodically re-measured, typically at the end of melt seasons.

When seasonal snow (snow that fell since the end of the preceding summer) is present at a site, we measure snow depth (all sites) and density (NPS sites). Snow depths at CAS-UAF sites were measured to the nearest centimetre using an avalanche snow probe, taking five or more measurements within a ~ 5 m radius and reporting the average. Measurements at NPS sites were conducted in snow pits for snow depths < 1.5 m, and at greater depths we core the remaining snowpack using either a Kovacs Mark III corer or a FELICS corer. In all cases we dug/drilled at least to the interface with the previous summer surface, a horizon which is obvious when the snow overlays glacier ice but requires careful analysis when the snow overlies firn. In such cases the boundary is identified through a combination of measured densities, snow crystal changes, ice lenses and other stratigraphic markers, and the presence of dirt/dust. Densities in the snowpit wall are measured using a 1000cc wedge sampler

at the center of each layer, as stratified by the hardness hand test. Densities in cores are measured in one subsampled section per coring drive. All masses are measured with a Pesola 1000g spring scale. Where snow densities were not measured (CAS-UAF sites), a value of 500 kg m^{-3} was used for seasonal snow measured in late spring/early summer and 300 kg m^{-3} for summer snow accumulation measured in summer/fall, based on values typically observed where measured.

At each site, point balances presented in kg m^{-2} (equivalent to mm water equivalent) are derived from the measurements described above using a set of standard assumptions. When surface lowering includes loss of ice, we assume a material density of 900 kg m^{-3} for ice. When surface lowering consumes the entire seasonal snowpack measured during a previous visit, we calculate the loss as the cumulative mass of the entire snowpack plus any ice loss that has occurred. Where surface lowering has removed only part of the previously measured snowpack, we assume that some of that lowering is due to densification of the remaining snow and therefore calculate the mass loss as the difference between the total masses of the prior and present snowpack measurements. During fall measurements, newly fallen snow ('summer accumulation') is sometime present on the glacier surface and is easily distinguished from older snow/ice. We include this summer accumulation in our reported measurements of seasonal snow depth and average density, consistent with a floating date mass balance. We also separately report the depth and density of the summer accumulation for readers interested in the stratigraphic summer balance.

In a few cases at our highest elevation site—'Gates 7200' in the glacier accumulation zone—we did not have an overwintering stake measurement to directly determine the net change in the height of the glacier surface over the winter portion of the hydrologic year. In these cases, we only determine an annual balance using the fall measurements of the remaining snowpack, but we cannot confidently attribute a start date (in the floating point system) to this balance because we do not know the precise day in the previous fall on which the measured snowpack began accumulating. These cases are identified in the annual balance

table and do yield a robust estimate of the annual balance—they just cannot be attributed with a start date or duration.

6.2 | Spatio-Temporal Variability and Effect of Debris Cover

The derived summer and annual balances are plotted in Figure 9. For bare ice sites, there is a clear linear mass balance gradient as a function of elevation, with a tendency for a steeper gradient below roughly 1200 m a.s.l. than above. This trend is broken by debris cover, which significantly reduces melt rates, and a lack of any elevation dependency. Summer 2022 was a record melt year at many sites. Melt for summer 2020 is underrepresented at a number of NPS stakes due to the late spring measurement as a result of the COVID-19 pandemic.

We fit a simple exponential decay function to the melt rate vs. debris thickness data of the form:

$$b = b_0 e^{-H/H_0} \quad (1)$$

where b is the melt rate, b_0 is the melt rate at zero debris thickness, H is debris thickness, and H_0 is the scale thickness at which sub-debris melt falls to $1/e$ of bare ice melt rates (Anderson 2000). This equation fits reasonably well to our measurements, with $R^2 = 0.74$ for both annual and summer measurements (Figure 10).

At four stakes sites, designated as “twin” sites, we drilled one stake into debris-covered ice and another into bare ice within < 100 m of each other (stake sites CAS-01, CAS-03, CAS-22, CAS-23, Table 2). We found that melt rates over bare ice were sometimes higher and sometimes lower than those over debris with no clear relation to debris thickness (Figure 11). However, only few such comparisons are available and interpretation is not straightforward. Although less than 100 m apart the debris-covered sites typically differed in morphology (such as slope, aspect, topographic shading, elevation) from the generally flatter and less hummocky clean-ice sites. In addition to melt being extremely sensitive to debris thickness (Figure 10), debris thermal properties, clast size, and porosity likely has a strong impact especially for thin debris layers (Evatt et al. 2015; Petersen et al. 2022).

6.3 | Ice Cliff Back Wasting Observations

To monitor ice cliff back wasting we installed an ablation stakes horizontally into four ice cliffs per year between 2021 and 2023. The same cliffs were targeted each season, capturing as best as possible roughly the four cardinal directions in the ice cliffs' slope aspect. The ice cliff stake sites are thus named N, S, E, and W (although in practice they may differ from the cardinal directions by up to 32°). In 2023, ice cliff stake S was abandoned due to its reburial by debris, and a new west-facing ice cliff, W2, was monitored. All ice cliff sites were

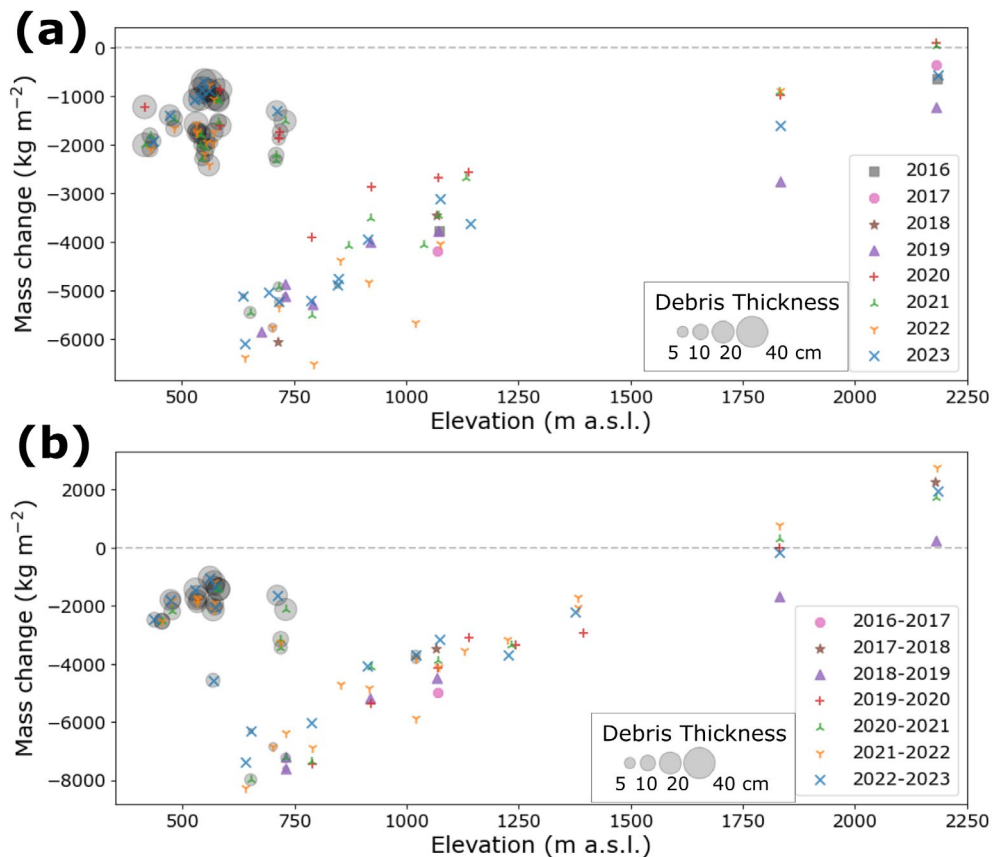


FIGURE 9 | Point mass balances at all stakes as a function of elevation for the mass-balance years 2016/2017 to 2022/2023 and (a) summer and (b) annual periods. Some of the variability is due to the different measurement periods. For example, in the 2020 summer season the ‘spring’ measurement was not taken until late June, resulting in underrepresented melt.

