Mapping seasonal glacier melt across the Hindu Kush Himalaya with time series SAR

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Abstract. Current observational data on Hindu Kush Himalayas (HKH) glaciers are sparse, and characterizations of seasonal melt dynamics are limited. Time series synthetic aperture radar (SAR) imagery enables detection of reach-scale glacier melt characteristics across continents. ~~and these records may be integral to the development and assessment of surface energy balance models of glacier ablation.~~ We analyze C-band Sentinel-1 A/B SAR time series data, comprised of 32,741 Sentinel-1 A/B SAR images, determine the duration of seasonal glacier melting for 105,432 mapped~~76,831~~ glaciers (83,102~~65,108~~ km^2 glacierized area), defined using optical observations, in the HKH across the calendar years 2017-2019. Melt~~Signals of melt~~ onset and duration are recorded at 90m spatial resolution and 12-day temporal repeat. All glacier areas within~~ across 97% (62,907 km^2) of~~ the HKH exhibit some degree of melt.~~cryosphere.~~ Melt signals persist for over half~~more than 40%~~ of the year at elevations below 4,000 m a.s.l. and for nearly one quarter of the calendar~~in excess of 15% of each~~ year at elevations exceeding 7,000 m a.s.l. ~~Melt retrievals resemble characteristics of glacio-climatic subregions of the HKH: melt onsets sooner and occurs for a longer portion of each year in the Central and Eastern Himalaya compared to the Western Himalaya and Karakoram regions.~~ Retrievals of seasonal melting span all elevation ranges of glacierized~~significant glacier~~ area in the HKH region, extending greater than 1km above the maximum elevation of an interpolated 0ºC summer isotherm and at the top of Mount Everest, where *in situ* data and surface energy balance models indicate the Khumbu glacier is melting at surface air temperatures below -10ºC. Sentinel-1 melt retrievals reflect broad-scale trends in glacier mass balance across the region where the duration of melt retrieved in the Western Himalaya and Karakoram is on average one month less than in the Eastern Himalaya sub-region. Furthermore, percolation zones are apparent from meltwater retention indicated by ~~signals of~~ delayed refreeze. Time series SAR datasets are

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suitable to support operational monitoring of glacier surface melt and the development and assessment of surface energy balance models of melt-driven ablation across the global cryosphere.

1 Introduction

Global warming driven by the anthropogenic release of geologic carbon is causing mass wasting of alpine glaciers worldwide (Brangers et al.; Zemp et al., 2006).~~[1, 2],~~ The Hindu Kush Himalaya (HKH) region, known colloquially as the "Third Pole," has the most ice-covered area on Earth after the high-latitude polar regions (Yao et al., 2012).~~[3],~~ In contrast to large ice sheets near the poles, these relatively small alpine glaciers – perched at some of the highest elevations on Earth – are among the most sensitive indicators within the global cryosphere of changes in global climate (Anthwal et al., 2006). Just as the recession of these sensitive mountain ice caps contributes to over one quarter of global sea level rise (Zemp et al., 2019), disturbances accompanying HKH glacier retreat pose~~[4]. Just as the recession of these sensitive mountain ice caps contributes to over 25 percent of global sea level rise [5], disturbances accompanying HKH glacier retreat pose additional and~~ innumerable hazards to humans and natural ecosystems. Glacier retreat threatens to disturb the dynamics of river systems delivering freshwater resources to nearly 2 billion people across South and Central Asia (Brown et al., 2007; Milner et al., 2017).~~[6, 7],~~ Outburst floods resulting from glacier mass wasting have killed at least 6,300 people in the Himalayas alone, and have caused extensive damage to property and livelihoods. These outbursts are expected to increase in frequency with continued glacier wasting (Carrivick and Tweed, 2016).~~[8],~~ Some organisms endemic to alpine aquatic ecosystems may become extinct as they lose biogeochemical regulation from upstream glaciers (Jacobsen et al., 2012).~~glaciers upstream [9],~~ As global temperatures rise and perennial snow and ice cover decreases, societies are faced with difficult decisions around the costs and benefits of adapting to a changing climate within and around the HKH region (Brown et al., 2007).~~[6],~~ Informed decision-making for successful climate change adaptation will require knowledge of the state of natural systems and how these systems are projected to change alongside future increases in population and global average temperature (Bogardi et al., 2012).~~[10],~~

Substantial uncertainties exist in the current understanding of projected disturbances associated with a changing climate, environment, and hydrologic regime across the greater Himalayas due to a lack of observations of hydrology and meteorology at high elevations (Litt et al., 2019). The magnitude and rate of ablation from surface melting is of particular importance as it drives changes in accumulation-zone snow-properties, such as percolation and densification, that feedback into increased melting (Alexander et al., 2019). Surface melting has also been linked to increased englacial temperatures resulting in faster ice motion (Miles et al., 2018). Although the general trajectory of changes to the HKH cryosphere is understood (i.e. accelerated glacier mass loss on a decadal scale in the Central and Eastern Himalaya), a consensus in projecting changes to HKH hydrology is lacking largely because of missing *in situ* snow and ice monitoring data across these glaciated river basins (Fujita and Nuimura, 2011). However, construction and maintenance of *in situ* monitoring station networks is costly and labor-intensive because of the complexity of the high-mountain glaciated terrain. Satellite imaging radar retrieval of alpine glacier melt

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characteristics has long been proposed as a source of data for hydrologic and glaciologic research (Shi et al., 1994). Understanding of surface melting from observation records will enable advanced climate change projections of glacier wasting that require snow property dynamics describing the retention, refreezing and drainage of liquid water within glacier snow and firn (Pritchard et al., 2020).

~~Substantial uncertainties exist in the current understanding of projected disturbances associated with a changing climate, environment, and hydrologic regime across the greater Himalayas due to a lack of observations of hydrology and meteorology at high elevations [11]. Although the general trajectory of changes to the HKH cryosphere is understood (i.e. accelerated glacier mass loss on a decadal scale), a consensus in projecting changes to HKH hydrology is lacking largely because of missing *in situ* snow and ice monitoring data across these glaciated river basins [12]. However, construction and maintenance of an *in situ* monitoring station network is costly and labor-intensive because of the complexity of the high-mountain glaciated terrain. Remote sensing observations are commonly used in lieu of weather station measurements. In particular, satellite imaging radar retrieval of alpine glacier melt characteristics has long been proposed as a source of data for hydrologic and glaciologic research [13]. Advanced climate change projections of glacier wasting require snow property dynamics that describe the retention, refreezing and drainage of liquid water within glacier snow and firn [14] and therefore observational records of this type are of great value. Surface melting drives accumulation zone snow properties, such as percolation and densification, that can increase the seasonal amount of melting [15] and has been linked to increased englacial temperatures resulting in faster ice motion [16].~~

Recent findings~~revelations~~ indicate that shortwave radiation drives melting at ~~high~~ elevations where air temperatures are perennially below freezing, such as those~~, above 5500 m a.s.l., like~~ on Mount Everest ~~,~~ where temperatures never exceed -10ºC (Matthews et al., 2019; Matthews et al., 2020).~~[17, 18],~~ These *in situ* findings indicate the degree to which~~finding assert that~~ temperature-indexed melt models are ~~surely~~ underestimating ablation at these elevations using a~~through the assumption that air temperatures greater than~~ 0ºC threshold for~~alone drive snow and~~ glacier melting~~melt~~. Further, studies of glacier wasting in High Mountain Asia have shown variability in patterns and magnitude of glacier wasting across sub-regions of the HKH that would be difficult to capture in numerical models using degree-day assumptions (Brun et al., 2017).~~[19],~~ An observationally based dataset providing~~on~~ characteristics of the glacier surface energy balance is necessary to ~~attempt to~~ capture seasonal and regional variability in glacier wasting across the HKH during melt-freeze cycles.

