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Seasonal Cold-Wave Propagation Into the Near-Surface Ice of Debris-Covered Khumbu Glacier, Nepal

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INTRODUCTION

Meltwater from high-elevation debris-covered glaciers—particularly those located in the greater Himalaya and Andes—shapes the water supply of major rivers and nourishes substantial terrestrial, estuarine, and marine habitats (Kraaijenbrink et al., 2017; Immerzeel et al., 2020). However, the relative inaccessibility and high elevation of such glaciers results in a paucity of data relating to their fundamental physical properties and processes, limiting the information available to constrain and evaluate numerical models of their behaviour and project future change. Knowledge of the subsurface properties of such glaciers is particularly deficient because it is largely obscured to satellite and airborne remote sensing; englacial investigations therefore commonly require direct access (Miles et al., 2020). Of the physical properties of glaciers, ice temperature exerts an important control over glaciological processes, such as glacier motion, and their modelled behaviour. For example, ice viscosity is sensitive to temperature such that, under the same stress, ice approaching the melting point deforms 5–10 times more rapidly than it would at −10°C (Deeley and Woodward, 1908; Cuffey and Paterson, 2010). Basal motion depends on lubrication facilitated by the presence of meltwater at the ice-bed interface and/or within the pore space of a subglacial sediment layer. Measurements of near-surface ice temperatures are important for modelling the surface energy balance and projecting the future mass-balance response of glaciers to anticipated climate change. This is especially the case for glaciers with a thick supraglacial debris layer that insulates the underlying ice (according to debris layer thickness and lithology), reducing ablation and potentially extending glacier longevity (Nicholson and Benn, 2006; Nicholson and Benn, 2013; Anderson and Anderson, 2016).

Here, we present a one-year time series of near-surface ice temperatures, measured between 1.5 and 7.0 m below the ice surface, in a borehole drilled by hot water into the debris-covered tongue of Khumbu Glacier, Nepal.

METHODS

Field Site

Khumbu Glacier is a large debris-covered glacier in the Nepal Himalaya (**Figure 1**) with a clean-ice accumulation area in the Western Cwm of Mount Everest, from ~5,800–8,000 m a.s.l., where mean annual air temperatures are of the order of −10 to −20°C (Matthews et al., 2020). The supraglacial