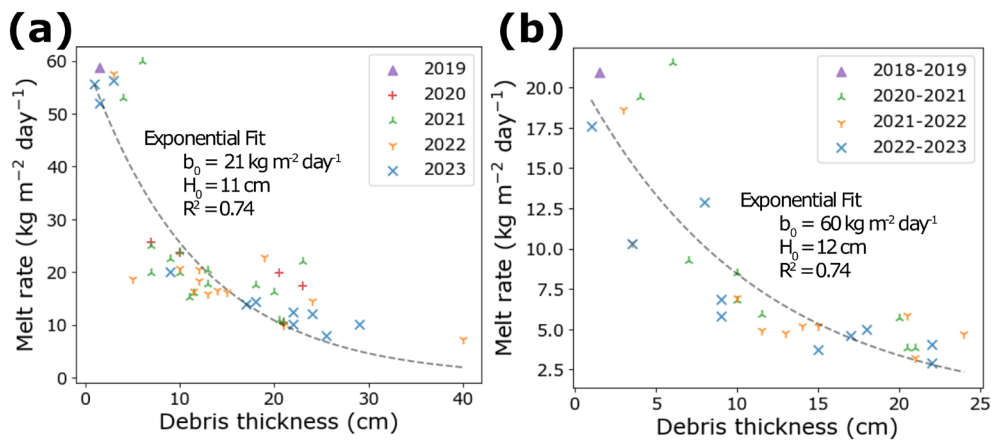


FIGURE 10 | Melt rate of ice below the debris as a function of debris thickness for (a) summer and (b) annual mass balance periods. A simple exponential decay function (Equation (1)) has been fit to the data. R^2 is the coefficient of determination.

within ~100–200 m of each other (Figure 1), in an area where supraglacial stream incision produced ice cliffs with many different slope aspects.

The stakes were drilled with a Heucke steam drill and the drill bit was typically inserted about 0.5 to 1 m above the bottom of the cliff while using a tiltmeter or bubble level to ensure level drilling (stake parallel to a flat ground surface). A compass was used to measure the slope aspect of the ice cliff and likewise confirm that the drill was inserted with the appropriate compass direction following the ice cliff slope aspect. Steady pressure was applied to the steam drill hose to maintain the angle, as a slow drilling speed could lead to increased melt orthogonal to drill direction and the drill bit angling downwards into the glacier. 12m ablation stakes (same PVC stake design as used for the point balance sites) were then installed in these horizontal boreholes and left to refreeze. Stakes were marked with electrical tape at 10cm intervals.

Ablation stakes were monitored with time lapse cameras placed nearby and programmed with 30 min image capture intervals. The time lapse cameras were installed on tripods floating on the glacier surface and were thus susceptible to destabilisation from the shifting surface debris. As a result, some cameras maintained their view of the stake through most of the summer season while others lost their view within a few weeks. The time lapse camera records were viewed and the timing of emergence of the 10 cm marks from the ice was recorded in order to constrain a near-real time record of ice cliff backwasting. The emergence timing was recorded when the entire strip of black tape marking the 10 cm marks was revealed; when poor lighting or camera angle makes it impossible to pinpoint exactly when a 10 cm mark emerged that mark is skipped in the record. Uncertainty on emergence timing is estimated at ± 1 h. Stake length emerged was also measured manually during field expeditions, and these measurements were also inserted into the record when the camera-derived record was not available. At times the ablation stake was not effectively frozen/set into the glacier ice due to draining of meltwater from the boreholes shortly after drilling. In these cases the stake was observed to slide rapidly and completely out of the borehole—an order of magnitude more rapidly than would be plausible due to melt rates; when this occurred the stake record was discarded. Due to the combination of this

effect as well as time lapse cameras toppling, some back wasting records are incomplete; the shortest time series spans 9 days and the longest roughly 3.5 months between the end of May and mid-September (Figure 12).

Figure 12 shows that the four ice cliffs with records exceeding three summer months backwasted a total of approximately 5–8 m. We corrected for slope to transform back wasting measurements to melt rates perpendicular to the ice cliff surface, and thus determined mean melt rates of between 4.6–14.9 cm d^{-1} or 41–134 $\text{kg m}^{-1} \text{ d}^{-1}$. This is ~2–10 $\times$ greater than melt rates measured over nearby debris-covered ice with a debris thickness of 2–25 cm (Figure 10), and exceeds the highest melt rates measured on clean or debris-covered ice. The monitored north-facing (NNW) ice cliff exhibited the lowest melt rates while the east-facing ice cliff exhibited the highest melt rates.

7 | Proglacial Lake Observations

7.1 | Lake Pressure Transducer Data

We measured water levels throughout summer 2021 in the west proglacial lake (409 m a.s.l.) as well as a supraglacial pond thought to be well connected with the glacial drainage system (428 m a.s.l.; Figure 13). Water levels were measured using an Onset Hobo U20L pressure transducer with a 10 m range and a reported uncertainty of 2 cm. The instrument also measured water temperature with a stated accuracy of $\pm 0.44^\circ\text{C}$. Data was logged at 60 min intervals. Water depths were calculated using air pressure measurements from the Amazon Creek AWS at 682 m a.s.l. assuming a standard lapse rate of 120 hPa km^{-1} (ISO 2533: 1975).

Both pressure transducers were installed by fixing the data logger to a wire, which was in turn anchored to a rock near the shoreline. The transducers were then tossed out several meters into the pond or lake. Both transducers were installed on 9 June 2021. The pond transducer was recovered on 8 September 2021, and the lake transducer was recovered on 31 May 2022 (the lake level was higher than the anchor rock on 8 September 2021, making recovery of the transducer not possible at that time).

TABLE 2 | Summary of mass balance measurement sites.

Site	Surface type	Elevation (m a.s.l.)	Institution	Initiation date (YYYY- MM-DD)	Retirement date (YYYY- MM-DD)	# Of stakes
CAS-01_Ice/ CAS-01_Debris	Twin Debris & Ice	637	CAS-UAF	2018-08-31		2
CAS-03_Ice/ CAS-03_Debris	Twin Debris & Ice	704	CAS-UAF	2018-09-04		2
CAS-05	Debris	713	CAS/UAF	2019-06-08	2020-09-01	1
CAS-06	Debris	697	CAS/UAF	2019-06-08	2023-09-04	1
CAS-09	Ice	1141	CAS/UAF	2019-06-12		1
CAS-10	Ice	1224	CAS/UAF	2019-06-12		1
CAS-11	Ice	1382	CAS/UAF	2019-06-12		1
CAS-16	Debris	728	CAS/UAF	2020-07-29		1
CAS-22_Ice/ CAS-22_Debris	Twin Debris & Ice	853	CAS/UAF	2021-06-07		2
CAS-23_Ice/ CAS-23_Debris	Twin Debris & Ice	1026	CAS/UAF	2021-06-07		2
P_AWS	Debris	571	UAF	2020-06-14		3
P_AWS2021	Debris	537	UAF	2021-06-02	2023-09-02	3
P_AWS2022	Debris	560	UAF	2022-05-29		7
P01	Debris	417	UAF	2020-06-24	2022-09-09	1
P02	Debris	437	UAF	2020-07-27		1
P05	Debris	553	UAF	2021-06-02	2022-05-28	1
P06	Debris	546	UAF	2021-06-05	2022-09-12	1
P07	Debris	545	UAF	2021-06-02	2022-05-28	1
P11	Debris	546	UAF	2023-06-08		1
P12	Debris	543	UAF	2023-06-08		1
P13	Debris	551	UAF	2023-06-08		1
Gates 3600	Ice	1078	NPS	2016-05-26		1
Gates 7200	Firn	2186	NPS	2016-05-26		1
Gates 9400	Firn	2874	NPS	2016-05-27	2016-05-27	1
Kenn 2300	Ice	716	NPS	2018-05-17	2018-08-29	1
Kenn 2700	Ice	791	NPS	2019-06-07		1
Kenn 3100	Ice	916	NPS	2018-08-29		1
Kenn 6100	Firn	1835	NPS	2018-08-29		1

Note: Four sites have “twin” stakes less than a few tens of meters apart with one stake drilled into bare ice and the other one into debris-covered ice. At three sites over debris several stakes were drilled less than 100 m apart.