1.1 Snowmelt Detection and Radar Imaging

This study builds on extensive research on~~into~~ microwave scattering from dry and wet snow and associated techniques for snowmelt retrieval from imaging radar data~~sensors~~ to present an operational monitor for spatially-resolved glacier surface melt characteristics using synthetic aperture radar (SAR) time series and outlines of~~up-to-date~~ glacier area~~outlines~~ derived from satellite optical imagery across the HKH. Microwave remote sensing has

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been~~is~~ used to reliably monitor melt patterns across glaciers and ice sheets (Abdalati and Steffen, 2001; Ashcraft and Long, 2007; Jezek et al., 1994b; Steiner and Tedesco, 2014).~~[20–25],~~ Because imaging radar is independent of solar illumination and largely unaffected by cloud cover and atmospheric conditions~~convection~~, the fidelity of radar observations is defined~~limited only~~ by the frequency of the satellite platform's observational opportunities and by the characteristics of the imaging sensor. At C-band frequencies, frozen glacier percolation areas are recognized as one of the brightest radar targets on Earth, and glacier surfaces are unambiguous targets for determination of surface melt/freeze characteristics (Jezek et al., 1994; Rott and Mätzler, 1987).~~[26, 27],~~ Detection of seasonal melt on ice surfaces at C-Band frequencies (4 – 8 GHz) depends on a strong radiometric response at melt onset (MO), when ~~a~~liquid water content introduced to an otherwise frozen snow or firn matrix causes a drastic decrease in the radar backscatter from the medium (Hallikainen et al., 1986).~~[28],~~ Deep, frozen snow and firn has a high scattering albedo across microwave frequencies (Matzler, 1998),~~[29],~~ resulting in high radar backscatter intensity over glaciated regions during the frozen months (Winsvold et al., 2018; Wiscombe and Warren, 1980).~~[30, 31],~~ The introduction of liquid water in the snow or firn matrix at even hydrologically minimal amounts ~~(<0.1% by volume)~~ causes a pronounced increase in the medium's dielectric constant, increasing radar signal attenuation and diminishing volume scattering, and leading~~. This leads~~ to a pronounced decrease in radar backscatter, usually by half power ~~(–3 dB)~~ or more (Kendra et al., 1998; Shi and Dozier, 1995).~~[32, 33],~~ In areas that are seasonally snow-free, *e.g.*~~like~~ for glacier ablation areas of debris-cover or bare ice, melting conditions are dominated by heterogeneous~~surface~~ scattering mechanisms following the disappearance of seasonal snow, a topic of study not well represented in the theoretical literature on radar physics likely due to the complex nature of the glacier ablation surface. Because~~that is significantly darker relative to winter conditions [34]. In part because~~ of the relatively strong signal produced at the onset of~~by~~ melting, radar-based melt-detection records have been developed across regions of the global cryosphere for several decades using both real and synthetic aperture radar sensors (Bhattacharya et al., 2009; Bindschadler et al., 1987; Koskinen et al., 1997).~~[35–37],~~ Subsequently, snowmelt detection algorithms have been developed using a host of radar sensors to monitor the onset and duration of snowmelt across glaciers and ice sheets (Abdalati and Steffen, 2001; Ashcraft and Long, 2007; Bahr et al., 1997; Jezek et al., 1994; Kayastha et al., 2019; Koskinen et al., 1997; Winebrenner et al., 1994).~~[20, 22, 24, 38–41],~~ Prior applications of SAR mapping of seasonal surface melting over ice sheets and glaciers have been limited by a lack of repeat observations such as those now available from the Sentinel-1 SAR constellation (Lund et al., 2019). ~~[42]. Launch of the Sentinel-1 C-band SAR constellation ushered the first openly-available SAR time series dataset for change detection at the Earth surface. Limited only by the frequency of observations (12-days per orbit direction).~~

Observations from time series SAR data have been~~are~~ used to delineate zones of glacier facies and regions of glacier mass balance (Winsvold et al., 2018).~~[31],~~ In glacier percolation zones, seasonally wet snow refreezes

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into ice lenses, pipes, and other percolation-related features that amplify both surface and volume scattering of C-band radar and result in the brightest SAR backscatter being captured during the frozen periods (Jezek et al., 1994; Rau et al., 2000).~~[26, 43],~~ Studies have shown that SAR backscatter ~~intensity~~ generally increases with elevation across glacier surfaces during frozen periods, from the glacier terminus, through frozen meltwater percolation zones, and eventually attenuating in zones where dry snow accumulates (Winsvold et al., 2018).~~[31],~~ In transitions between these zones there are pronounced backscatter contrasts rather than smooth, gradual transitions. At C-band frequencies, ~~strong~~ radar scattering within glacier percolation areas dominates the backscatter amplitude~~intensity signal~~ during frozen periods (Jezek et al., 1994).~~[26],~~ Importantly for melt retirevals, the diminished~~loss of~~ volume scattering during surface melting in areas of meltwater percolation creates a pronounced~~,~~ and unambiguous~~,~~ radar signature~~signal~~ in time-series observations. The sensitivity of SAR backscatter~~sensors~~ to the introduction of liquid water in~~to~~ an otherwise frozen snowpack or firn structure provides~~is~~ a reliable mechanism~~target~~ for the retrieval of percolation zone ~~glacier surface~~ melt characteristics (Lievens et al., 2019).~~,~~ In refreezing percolation zones, the upper layers of firn will freeze~~become frozen~~ first with the freezing front advancing~~and freeze~~ downward across layers, thus progressivly increasing backscatter and with decreasing total-column liquid water content (Ashcraft and Long, 2005).~~[44],~~ In this way, the timing of refreeze relative to the surface energy balance at the surface provides a direct and spatially resolved indicator of subsurface meltwater storage within the snow or firn and deliniates the percolation zones over mountain glaciers.