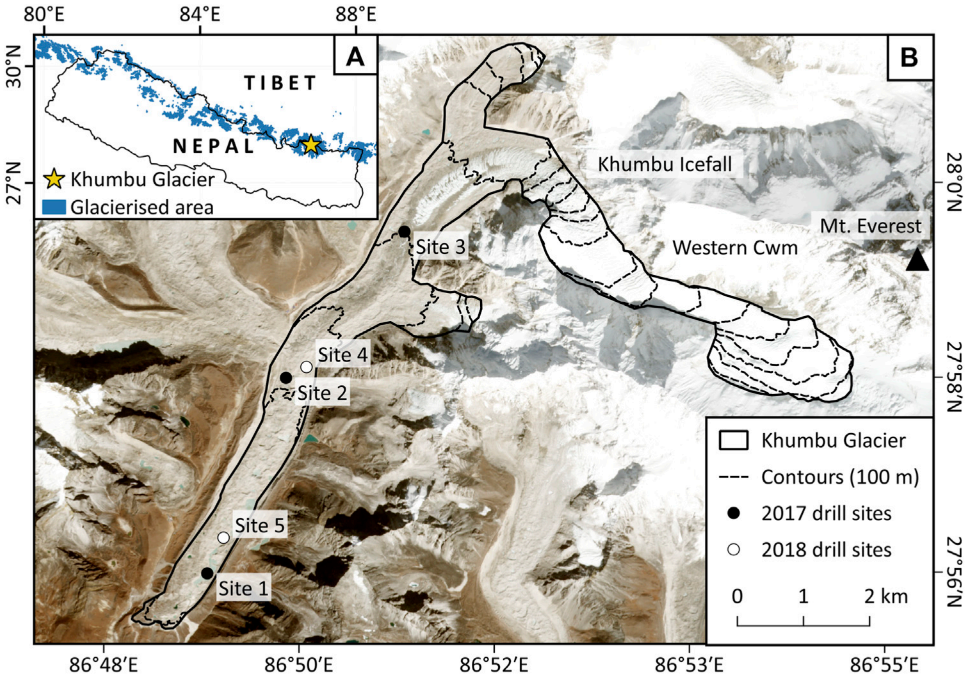

FIGURE 1 | Location of Khumbu Glacier and drill sites. **(A)** Location of Khumbu Glacier, Nepal. **(B)** Location of drill sites on the glacier in 2017 and 2018. Background is a Sentinel-2A image acquired on October 30, 2018 (Planet Team, 2017). Glacier contours are at 100 m intervals from 4,900 to 6,800 m a.s.l., created from the 2015 SETSM DEM (Noh and Howat, 2015).

debris layer begins to form just beyond the base of the Khumbu Icefall at ~5,400 m elevation, increasing in thickness to several metres at the terminus (Iwata et al., 1980; Miles et al., 2020; Miles et al., 2021). Below the depth of zero annual temperature variation (~15 m), the glacier is polythermal, based on records from deep thermistor strings across the ablation area (Sites 1–3, **Figure 1B**) (Miles et al., 2018).

Methods and Data Analysis

Twenty-seven boreholes were drilled by hot water at five sites across the debris-covered ablation area of Khumbu Glacier in 2017 and 2018 (Miles et al., 2019). Deep ice temperatures were measured at Sites 1–3 (**Figure 1B**); the first 6 months of measurements between May and October 2017 were reported in Miles et al. (2018). In this data report, we present hitherto unreported shallow ice temperature measurements from Site 4 recorded between May 2018 and May 2019. The temperature data herein were measured by a string of 12 thermistors installed at 0.5 m depth increments, from 1.5 to 7.0 m, below the ice surface at Site 4 (**Figure 1B**). Before drilling, supraglacial debris of ~0.6 m in thickness was removed from an approximately circular area of ~0.5 m diameter around the borehole location (Miles et al., 2019; Miles et al., 2021). When revisited 1 year later, the borehole was beneath a debris layer that was visually indistinguishable in thickness and character from that more generally present in the area, though the rate of reformation through englacial debris melt-out and gravitational processes is not known at this site.

Following Miles et al. (2018), Honeywell UNI-CURVE 192-502-LET-AOI thermistors were used to record ice temperatures to an accuracy of ± 0.05°C at 0°C following calibration in a distilled water and ice bath (Iken et al., 1993; Bayley, 2007; Doyle et al., 2018). Thermistor resistance was measured by a Campbell Scientific CR1000 data logger located at the glacier surface, as detailed by Miles et al. (2018). Measurements were made every 10 min between May 5, 2018 and November 14, 2018, and every hour between November 14, 2018, and May 30, 2019 to ensure memory capacity of the data loggers was not exceeded. Resistance was converted to temperature using a Steinhart and Hart (1968) polynomial fitted to the manufacturer's calibration curve, corrected using a freezing-point offset for each individual thermistor obtained from the ice-bath calibration.

CONCLUSION

The data we present herein comprise a time series of shallow ice temperatures measured between May 2018 and May 2019 at Khumbu Glacier, Nepal. Ice temperatures were recorded simultaneously by 12 thermistors installed at increments of 0.5 m below the ice surface, from 1.5 to 7.0 m depth.