Upon recovery, the water levels were below the location of the transducers, which were found resting in, although not fully buried by, fine silts. Pond levels were observed to fall to 0 m on 18 August 2021, and lake levels were observed to fall to 0 m on 18 September 2021. We trimmed off the data after these dates, as strange results were observed in winter months, likely from the pressure of ice formation.

The lake level variations in both water bodies tend to co-vary on both seasonal and diurnal time scales reflecting variations in melt and rain water input (Figure 13b). Water level above the transducer varies by up to 2 m in the supraglacial pond and more than 3 m in the proglacial lake over the observation period. The depths of the transducers start at similar levels, but as the summer wears on, the level at the supraglacial pond

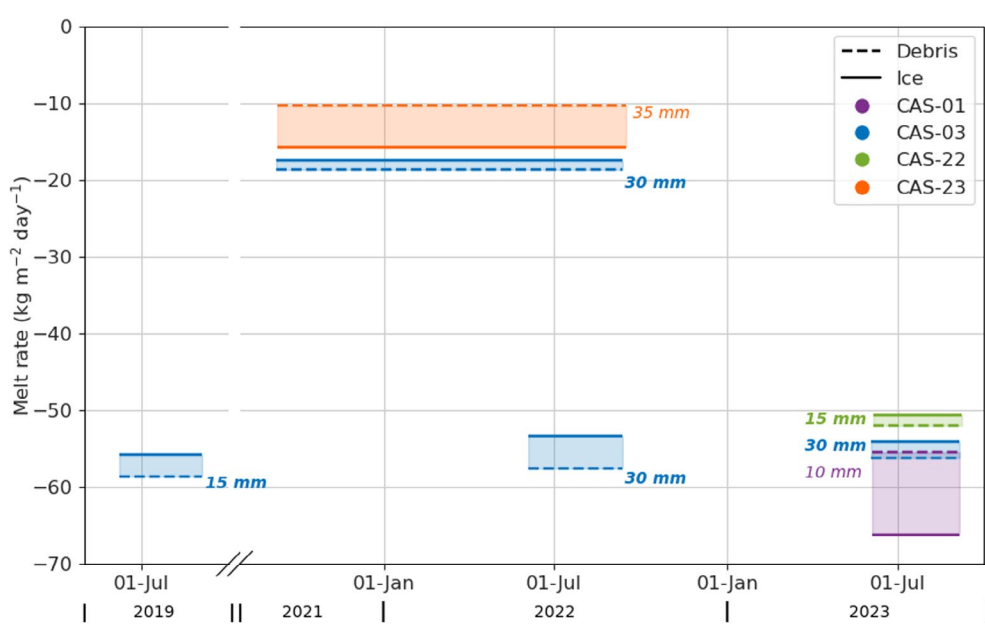


FIGURE 11 | Mean specific mass balance rates of all twin stake sites where one stake is over clean ice and another close by over debris. Lines extend over the periods each mean balance was computed. The shading highlights the difference for each stake. The annotated numbers in mm refer to debris thickness.

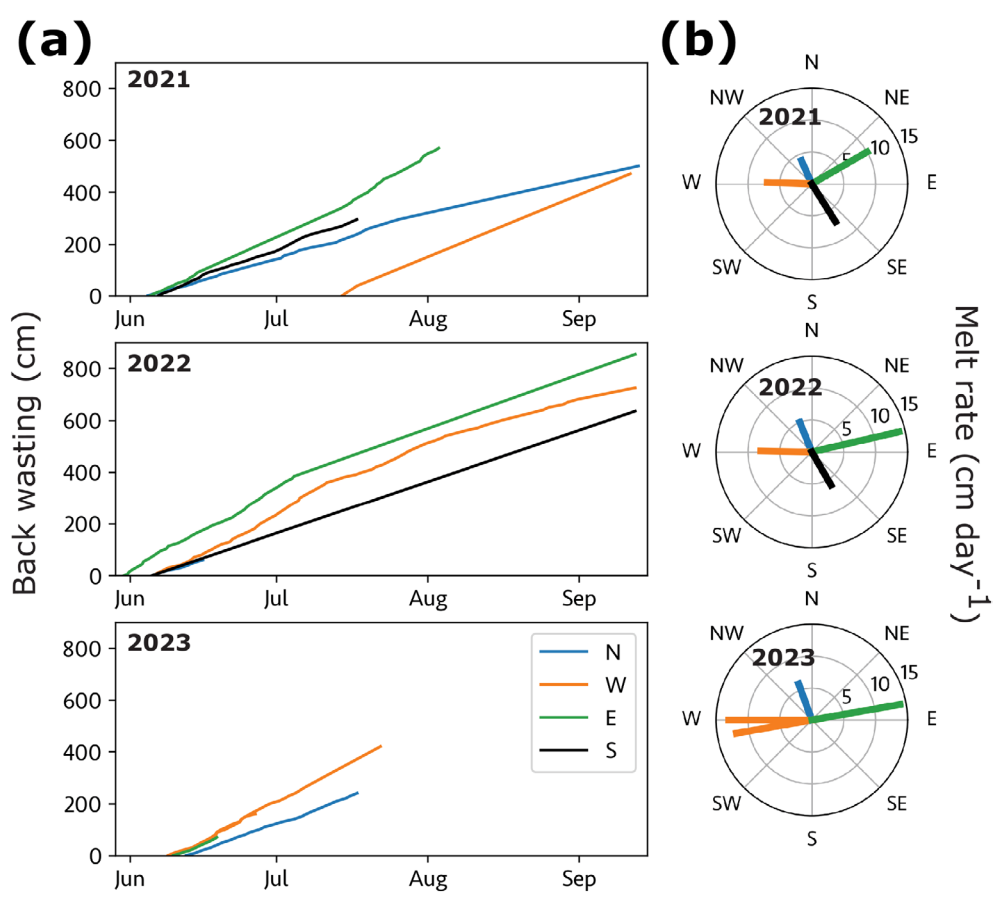


FIGURE 12 | Ice cliff backwasting measurements, (a) cumulative through time and (b) converted to mean melt rates over each site's total observation period, perpendicular to ice cliff surface slope, as a function of ice cliff aspect. Cumulative backwasting in (a) starts at the initial date of observation in a given measurement year, which may vary from site to site.

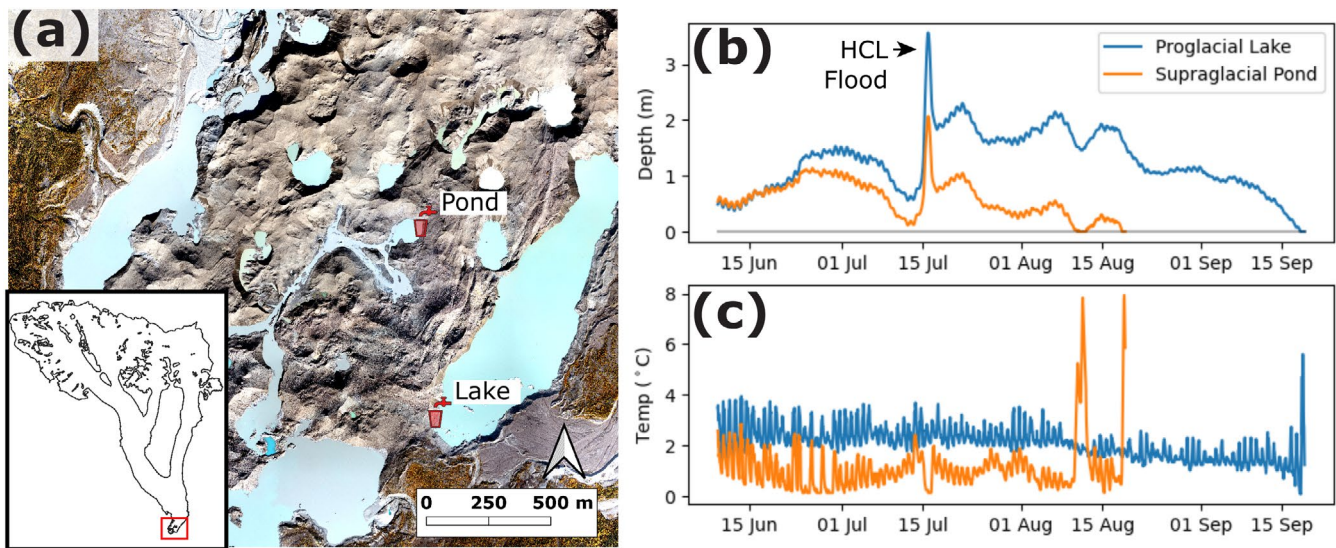


FIGURE 13 | Hourly water level and temperature data. (a) Map of the locations of the supraglacial pond and proglacial lake pressure transducers. Base map is an orthophoto from an airborne photogrammetry dataset acquired in 2018 (Petersen, Hock, and Loso 2024). Inset shows the location in the context of the larger glacier. (b) Water depth relative to the lake bottom measured at each of the transducer locations; the spike in level associated with the Hidden Creek Lake (HCL) glacial outburst flood is labelled. (c) Water temperature measured at the locations.