This study enlists~~This study applies methods used for decades in the canon of research on retrieving melt characteristics from glaciers and ice sheets but using~~ SAR data acquired at a spatiotemporal resolution that captures melt ~~can capture~~ variability across ~~a~~ mountain glacier surfaces suitable for constraining~~surface and with a frequency of data acquisition that can illustrate~~ seasonal characteristics of melt onset and duration while building on associated methods often employed for glaciers and ice sheets.~~,~~ In this paper we utilize SAR data to retrieve~~provide a brief history on the use of imaging radar for~~ melt status~~retrieval~~ on HKH glacier surfaces with~~to motivate~~ a simple threshold-based ~~method for~~ change detection classification melt/~~of surface~~ freeze~~/thaw~~ state - an observational constraint on the surface energy balance.~~,~~ It is likely that intense incident solar radiation is driving these melt processes at elevations above the 0ºC summer isotherm (Matthews et al., 2019)~~[17]~~ across the entirety of the HKH, and~~so~~ that the sensitivity of SAR backscatter~~sensors~~ to changes in the glacier surface melt/freeze condition as seen when water transitions between solid and liquid phases provides a real~~of glacier surfaces is a viable~~ alternative to temperature elevation lapse rate estimates of melting (Litt et al., 2019) for assessing~~rates [11] in order to develop and assess~~ surface energy balance models of glacier ablation. Though coarse in temporal resolution relative to ~~a~~ typical meteorological datasets~~dataset~~, retrieval of melt status using SAR time series produces mappings with very high spatial resolution and a continuous record of melt timing and duration across glaciated regions. We present an application of this melt

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retrieval technique at the scale of the HKH with spatiotemporal fidelity adequate to capture seasonal variability in melt timing and duration across individual glacier surfaces and capture sub-regional heterogeneities across the HKH.

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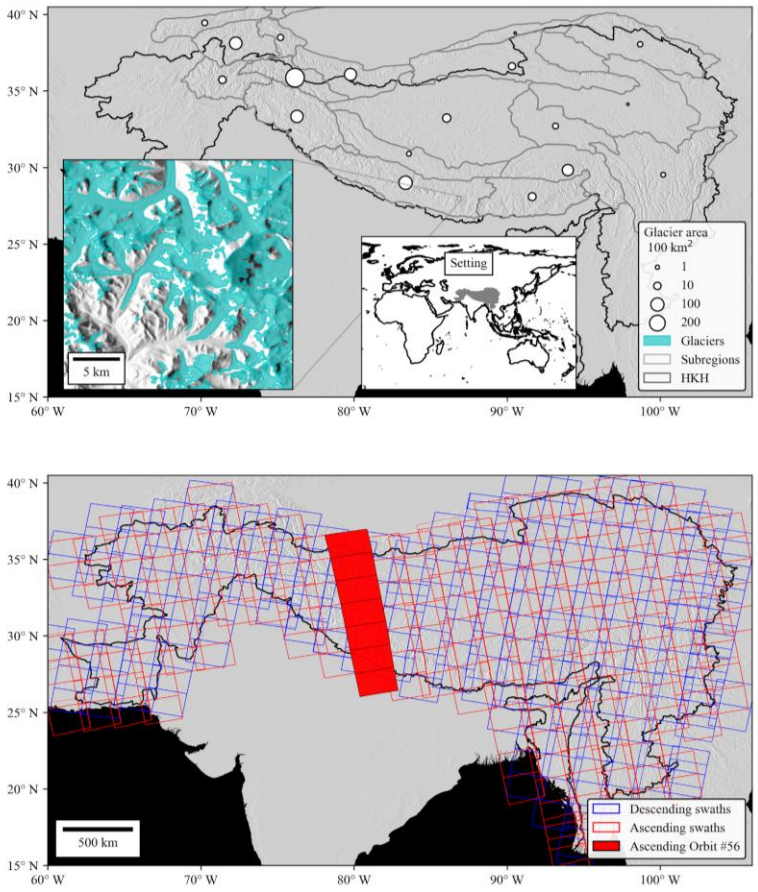
2 Setting and Data

The HKH region (*Fig. 1*) spans 13 million km^2, including areas inhabited by 240 million people with nearly 2 billion people relying on the delivery of water resources from catchments that originate within the region (Scott et al., 2019). Within the high elevation HKH, seasonal meltwater from snow and glacier ice is the primary source of domestic freshwater supply (Bolch et al., 2012). Wasting of HKH glaciers poses a risk to the domestic water resources supply for those populations living within these high elevation HKH catchments (Wood et al., 2020). Glacier wasting in the HKH is heterogeneous; increases in global average temperature have caused wasting of mountain glaciers across all HKH sub-regions, save the eastern Karakoram, Kunlun Shan, and adjacent sub-regions at the intersection of South and Central Asia (Gardelle et al., 2012). Distinct glacio-climatic sub-regions are characterized by these unique dynamics of glacier wasting (Bolch et al., 2019a). The wasting of HKH glaciers is thus a spatially and temporally heterogeneous phenomenon where distinct glacio-climatic regimes control ablation (Bolch et al., 2012). In this study, we refer to glacio-climate sub-regions delineated in Bolch, et al. (2019a) and modified by Shean, et al. (2020). These delineations of glacio-climate were produced by the Hindu Kush Himalaya Monitoring and Assessment Program (HiMAP) and we will refer to the sub-regional delineations as "HiMAP regions" throughout the text. We selected 17 HiMAP subregions that intersected with a boundary of the HKH region delineated by the International enter for Integrated Mountain Development (ICIMOD). The HKH region, HiMAP sub-regions, and glaciated area summaries within each HiMAP sub-region are illustrated in *Fig. 1* alongside Sentinel-1 acquisition plan.



2 Setting and Data

The HKH region (Fig. 1) spans 13 million km^2, including areas inhabited by 240 million people with nearly 2 billion people relying on the delivery of water resources from catchments that originate within the region [45]. Glaciers in the HKH region have been wasting rapidly alongside increases in global average temperature with the exception of the Karakoram mountain range at the intersection of South and Central Asia [46]. It has been argued that the Karakoram region has maintained a state of relative equilibrium in its glacier mass balance because of its high latitude and inland setting which shields the region from monsoonal controls on melt that are active in other Himalayan catchments [47]. The wasting of HKH glaciers is thus a spatially and temporally heterogeneous phenomenon where distinct glacio-climatic regimes control ablation across [48].