The time series (**Figure 2**) captured the propagation of the cold-season cold wave into the near-surface ice of Khumbu Glacier. The thermistors froze into the borehole within 6 weeks. Beyond the settling curve, the ice temperature increased by ~0.5°C through the remainder of the warm season (to November), decreased by several degrees through the cold season, and finally began to warm again into the following warm season. The record quantified three

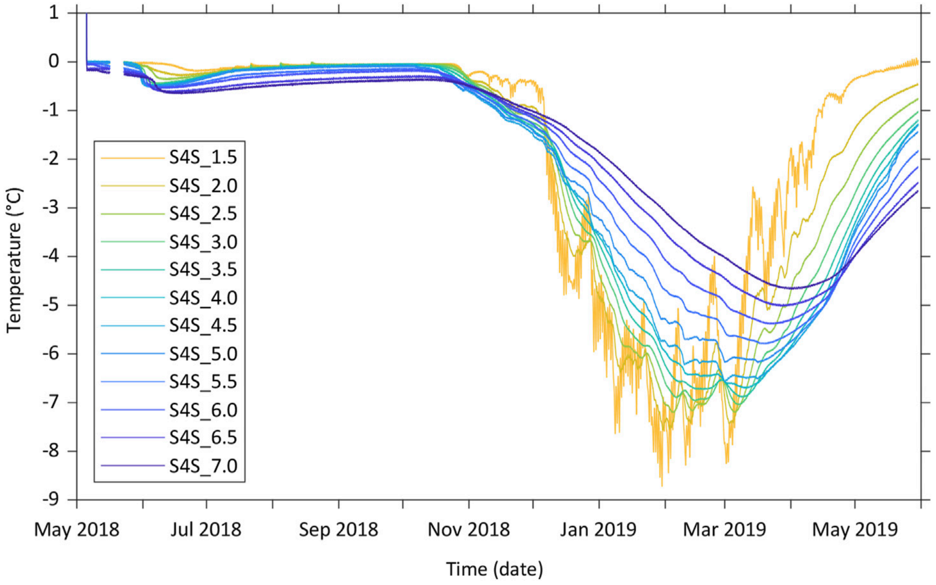

FIGURE 2 | Time series of temperature data measured by the Site 4 shallow-depth thermistor string, colour-coded by thermistor depth. Our thermistor naming convention (e.g., S4S_1.5) is comprised of the borehole site (here, "S4S" refers to "Site 4 shallow"), followed by the depth (in metres) of each thermistor below the surface (here, 1.5 m).

anticipated effects as the cold wave propagated to depth: 1) it was delayed, 2) its amplitude decreased, and 3) its high-frequency elements were progressively filtered out. Using daily mean values through the full cold season, the relationship between the rate of change of temperature and second derivative of temperature change with depth (Cuffey and Paterson, 2010) yielded a material thermal diffusivity of 1.1 m^2 s^{-1}, and hence a thermal conductivity of 2.1 m^{-1} K^{-1}. These values are typical of glacier ice close to its melting point (Cuffey and Paterson, 2010).

The dataset could be relevant to:

- Comparing shallow englacial temperatures, and interannual variability in them, with air temperatures from AWS data (e.g., Sherpa et al., 2017).
- Investigating near-surface ice mechanics and fracture (e.g., Podolskiy et al., 2018) and constraining thermo-mechanical models of glacier ice deformation (e.g., Gilbert et al., 2020).
- Investigating englacial liquid water availability and microbiology (e.g., Hotaling et al., 2017).
- Extending models of energy transfer through supraglacial debris into the underlying ice (e.g., Nicholson and Benn, 2006; Evatt et al., 2015), possibly including known debris temperature gradients (e.g., Rowan et al., 2021).
- Estimating the timing of the onset and end of the ablation season.
- Estimating the shallow ice temperature gradient along the glacier, and thus its equilibrium line altitude.

DATA AVAILABILITY STATEMENT

The datasets presented in this study can be found in online repositories. The names of the repository/repositories and accession number(s) can be found below: https://doi.org/10.6084/m9.figshare.14673837.

AUTHOR CONTRIBUTIONS

DQ, AR, and BH led the EverDrill research project. KM, BH, and SD designed and assembled the thermistor strings. KM, DQ, EM, BH, and AR participated in the fieldwork, including borehole drilling and thermistor string installation. KM led manuscript writing, to which BH, DQ, EM, AR, and SD contributed.

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Conflict of Interest: The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

The reviewer AB is currently organizing a Research Topic with one author DJQ.