becomes progressively less than that at the proglacial lake. This dropping of the supraglacial pond level relative to that of the proglacial lake appears to occur most dramatically after flood events or water level raising events, including a pronounced rise in level on 23 June and an extreme increase on 15–16 July caused by the Hidden Creek Lake outburst flood. This is likely due to the fact that the pond is connected to the drainage system of the stagnant glacier terminus. Progressive enlarging of subglacial drainage conduits in stagnant ice through the summer leads to more efficient drainage, and thus a shorter storage time and lower base level in the supraglacial pond (Hooke 1989).

Water temperature tends to fluctuate on a diurnal timescale between 0°C and 3°C (supraglacial pond) and 1°C–4°C (proglacial lake, Figure 13c). When the water surface approaches the pressure transducer, the temperature rises steeply due to radiative heating. At the supraglacial pond, drops in temperatures tend to correlate with increases in water depth.

7.2 | Proglacial Lake Bathymetry

We measured bathymetry of the largest proglacial lakes ('East' and 'Southwest') at the Kennicott Glacier terminus. Depth soundings were collected from a small inflatable raft from 21 to 23 August 2018. Soundings were measured concurrently using a Sontek M9 acoustic doppler current profiler (ADCP) and a Lowrance depth sounder. When the two data streams were later merged, the better resolution measurements from the ADCP were retained only from shallow water (<10 m). Positions were collected in real-time using a survey grade GNSS receiver with boat-mounted external antenna. We also used the receiver to directly measure lake surface elevations on 22 August 2018. Lake surface elevations at that time, in height above ellipsoid, were 428.96 (± 20 cm) m for the east lake and 428.68 m (± 20 cm) for the southwest lake. After differential correction of the GNSS

surveys and initial processing of the sounding data, discrete sounding measurements were tabulated with date, latitude, longitude, depth (m), and bed height (in meters above ellipsoid). Sounding depths were interpolated to 2 m spatial resolution by inverse distance weighting and extrapolated to zero at the terrestrial lake margin, but were not interpolated into unmeasured areas with large icebergs.

Interpolated bathymetry is shown in Figure 14, along with positions of the source measurements, and reveals that both lakes are generally deepest near the ice margin with maximum depths up to 61 m (in the east lake) and 64 m (in the southwest lake). Mean depths are 25 m and 17 m respectively. Survey coverage was comprehensive with along-track distances between measurements usually <10 m and more commonly ~5 m, and distances between tracks 30 m. Small gaps in coverage occurred only near shallow terrestrial shorelines, in deep water near the glacier edge, and around large icebergs where adjacent depths were variable. In total, the interpolated maps are based upon 4092 discrete measurements in the east lake (75.4 m²/measurement) and 14,039 measurements in the southwest lake (82.8 m²/measurement). Reported depth error on both sounding units is <2%. We expect larger errors to stem from the interpolation across unmeasured areas and assume a maximum depth error of ± 2 m.

8 | Supraglacial Debris

8.1 | Debris Thickness

Debris thickness was measured at 150 locations on Kennicott Glacier from June 2020 through September 2023, at elevations ranging from 422 to 1054 m a.s.l. Measurements were taken in a range of locales, from continuous debris cover to medial moraines, with measurements representing the tops of hummocks, bottoms of pits, side hills, and saddles/shelves.

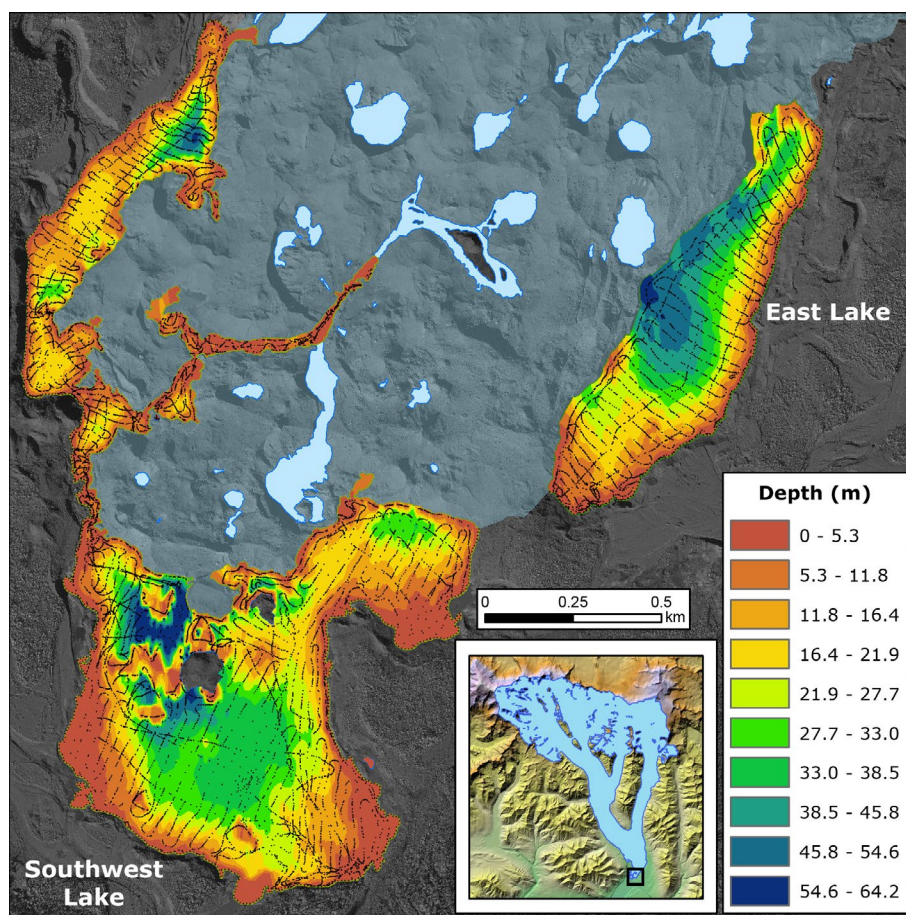


FIGURE 14 | Bathymetry of the major proglacial lakes at the Kennicott Glacier terminus. Interpolated lake depths (in meters) are colour coded, and overlain with actual 2018 measurement locations (trails of black dots). Lakes shown in pale blue were not surveyed. Background is grayscale 12 September 2018 Worldview satellite image.

Debris thickness was measured by manually digging to the ice surface, leaving an intact rim of surface debris around the pit. A pole or rigid tape measure was placed across the intact rim, and the distance from this reference to the ice surface was used to determine debris thickness. For each debris thickness measurement, the clast size distribution was qualitatively described (with such descriptors as boulders, rocks, cobbles, gravels, sand, silt). The positioning of each debris thickness measurement was recorded from a handheld Garmin GPS unit.

Measured debris thickness ranged between 1 and 69 cm, with a median of 16 cm, mean of 17 cm, and standard deviation of 11 cm. While debris thickness generally increases downglacier (Figure 15), there is high variability, both locally and within elevation bins. Debris sampled over lateral and medial moraines tends to be thicker. Debris thickness may also depend on source rock lithology, erosion rates, travel distance, and redistribution through mass wasting or glaciofluvial processes. At the site of the summer 2020 AWS, debris thickness varied from 5 to 30 cm within a < 15 m radius.