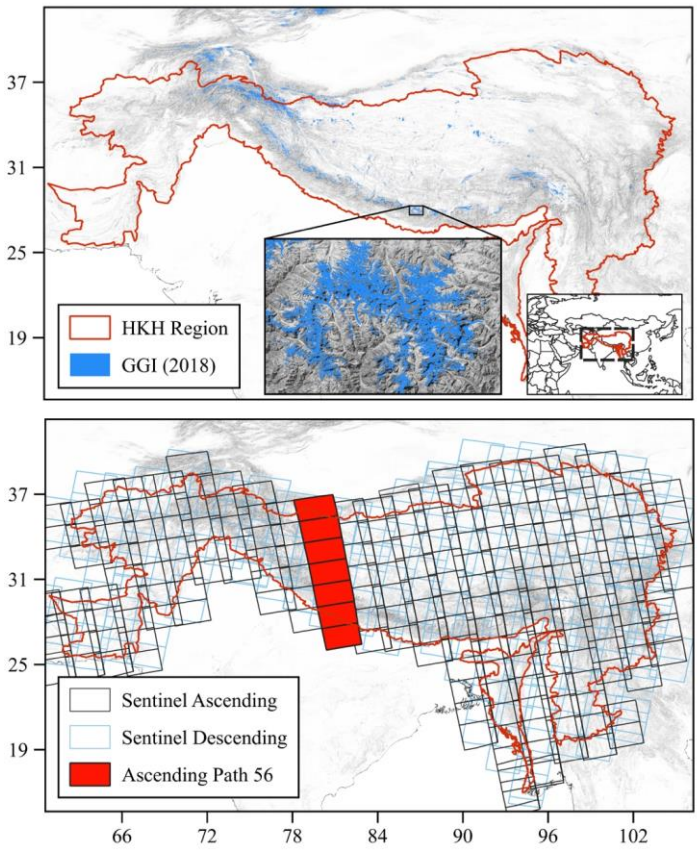


Figure 1.~~1.~~ (Top) Hindu Kush Himalaya (HKH) region ~~(red outline)~~ and 2018 GAMDAM glacierized areas summed across glacio-climate sub-regions from Shean, et al. (2020). An~~glacier inventory (GGI) (blue). The region highlighted with the~~ inset map highlights~~shows GGI glacier areas across~~ the spatial fidelity of GAMDAM outlines~~Trishuli Basin~~ in the top panel.~~Nepal.~~ GGI and HKH data overlay~~are overlaid onto~~ a 30m Shuttle Radar Topography Mission (SRTM) DEM hillshade (Farr, 2007a).~~hill shade.~~ **(Bottom)** Sentinel-1 ascending (red~~black~~) and descending (blue) swath footprints acquired across the study region. Ascending orbit cycle number 56 is highlighted in red to illustrate the SAR image processing approach for time series analysis across distinct orbit cycles.

2.1 GAMDAM Glacier inventory (GGI)

The Glacier Area Mapping for Discharge from the Asian Mountains (GAMDAM) glacier inventory (GGI) is a contemporary~~recently updated~~ (July 2019) database on glacier outlines for the region of High Mountain Asia (*Fig. 1*). These outlines were originally delineated automatically using cloud and snow-free satellite optical imagery in an initial release of the database (Nuimura et al., 2015).~~[49].~~ As a recent update to the database, each outline was

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individually inspected for quality control to correct discrepancies where automatic glacier delineation lost accuracy in terrain ~~-~~occluded areas, at debris covered portions of glaciers, and through obstruction under seasonal snowpack. The recently updated glacier outlines were derived from satellite optical imagery captured across the HKH by Landsat 5 and 7 between 1990-2010 (Sakai, 2019). Although these data are the most current in terms of quality control spanning the study region~~The recently updated dataset covers a much larger area than the previous version [50]. Although these data are the most current,~~ they do not necessarily capture debris-covered portions of glaciers due to confusion with land in optical image classification schemes; an issue that may be resolved with interferometric SAR phase decorrelation (Bolch et al., 2019b). The 2018 GAMDAM database contained within the HiMAP sub-regions includes 105,432 distinct glacier outlines spanning a total area of 83,102 km^2 within the HKH (Nuimura et al., 2015). ~~[51]. The 2018 GAMDAM database includes 76,831 distinct glacier outlines spanning a total area of 65,108 km^2 within the HKH [49].~~

2.2 Sentinel-1 Synthetic Aperture Radar

The Sentinel-1 A/B satellites were launched in April of 2014 and 2016, respectively, and collect C-band (5.405 GHz) SAR data with a combined revisit interval of 6-days over of the majority of the ~~mid-latitude~~ terrestrial Earth. Each Sentinel-1 scene acquired in the interferometric wide-swath (IW) mode has a width of 250 km and a resolution of 5x20 meters in range and azimuth at the equator. This study utilized~~considered~~ images taken in the IW mode and in ~~both co-polarized and~~ cross-polarized state (~~VV,~~ VH). Sentinel-1 data were accessed through a cloud-computing platform (discussed below) wherein SAR scenes were radiometrically terrain corrected to backscatter intensity values in decibels (dB) using the European Space Agency's (ESA) Sentinel Application Platform (SNAP) toolbox and the Shuttle Radar Topography Mission (SRTM) 30m digital elevation model (DEM) (Farr, 2007) upon ingestion into the cloud environment.~~[52] upon ingestion into the cloud environment.~~ Data from both the ascending and descending orbit nodes were analyzed across the study region for a total consideration of 32,741 individual Sentinel-1 A/B IW scenes across 46 unique orbit cycles captured across the calendar years 2017-2019 *(Table 1, Fig. 1b).* By combining orbit directions, we utilize observations acquired at day and night. For the purpose of this study we do not attempt to resolve diurnal-scale melt-freeze processes and instead focus on retrieving seasonal and annual characteristics of melt timing and duration.

Cross-polarized SAR backscatter provides enhanced observational sensitivity to volume~~volumetric~~ scattering of the radar signal in deep, dense and weathered snowpack and firn (Rott and Mätzler, 1987). We selected~~[27]. For this study we use~~ cross-polarized (VH) Sentinel-1 A/B observations ~~for the purposes of melt retrieval~~ because VH data show less angular~~of the greater~~ sensitivities to contrasts between dry and wet snow (Nagler et al., 2016). Cross~~volumetric scattering across frozen glaciated surfaces relative to co~~-polarized Sentinel-1 SAR did not become available over the HKH until early 2017 and thus restricted this study timeframe.~~observations.~~ As illustrated in *Fig.*~~Figure~~ *2*, we observe a large (>3dB) difference~~greater seasonal separability~~ in the seasonal radar backscatter~~brightness~~ between frozen and melting conditions across the entirety of glacier surfaces in cross-polarized (VH) SAR data~~ relative to co-polarized data (VV). This is especially apparent across areas of glacier ablation where VV data shows a limited response relative to VH data [53].~~

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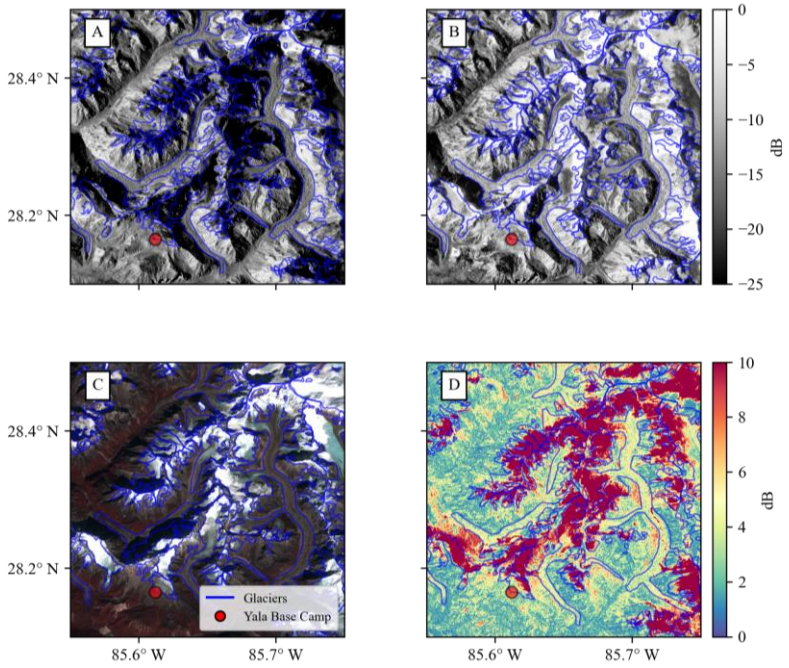
Table 1. ~~Number of~~ Sentinel-1 image count and orbit paths~~images~~ used in this study ~~by year and orbit cycle direction~~.