8.2 | Debris Temperatures

In this paper we present data from 12 debris thermistor profiles installed in supraglacial debris 17–39 cm thick. Each summer from

2020 through 2023 between two and four profiles comprised of 2–8 thermistors were active. Thermistor profiles are summarised in Table 3, and their locations are shown in Figure 16.

During installation at each location, surface debris was removed down to the ice-debris interface and its thickness measured as described in Section 8.1. Care was taken when removing debris from these pits to preserve any present sorting/stratigraphy as best as possible. A tarp was used to store and sort debris as it was removed from the pit, allowing for us to replace debris as faithfully as possible. However, it is impossible to replace debris perfectly, and the debris thermal state, packing, and moisture content are also likely highly altered during the disinterment and installation process. Thus, we disregard the first several days of data following installation to allow the debris layer to re-equilibrate.

Each thermistor profile was constructed using Onset Hobo Tidbit v2 temperature sensors with a stated accuracy of $\pm 0.2^{\circ}\text{C}$ and resolution of $\pm 0.02^{\circ}\text{C}$. Sensors were attached to a coated galvanised steel wire at a constant spacing determined for each site dependent on debris thickness and the number of thermistors utilised. Thermistor spacing ranged between 3 and 10 cm. Data was collected at 5 min intervals. An example timeseries of debris thermistor profile data is shown in Figure 17; box-whisker plots displaying statistics for all thermistor profiles are shown in Figure 18.

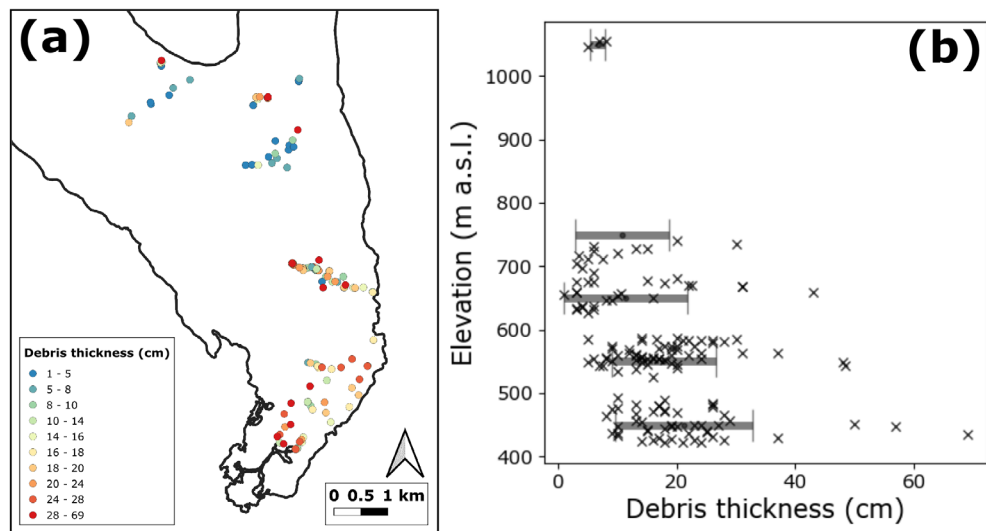


FIGURE 15 | Debris thickness measured through manual excavation on Kennicott Glacier. (a) Map of debris thickness measurements. (b) Debris thickness as a function of elevation; dots and bars represent mean and standard deviation of debris thickness in 100 m elevation bands.

TABLE 3 | Table summarising supraglacial debris thermistor profiles deployed on Kennicott Glacier, including the number N of thermistors in each profile as well as the depth-averaged thermal conductivity *k*.

Thermistor profile	Ablation stake	Depth-averaged <i>k</i> (W m ⁻¹ K ⁻¹)	<i>N</i>	Period of observation	Debris depth (cm)	Debris grain description
KDT_2020a	P_AWS_1	1.52	4	27 July to 6 Sept 2020	25	Cobbles/pebbles over sandy cobbles/pebbles
KDT_2020b		0.91	2	27 July to 6 Sept 2020	22	Cobbles/pebbles over sandy cobbles/pebbles
KDT_2021a		0.97	4	6 June to 20 July 2021	19	Cobbles over sandy gravel
KDT_2021b		1.86	4	18 July to 11 Sept 2021	39	Cobbles over sandy gravel
KDT_2021c		0.57	4	6 June to 12 July 2021	20	Cobbles over gravelly sand
KDT_2021d	P11	0.53	4	6 June to 10 Sept 2021	22	Cobbles over gravel over sand, well sorted.
KDT_2022a		0.81	4	31 May to 12 Sept 2022	17.5	Cobbles over sandy gravel
KDT_2022b		0.69	4	31 May to 24 Aug 2022	17	Cobbles over sandy gravel
KDT_2022c		0.96	8	31 May to 12 Sept 2022	34	10s cm clasts over gravelly cobbles over sandy gravel
KDT_2023a		0.95	5	10 June to 12 Sept 2023	24	Cobbles over sandy gravel
KDT_2023b	P12	1.00	4	10 June to 12 Sept 2023	32	Cobbles over gravelly sand
KDT_2023c	P13	0.84	4	10 June to 12 Sept 2023	26	Cobbles over sandy gravel

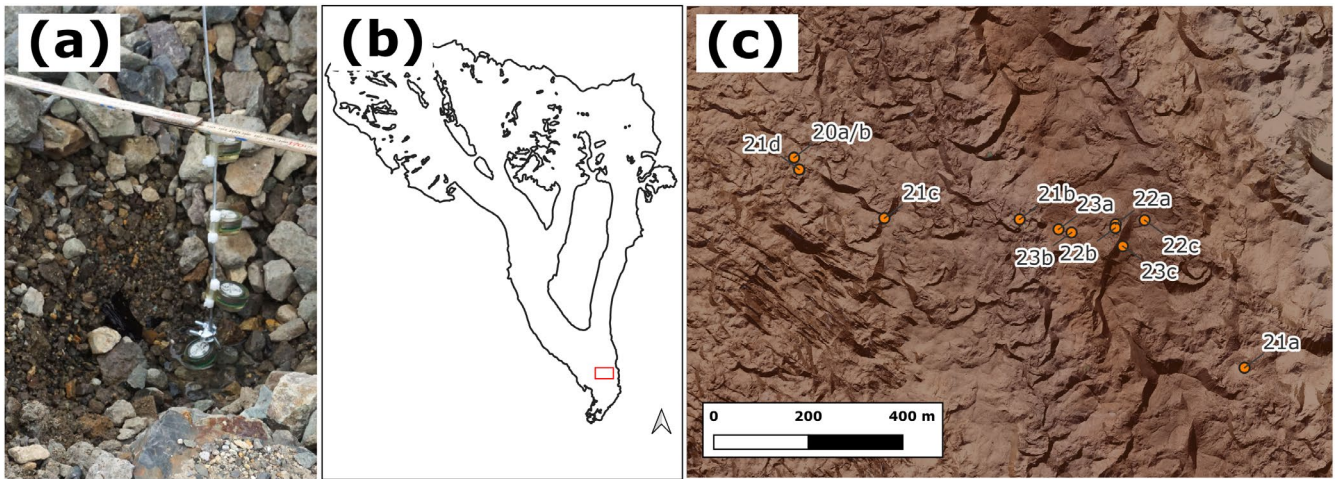


FIGURE 16 | (a) Image of debris thermistor in the process of installation into debris pit. (b-c) Map displaying location of thermistor profiles on Kennicott Glacier's debris-covered tongue. Base map in (c) is an orthophoto from an airborne photogrammetry dataset acquired in 2018 (Petersen, Hock, and Loso 2024). Thermistor profile names have been shortened to the last three characters for the purposes of labelling.