Orbit Direction	Number of S-1 Images by Year			Relative orbit cycle
	2017	2018	2019	
Descending	4,424	5,436	5,253	4, 5, 19, 20, 33, 34, 48, 49, 62, 63, 77, 78, 92, 106, 107, 121, 122, 135, 136, 150, 151, 164, 165
Ascending	5,302	6,097	6,150	12, 13, 26, 27, 41, 42, 55, 56, 70, 71, 85, 86, 99, 100, 114, 115, 128, 129, 143, 144, 158, 172, 173



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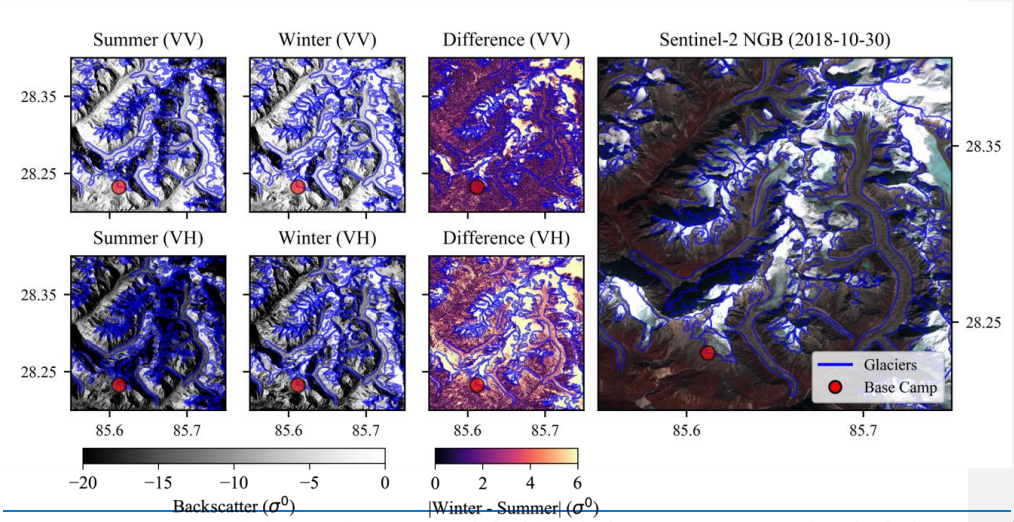

Figure 2. (A) Mean summer (July-August) 2018 cross-polarized (VH) backscatter across an example region in the Trishuli basin, Nepal. **(B)** Mean 2018 winter (January- February) VH backscatter from Sentinel-1. **(C)** ~~2.~~ Sentinel-2 false~~NGB: False~~-color (near-infrared, green, blue) image ~~of an example region (Trishuli basin, Nepal)~~ acquired by Sentinel-2 on October 30, 2018. Glacier outlines are shown in blue and the Yala glacier base camp meteorological station is marked in red. Note the snow covered and bare-ice portions of outlined glaciers and other debris-covered portions of glacier ablation areas. **(D)** The difference between mean summer and winter VH backscatter from Sentinel-1. ~~Summer (VV): Mean co-polarized (VV) seasonal backscatter from Sentinel-1 SAR A/B during summer (July–August) in 2018. Winter (VV): Mean VV backscatter during winter months (January–February). Difference (VV): The absolute difference between the mean summer and winter backscatter from Sentinel-1 during 2018 in the VV polarization. Note the larger seasonal difference across debris-free portions of glacier accumulation areas but a smaller magnitude seasonal difference across debris-covered portions of glacier ablation areas. Summer and Winter (VH): Mean 2018 summer and winter backscatter response of cross-polarized data from Sentinel-1 during 2018. Difference (VH): The absolute difference between mean summer and winter VH backscatter from Sentinel-1. Note the larger cross-polarized (VH) response across a greater amount of area compared to co-polarized (VV) data.~~

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2.3 Computing Infrastructure

A cloud-computing platform and application programming interface ~~(API)~~ with pre-processed radiometrically terrain corrected Sentinel-1 A/B data was used to detect melt characteristics across the region (Gorelick et al., 2017).~~[54],~~ Radiometric terrain correction of Sentinel-1 data was conducted upon ingestion to the cloud server using the ESA's method contained within the Sentinel Applications Platform (SNAP) processing toolbox. The SNAP toolbox is used for Sentinel-1 images to update orbit metadata with restituted orbit files, remove invalid edge data and low intensity noise, remove thermal noise, compute σ^0 backscatter, and conduct orthorectification upon ingestion of data to the server (Google, 2020). The SNAP toolbox ~~[55]. This method for~~

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~~radiometric~~ terrain correction functionality ~~(RTC)~~ utilizes the 30m spatial resolution SRTM DEM (Farr, 2007; Margulis et al., 2019). The pre-processed~~. The~~ SAR times series data and API functionality used to derive glacier melting characteristics are~~is~~ available from Google Earth Engine and can be used to recreate the work presented in this study ~~(GEE) [54].~~

2.4 Automated Weather Station Data

Measurements from two automated weather stations (AWS) are used to estimate surface energy balance (SEB) and evaluate surface melting conditions over high elevation glaciers. The Camp II (27.9810°N, 86.9023°E, 6,464 m a.s.l.) and the South Col (27.9719°N, 86.9295°E, 7,945 m a.s.l) AWS were installed around Mount Everest, Nepal as part of the National Geographic and Rolex Perpetual Planet Expedition to Mt. Everest in April-May 2019 (Matthews et al., 2019). Measurements were collected at an hourly interval and include air temperature, wind speed, relative humidity, incoming shortwave and longwave radiation and barometric pressure. Time series plots of meteorological observations are shown in *Supplementary Information Fig. S1*. Please see Matthews et al. (2020) for a complete description of sensor specifications and sampling interval.

3 Methods

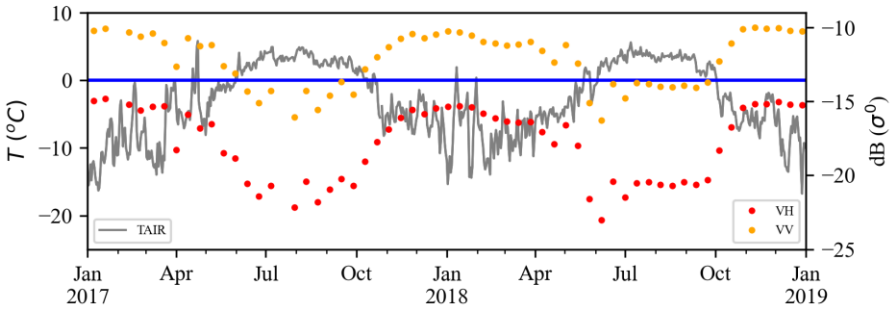
3.1 Melt Classification

We use a threshold-based change detection algorithm applied to time series radar backscatter intensity to classify melt conditions (Ashcraft and Long, 2007). ~~[40].~~ Melt detection is conducted across Sentinel-1 A/B ascending and descending orbit track time series separately and mosaicked into a final image based on a statistical score for seasonal melt magnitude after classification. To classify snowmelt, we conduct a pixel-based temporal classification by comparing each image at interval ***i*** to a dry/frozen winter average backscatter value calculated from January to February for each study year. Due to missing VH acquisitions at some locations during the 2017 frozen months, (Jan – Feb) we utilized 2018 frozen month reference data for melt retrieval across the calendar year 2017, as regular acquisitions across the HKH began in late February 2017. Snowmelt at each image acquisition interval (m_i) was classified using *Eq. (1)*:

$$m_i = \begin{cases} 1, & if\ {\sigma^0}_i < {\bar{\sigma}^0}_w - b, \\ 0, & if\ {\sigma^0}_i > {\bar{\sigma}^0}_w - b, \end{cases} \quad (1)$$

where the ground-range detected backscatter intensity at each image acquisition (${\sigma^0}_i$) within the times series must be less than the difference between the mean winter backscatter (${\bar{\sigma}^0}_w$) and a fixed threshold (b). Threshold values (b) have been developed across numerous studies of melt detection with C-band scatterometer and SAR datasets using both ground-based observations and radar scattering model results of changes to backscatter magnitude at the onset of melt. We ~~For the purposes of this study we~~ followed previous studies (Baghdadi et al., 1997;

Bhattacharya et al., 2009; Engeset et al., 2002; Nagler and Rott, 2000; Oza et al., 2011; Rott and Mätzler, 1987; Steiner and Tedesco, 2014; Trusel et al., 2012)~~[27, 35, 56-61]~~ and selected a ***b*** value equal to one half of the signal power (~~-~~(3 dB). *Figure 3* provides an illustration of the SAR melt signal for a~~Due to the lack of~~ high ~~-~~ elevation (4,950m a.s.l)~~meteorological data available across the study years, we were limited in our accuracy assessment to only one high elevation (>4,000m a.s.l.)~~ meteorological station, located at the Yala glacier base camp~~. (Fig. 3).~~ Backscatter values averaged across the Yala glacier ~~(4,950m a.s.l)~~ acquired along the Sentinel-1 A/B descending orbit direction are plotted alongside mean daily air temperature recorded at the Yala glacier base camp automatic weather station (Shea, 2016).~~[62].~~ If we consider air temperature above 0ºC to control glacier surface melt at this location, classification accuracy for melt retrieval using *Eq. (1)* is 96% in the VH polarization.



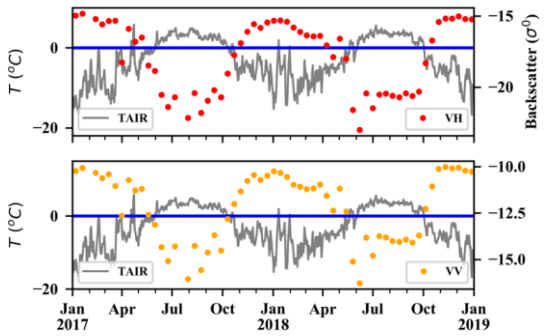


Figure 3.~~3. (Top)~~ Time-series chart of air temperature measured at the Yala glacier base camp (4,950 m~~950m~~ a.s.l) and Sentinel-1 A/B descending ~~VH polarized~~ backscatter averaged across the Yala glacier for the years 2017-2018. Assessment of algorithm performance assuming mean daily air temperatures above 0ºC indicates active melt results in 96% accuracy for melt classification across this time series in the VH polarized backscatter. ~~(Bottom) VV polarized backscatter time series averaged across the same glacier shows a smaller magnitude seasonal signal compared to the VH polarized backscatter data.~~

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3.2 Quantifying algorithm performance

Sentinel-1 SAR viewing geometry will vary as the local incidence angle increases with across-track range. At high incidence angles (far range), the sensitivity to volume scatter is diminished and the melting signal is reduced. At C-band frequencies, these effects on volume scatter are strongest only at very high incidence angles (closer to grazing) (Nagler and Rott, 2000).~~[57],~~ We classified areas as valid for melt detection using a metric of statistical separability for seasonal backscatter intensity across frozen and melt periods, which we interpret as a measure of the strength of the seasonal melt signal *Eq. (2)*:

$$z = \frac{\bar{\sigma}^0_w - \bar{\sigma}^0_s}{s(\sigma^0_w)}, \qquad (2)$$

where the score for seasonal separability of backscatter intensity (z) was calculated across each SAR pixel's time series using the difference between the mean winter $\bar{\sigma}^0_w$ (January-February) and summer $\bar{\sigma}^0_s$ (July-August) season backscatter intensities, as compared to the standard deviation of backscatter across the winter months $s(\sigma^0_w)$. In computing z, we employed consistent repeat-pass observation geometries thereby allowing application of the time series melt-detection algorithm in regions of complex terrain. This metric serves as a measure of the magnitude of the seasonal melt signal across each pixel's time series. It is used here as a criterion to identify valid melt observations and for selection of pixels employed in regions of overlapping orbital tracks, based on the sensitivity of~~to~~ the radar backscatter to melting. We apply this metric to choose which orbit direction (ascending or descending) to use for melt classification on a per-pixel basis after applying *Eq. (1)* across each orbit cycle time series, so as to capture the maximum area of melt signals occurring across the complex terrain.

Sentinel-1 A/B interferometric wide (IW) swath images have a range in viewing angle between 29.1-46.0° (ESA). Glacier melt retrieval using SAR data commonly begins with a normalization of radar images by viewing angle on a scene by scene basis (Adam et al., 1997; Huang et al., 2011; Rott and Mätzler, 1987; Winsvold et al., 2018). We consider changes for each individual orthorectified 10x10m pixel time series across distinct, repeating orbit tracks and directions. This approach holds the local incidence angle effectively constant for each region observed by a given set of orbit tracks.~~We consider the seasonal signal valid for time series melt detection if the~~ Glacier melt classification and **z**-score calculation are carried out across images acquired along identical orbit tracks in distinct orbit directions (*Fig. 1*) and mosaicked into a final dataset for each study year using the greatest **z**-score observed across each orbit cycle path and in each orbit direction. We thus limit temporal resolution of melt retrievals to 12-days by choosing only observations from the orbit direction with the greater **z**-score on a per-pixel basis. Time series analysis of SAR acquisitions on distinct orbit tracks eliminates the need to normalize each scene by incidence angle for the purposes of melt retrieval. This method reduces computational cost and eliminates artefacts that may originate from overlapping orbit paths and differences in radar viewing angle. Areas where complex topography controls the backscatter should show little time series variability in backscatter change at the SAR pixel scale when viewed at a distinct and consistent orbit path and direction and should not pass the **z** score test.