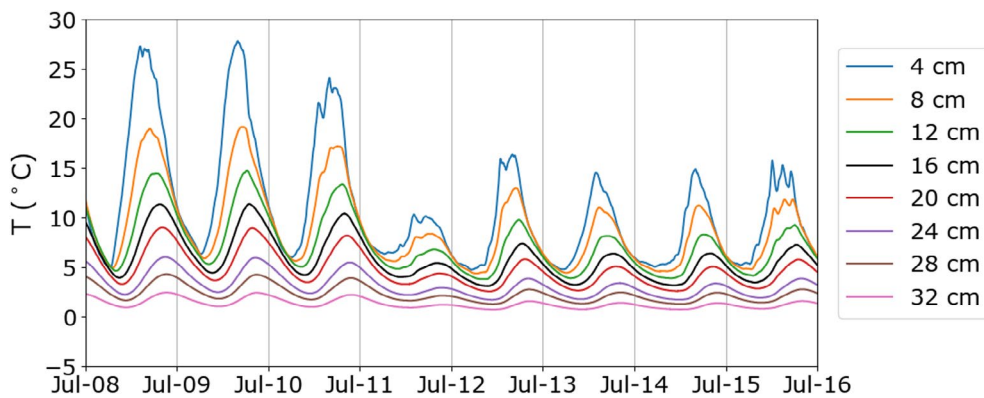


FIGURE 17 | Debris temperature profile data from KDT_2022c plotted for the week of 8 July 2022. Thermistors are spaced at 4 cm intervals; depth of each sensor is indicated in the legend to the right.

8.3 | Debris Thermal Heat Diffusivity and Conductivity

We followed the method of (Petersen et al. 2022) in determining thermal heat diffusivity using a multiple linear regression on temperature and its derivatives in time and space. The results of this analysis are shown in Table 4.

Four debris thermistor profiles coincided with the locations of ablation stakes—KDT_2020b, KDT_2023a, KDT_2023b, and KDT_2023c. For these profiles, we can calculate the following independent estimate of the thermal conductivity k :

$$k = \frac{M \rho_i L_f}{\partial T / \partial z} \quad (2)$$

where M is melt, $\rho_i = 900 \text{ kg m}^{-3}$ is the density of ice and $L_f = 334,000 \text{ J kg}^{-1}$ is its latent heat of fusion/melting (Cuffey and Paterson 2010). These values of k can then be used along with the thermal diffusivity κ determined from thermal analysis to constrain $\rho c = k/\kappa$, where ρ is the density and c is the heat capacity of supraglacial rocky debris.

We calculated ρc from $1.22\text{--}2.13 \times 10^6 \text{ J kg m}^{-3} \text{ K}^{-1}$, with an average value of $1.76 \times 10^6 \text{ J kg m}^{-3} \text{ K}^{-1}$. This is consistent with a debris layer having a heat capacity of 950 J K^{-1} , rock density of 2700 kg m^{-3} , and porosity of 31%; all these values are comparable to values used in the literature to model supraglacial debris, including heat capacities of $750\text{--}950 \text{ J K}^{-1}$, rock densities of $1500\text{--}2700 \text{ kg m}^{-3}$, and porosities of 20%–40% (Nicholas and Quine 2007; Reid and Brock 2010; Fyffe et al. 2014; Rounce and McKinney 2014; Giese et al. 2020). This value of ρc was thus used to estimate thermal conductivity k from thermal diffusivity κ for the remaining profiles.

Depth-averaged thermal conductivity k ranges from $0.53\text{--}1.86 \text{ W (mK)}^{-1}$, with a mean of 0.97 W (mK)^{-1} and median of 0.93 W (mK)^{-1} across all profiles. In most but not all cases, slightly higher thermal conductivities are observed at depth.

9 | Conclusions

Large compound valley glaciers can be a challenge for mass balance modelling due to their large spatial footprint/elevation

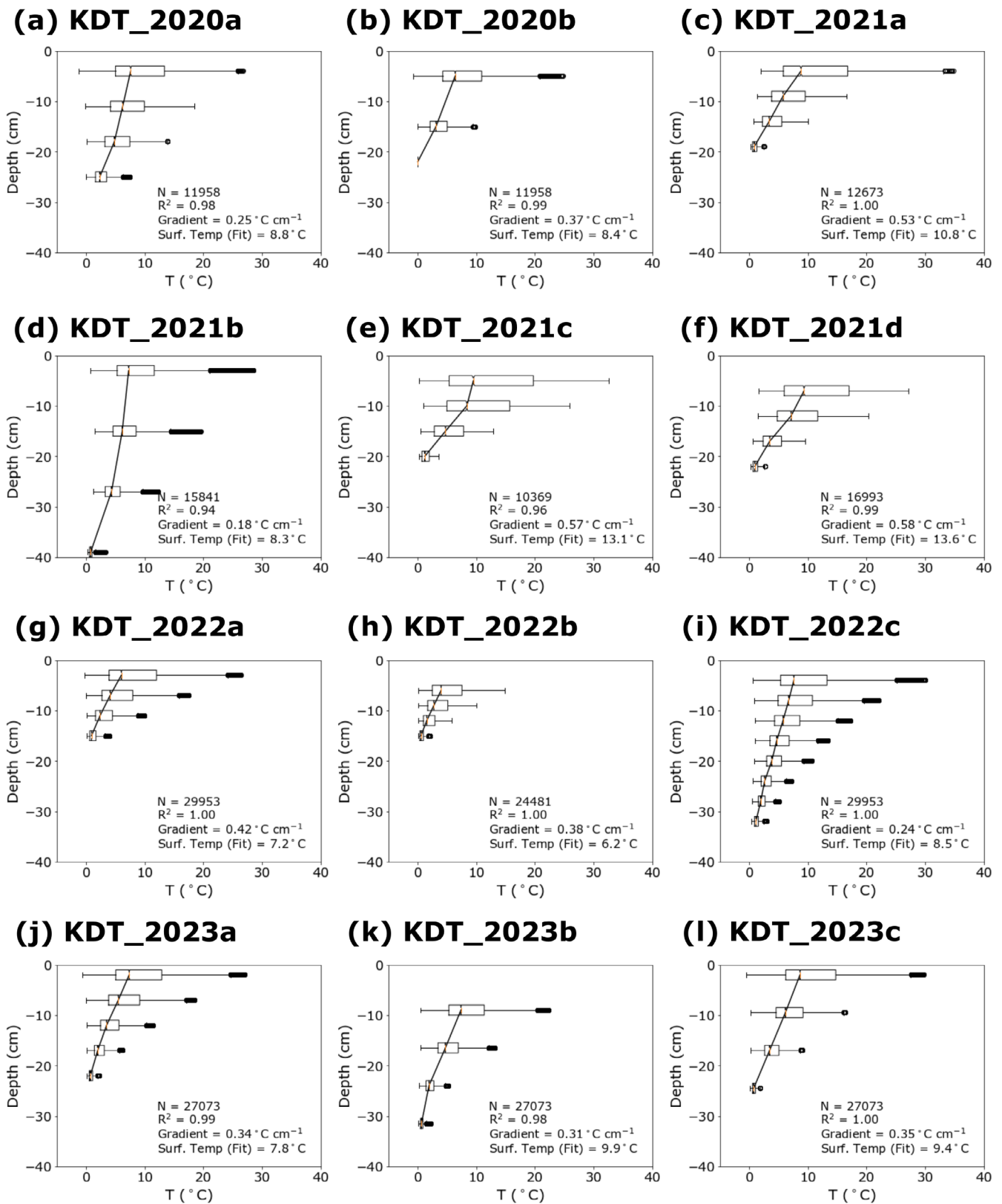


FIGURE 18 | Box-plot diagrams depicting statistics of debris temperature data for thermistor profiles in 2020 (a, b), 2021 (c–f), 2022 (g–i), and 2023 (j–l).

range and the existence of extensive debris cover in their terminal zone, which provides a strong control on local melt rates. Debris-covered ice on these glaciers produces reduced melt rates under thick debris as well as locally enhanced melt rates

at melt hot spots, including ice cliffs and supraglacial ponds. We presented a wide range of meteorological and glaciological measurements on Kennicott Glacier from 2016 to 2023 that will support these modelling efforts.

TABLE 4 | Results of analysis following (Petersen et al. 2022) to determine thermal diffusivity κ and conductivity k as a function of depth D within supraglacial debris. k_{melt} indicates the thermal conductivity constrained using cumulative melt measured at neighbouring ablation stake; ρc is the value of k_{melt}/κ . k is calculated for all profiles/depths using the average determined value of ρc .