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We apply time series melt detection only where inter-seasonal backscatter intensities are separated by greater than two standard deviations (**z** > 2), representing better than 9895% confidence in the presence of an annual melt signal. For all locations, the ~~To choose which~~ orbit direction and orbit cycle that has the greatest **z** value is used~~to use~~ for melt classification., ~~we pick the pixel with the greatest z.~~ We find that **z** generally increases with elevation across sub-regions~~subregions~~ of the HKH ~~(Karakoram, western, central, and eastern Himalaya) up to about 5,000m a.s.l.~~ and that, across elevation ranges, the mean **z** is above the threshold for melt retrieval, indicating detection of a seasonal melt signal across all ranges of glacier elevation spanning the ~~four major glacio-climatic subregions of the~~ HKH (*Fig. 4*). Areas of debris-cover may exhibit radar brightening with snow-free conditions above winter mean (**z** < 0). These areas occur towards lower elevations where seasonal snow, or firn, does not have significant contribution to the seasonal backscatter response and are not included in our melt classification approach~~.~~

~~Sentinel-1 A/B interferometric wide (IW) swath images have a range in viewing angle between 29.1-46.0° [63]. Glacier melt retrieval using SAR data commonly begins with a normalization of radar images by viewing angle on a scene by scene basis [25, 38, 64, 65]. We consider changes for each individual 10x10m pixel time series across distinct, repeating orbit tracks and directions. This approach holds the local incidence angle effectively constant in time. Glacier melt classification and z-score calculation are carried out across images acquired along identical orbit tracks in distinct orbit directions (*Fig. 1*) and mosaicked into a final dataset for each study year using the greatest z-score observed across each orbit cycle path and in each orbit direction. We thus limit temporal resolution of melt retrievals to 12-days by choosing only observations from the orbit direction with the greater z-score. Time series analysis of SAR acquisitions on distinct orbit tracks eliminates the need to normalize each scene by incidence angle for the purposes of melt retrieval. This method reduces computational cost and eliminates artefacts that may originate from overlapping orbit paths and differences in radar viewing angle.~~ following **z**-score thresholding. Nonetheless, there exists retrievable melt signals (i.e. **z** > 2) across ablation surfaces such that median window filtering across ablation zones can result in a geospatial dataset with more complete coverage. We ~~Areas where local incidence angle varies significantly because of complex topography should show little time series variability in backscatter change at the SAR pixel scale when viewed at a distinct and consistent orbit path and direction.~~

obtain more robust estimates of melting onset and refreeze by spatially aggregating results of the glacier surface melt timing (*Eq. 1*) using a median window filter of 9x9 pixels after melt classification and **z**-score validation. Reach-scale regions where SAR signals fail the **z**-score test are thus interpolated over using 9x9 pixel median window filtering. The complexity of SAR signals involves the diverse scattering mechanisms on ablation surfaces following the disappearance of seasonal snow. Because sufficient data is retrievable on ablation surfaces (i.e. **z** > 2), median window filtering enables greater spatial continuity in SAR-derived melt retrieval data. All spatiotemporal characteristics we report herein are after median window filtering of melt retrievals from 10m native resolution to 90m resolution. In *Fig. 4* we show the mean **z** across HiMAP sub-regions in order to illustrate that, on average, even where debris-covered portions of glaciers may exhibit an inverse response to melt with the disappearance of snow, Sentinel-1 records a mean **z** indicative of a seasonal snowmelt signal across all elevation ranges of glaciation. Mean seasonal melt magnitude averaged over 100m elevation bins over all three calendar years of data shows strong (**z** > 2) melt signals across glacio-climatic sub-regions and across all elevation ranges of significant glaciation (*Fig. 4*). ~~4). The occurrence of seasonal melt signals across all ranges of elevation in the HKH is both noteworthy and striking. Until very recently, glacier ablation in the HKH region has been treated in numerical model studies to be controlled by air temperatures greater than 0ºC [11]. Our finding that SAR backscatter time series observe pronounced~~

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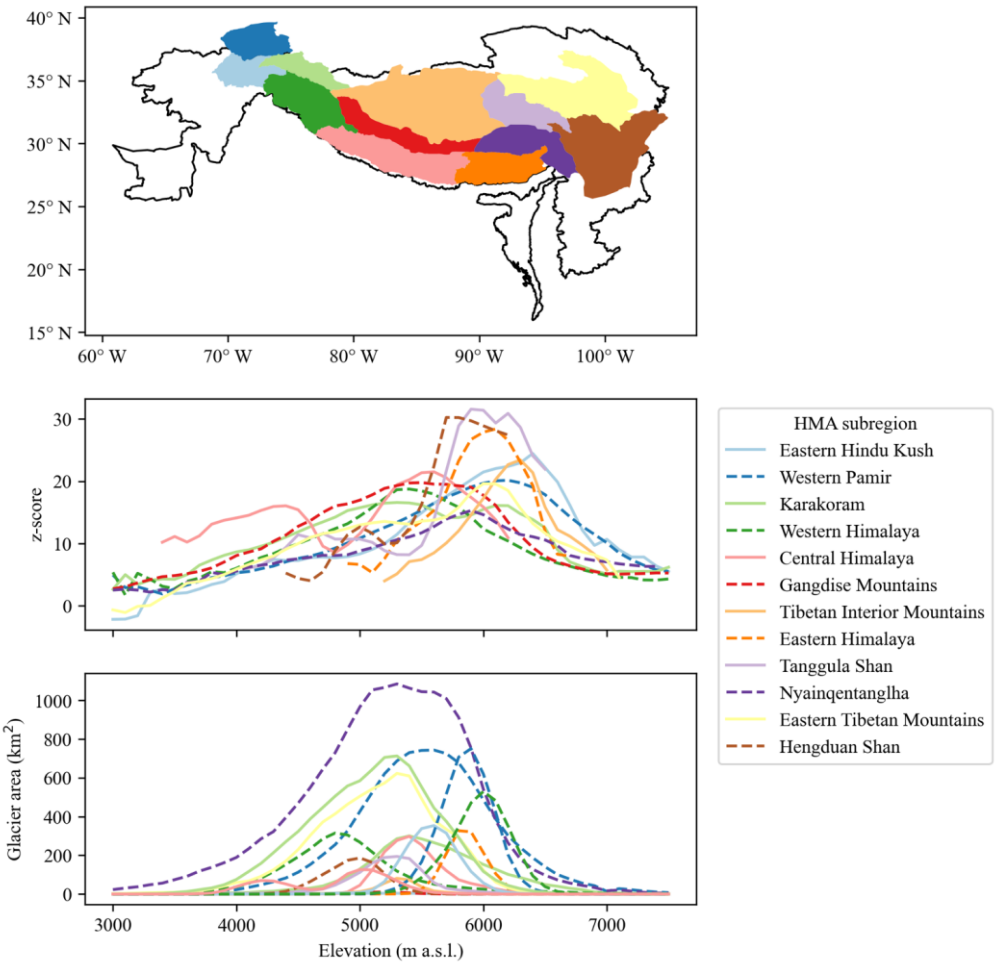
~~melt/freeze cycles across high elevation ranges of HKH glaciers supports other recent findings that intense incident solar radiation is driving glacier melt processes at elevations above the 0ºC monsoon season isotherm [17].~~