Profile	D (cm)	R^2	κ ($\text{m}^2 \text{s}^{-1}$)	$\frac{\partial \kappa}{\partial z}$ (m s^{-1})	k ($\text{W m}^{-1} \text{K}^{-1}$)	k_{melt} ($\text{W m}^{-1} \text{K}^{-1}$)	(ρc) ($\text{J kg m}^{-3} \text{K}^{-1}$)
KDT_2020a	11	0.39	8.76×10^{-7}	1.60×10^{-6}	1.54		
	18	0.95	8.60×10^{-7}	-6.13×10^{-6}	1.52		
KDT_2020b	15	0.89	5.22×10^{-7}	-1.33×10^{-6}	0.92	0.638	1.22×10^6
KDT_2021a	9	0.46	3.42×10^{-7}	3.48×10^{-6}	0.60		
	14	0.68	7.69×10^{-7}	-1.29×10^{-6}	1.36		
KDT_2021b	15	0.66	9.81×10^{-7}	-8.44×10^{-7}	1.73		
	27	0.65	1.14×10^{-6}	-5.01×10^{-6}	2.01		
KDT_2021c	10	0.42	2.92×10^{-7}	-5.37×10^{-6}	0.51		
	15	0.70	3.62×10^{-7}	1.69×10^{-6}	0.64		
KDT_2021d	12	0.64	3.23×10^{-7}	-2.09×10^{-6}	0.57		
	17	0.60	2.79×10^{-7}	2.22×10^{-6}	0.49		
KDT_2022a	7	0.91	3.67×10^{-7}	9.09×10^{-7}	0.65		
	11	0.95	5.53×10^{-7}	2.46×10^{-6}	0.97		
KDT_2022b	9	0.64	3.93×10^{-7}	1.19×10^{-6}	0.69		
	12	0.10	8.74×10^{-8}	2.63×10^{-7}	0.15		
KDT_2022c	8	0.69	3.70×10^{-7}	1.06×10^{-6}	0.65		
	12	0.96	4.92×10^{-7}	9.90×10^{-7}	0.87		
	16	0.88	6.73×10^{-7}	4.67×10^{-6}	1.19		
	20	0.92	5.49×10^{-7}	-4.52×10^{-6}	0.97		
	24	0.75	5.98×10^{-7}	7.98×10^{-6}	1.05		
KDT_2023a	28	0.60	6.12×10^{-7}	-2.06×10^{-6}	1.08		
	7	0.95	4.73×10^{-7}	3.76×10^{-7}	0.83		
	12	0.93	5.38×10^{-7}	3.49×10^{-6}	0.95		
	17	0.61	6.19×10^{-7}	2.57×10^{-6}	1.09	1.319	2.13×10^6
KDT_2023b	16.5	0.97	5.93×10^{-7}	2.58×10^{-7}	1.04		
	24	0.74	5.46×10^{-7}	5.46×10^{-6}	0.96	1.113	2.04×10^6
KDT_2023c	9.5	0.89	4.33×10^{-7}	1.11×10^{-6}	0.76		
	17	0.92	5.29×10^{-7}	-3.09×10^{-8}	0.93	0.878	1.66×10^6
						Avg. ρc :	1.76×10^6

Meteorological data were presented that represent local conditions off glacier, on glacier ice, and on debris-covered glacier ice at elevations from 585 to 2200 m a.s.l. Summer lapse rates on clean ice were determined at $3.72^\circ\text{C km}^{-1}$, while for debris-covered ice they were estimated at $4.86^\circ\text{C km}^{-1}$, indicating warmer air temperatures overall for debris-covered than bare-ice glacier surfaces. Simple linear regression transfer functions were shown to be useful in reconstructing on-glacier summer air temperatures from longer term off-glacier meteorological records.

Measurements of point mass balance were reported at 27 sites across the accumulation zone, clean ice ablation zone, and debris-covered ablation zone. Annual and summer surface mass balance is heavily dependent upon elevation, with an ELA near ~ 1850 m a.s.l. This relationship is broken by the presence of supraglacial debris cover, which attenuates melt rates exponentially as a function of debris thickness.

Supraglacial debris temperature profiles were measured at 12 sites, providing data for estimating thermal heat conductivity as

the basis for modelling heat fluxes resulting from surface energy balance. We report depth-averaged thermal heat conductivity in the range $0.53\text{--}1.86\text{ W m}^{-1}\text{ K}^{-1}$. Debris thickness ranges from discontinuous coverage $<1\text{ cm}$ thickness to a measured 69 cm (greater thicknesses expected locally).

Summer melt rates were measured in real time at several ice cliffs using time lapse cameras trained on ablation stakes. We measured mean melt rates up to 14.9 cm d^{-1} , $\sim 2.5\times$ greater than comparable melt rates on clean ice or under thin debris.

We also presented bathymetric measurements of the proglacial lake system and water level measurements at the east proglacial lake and a nearby supraglacial pond which demonstrate hydrologic connectivity and the evolution of the drainage system at the glacier terminus through the summer.

These datasets provide many opportunities for investigating meteorological, surface melt, and hydrological processes relevant to debris-covered compound valley glaciers in the subarctic. They may be readily utilised to serve as inputs to constrain and assess energy balance and temperature index melt models. The data also provide a baseline for evaluating future changes.

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Conflicts of Interest

The authors declare no conflicts of interest.

Data Availability Statement

The data that support the findings of this study are openly available in Zenodo at <https://zenodo.org/records/16389806>.

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Appendix A

Additional Meteorological Plots

Figures A1–A4

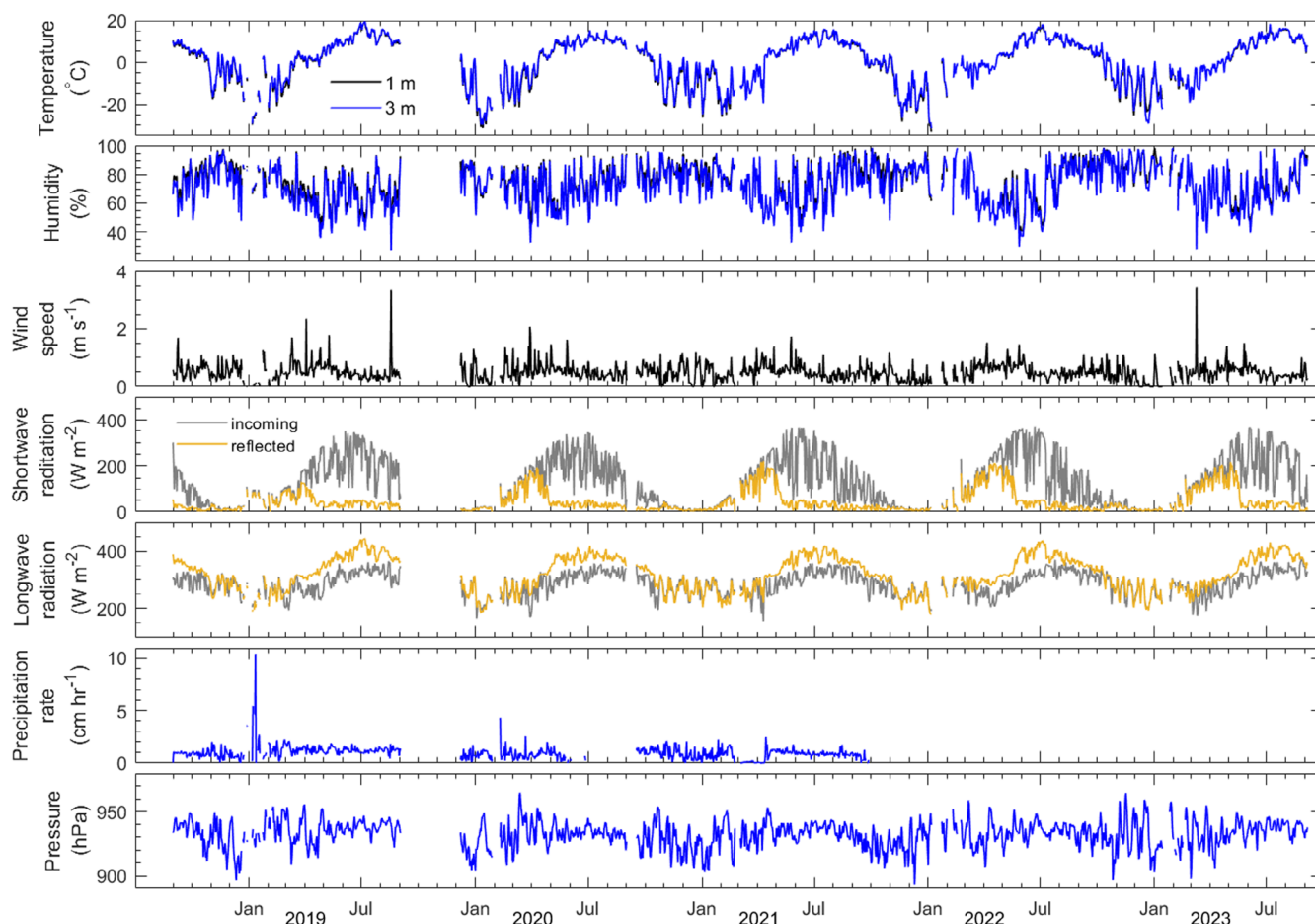


FIGURE A1 | Daily values for meteorological variables measured at Amazon Creek automatic weather station.

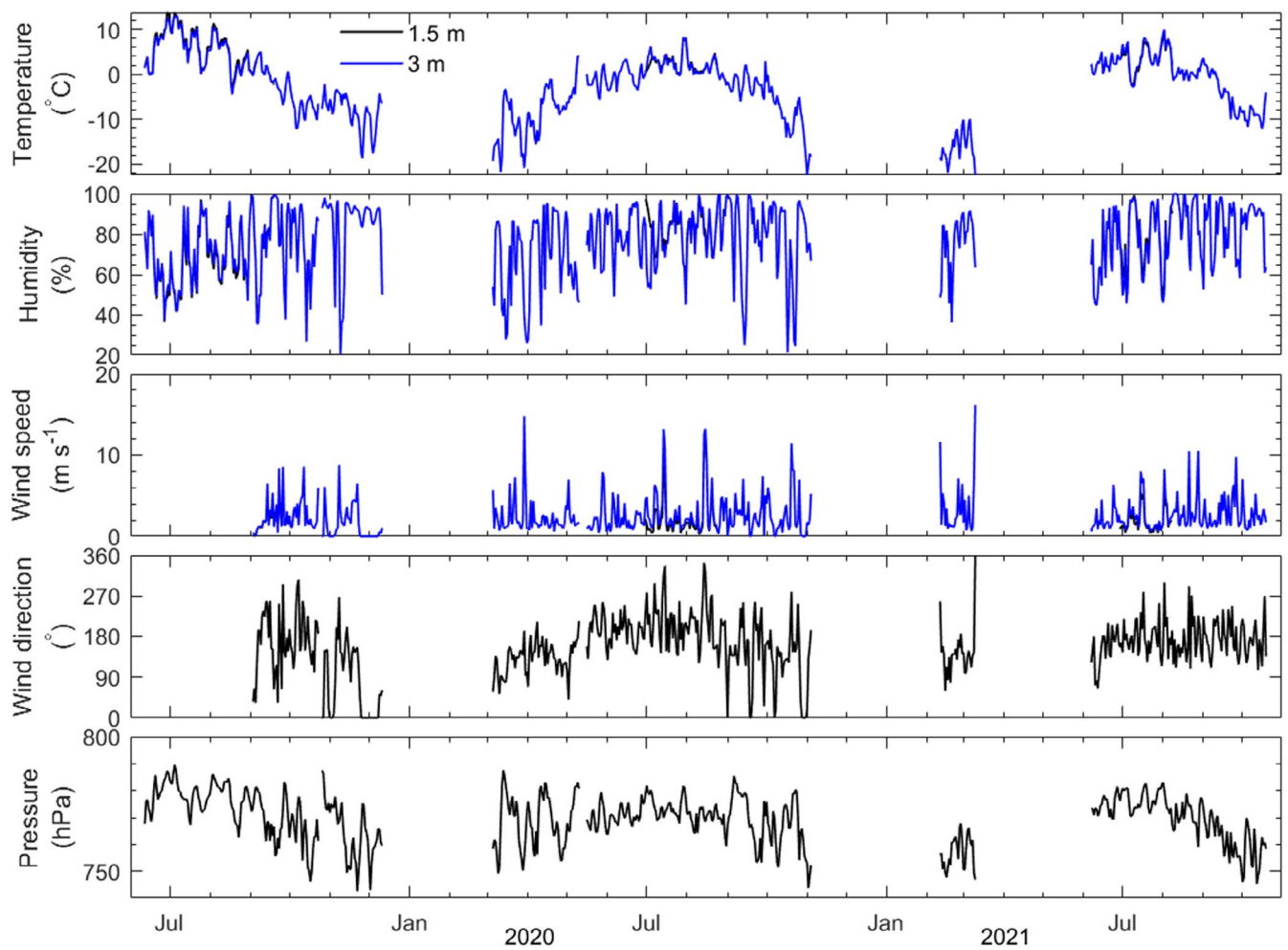


FIGURE A2 | Daily values for meteorological variables measured at LaChappelle Nunatak automatic weather station.

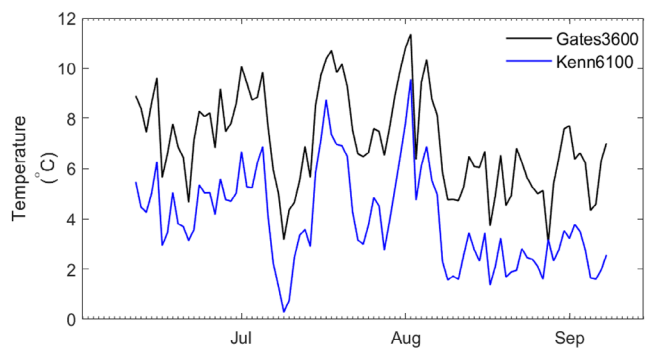


FIGURE A3 | Daily values of air temperature measured over bare ice surfaces on glacier.

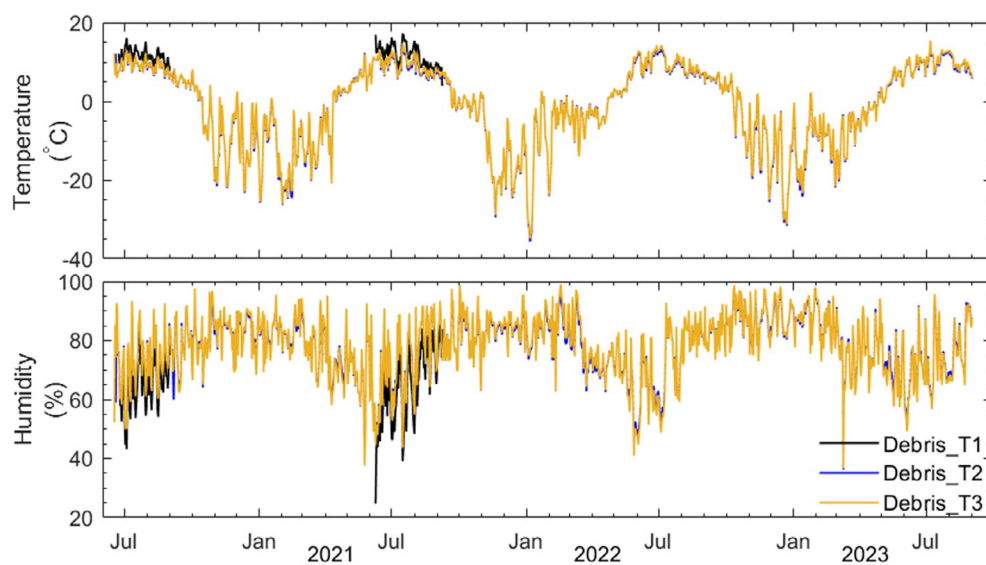


FIGURE A4 | Daily values of air temperature and relative humidity measured over debris-covered surfaces on glacier.