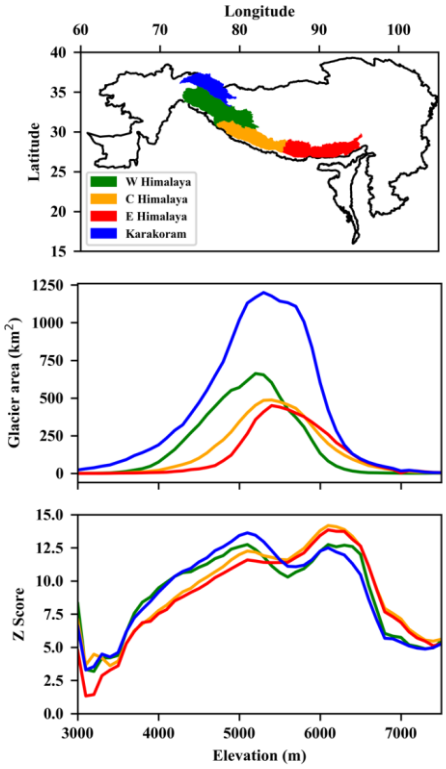


Figure 4.4. **(Top)** Glacio-climate ~~The Hindu Kush Himalaya (HKH) region (black outline) with four major Randolph Glacier Inventory glacio-climatic~~ sub-regions ~~. (Middle) Glacier area by elevation for each sub-region identified~~ within the Hindu Kush Himalaya codified in Shean, et al. (2020). **(Middle)** Mean z-score (2017-2019) by 100m SRTM elevation bin over each sub-region in the HKH. ~~2018 GAMDAM glacier inventory database.~~ **(Bottom)** Mapped glacier area from ~~Average magnitude of~~ the GAMDAM database (Sakai, 2019) ~~seasonal melt signal (z) for all three study years~~ over 100m SRTM (Farr, 2007) elevation bins for ~~in~~ each sub-region.

3.3 Surface Energy Balance and Surface Melting

Sentinel-1 SAR (S1-SAR) detects ~~of the HKH. Note how, on average, there is~~ a substantial area and duration of melting at ~~strong seasonal melt signal (z > 2) across all~~ elevations where air temperatures should be well below freezing. Although measurement data in these areas are scarce, AWS installed during 2019 at Mt Everest Nepal can provide two instances of point-scale validations of glacier melting using surface energy balance (SEB) modelling based on *in situ* measurements. As described in Matthews et al. (2020), the highest AWS on the Earth are installed adjacent to the Khumbu Glacier, Nepal. We use AWS observations to compute SEB described in

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Matthews et al. (2020). In our SEB modelling, turbulent fluxes are determined using the aerodynamic roughness at the glacier surface taken from measurements in low latitudes (Brock et al., 2006) and evaluated over the 5th to 95th percentile of this sample to capture uncertainty. Surface melting is defined by the glacier surface temperatures (T_s) that is evolved from air temperatures and the residual downward glacier heat flux in the iterative approach from Wheler and Flowers (2011). Melting days are defined where $T_s = 0^o C$ at any point during the day. Supplementary information for this paper is provided to describe the SEB methodology in further detail (*Supplementary Information Section S1.1).*

A comparison of S1-SAR and SEB derived melting is shown in *Fig. 5*. During 2019, the average daily air temperature measurements at the Camp II station (*Fig. 5A*) are never above zero but experience above zero maximum glacier surface temperatures during starting in June 2019 and ending in September 2019. At the South Col AWS, the average temperature is much less, close to -10ºC on average during summer months (*Fig. 5B*). S1-SAR estimates of surface melting use two aggregated backscatter time-series over 90m x 90m areas where area centers are located nearest to each of the AWS stations over the Khumbu glacier, Nepal. For the Camp II AWS, this is centered at 6,483 m~~>3,600m~~ a.s.l. and for the South Col AWS, 7,128 m a.s.l. Melting signals are apparent at both Camp II (*Fig. 5C*) and South Col (*Fig. 5D*). A more robust comparison would match the timings of satellite overpasses and meteorological observations and acknowledge that some disagreement between melting estimates is resultant from this difference.

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Melting is detected at high elevations in both SAR observations and SEB modelling output where daily average air temperatures remain below zero. We find that S1 and SEB estimates of surface melting at the Everest Camp II AWS (6,464 m a.s.l.) have an agreement score, the percentage of days where the SEB and SAR find the same condition, that ranges from 73% to 85% depending on the parameterization of surface roughness used in SEB estimates of melting. At Mt. Everest South Col (7,945 m a.s.l.) the agreement score varies from 63 to 68 percent We find that the S1-SAR finds 133 days of melting at Camp II while the SEB indicates from 93 to 100 days. At Mt. Everest South Col the S1-SAR finds 72 days of melting while the SEB indicates 43 to 56. The start of surface melting at Camp II from SEB modeling is day of year (DOY) 153 and DOY 142 from S1-SAR, at South Col melt onset is DOY 152 from SEB and DOY 146 from S1-SAR. The end of surface melting at Camp II from SEB modeling is day of year (DOY) 270 and DOY 290 from S1-SAR. At South Col, refreeze at the surface from SEB is DOY 256 and DOY 244 from S1-SAR.

Using SEB outputs we find good agreement on surface melt timings, S1-SAR detects melt onset to within 9 days on average at two locations on the Khumbu Glacier in Nepal and refreeze to within 16 days. Although limited by observational data, the agreement in melt duration between S1-SAR and SEB modeling, and the understanding of the physical basis of SAR measurements we have a high degree of confidence in our methodology and in the ability of the SAR backscatter to detect melting-and in data-poor regions such as HMA.

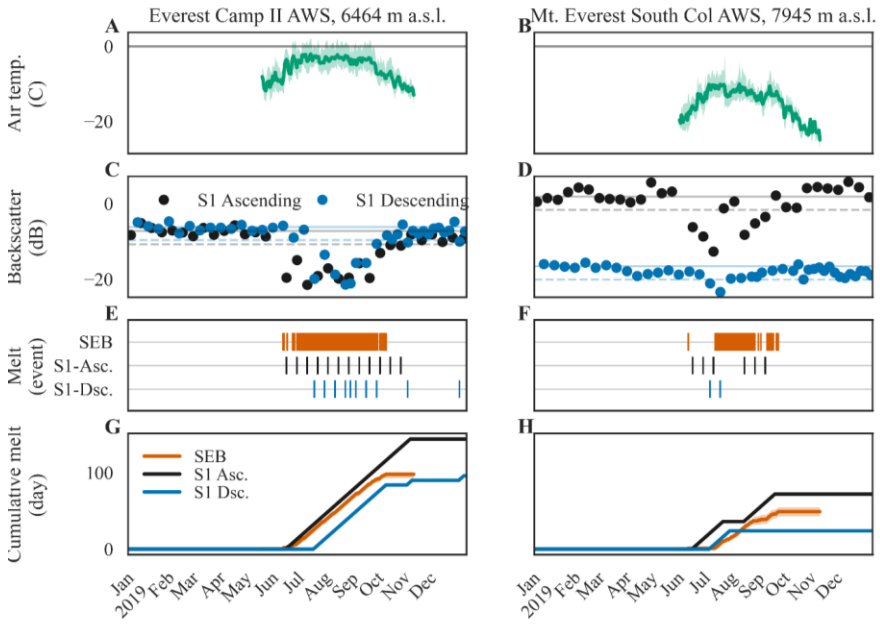

Figure 5. Air temperature measurements from (**A**) the Everest Camp II automated weather station (AWS) and (**B**) the Mt. Everest South Col AWS are compared to glacier surface melting observations from the Sentinel-1 satellite synthetic aperture radar (SAR). (**C**) The radar backscatter from the Khumbu Glacier (at 6,483 m a.s.l.) adjacent to the Camp II AWS, show a pronounced decrease in backscatter over several months associated with on-going surface melting during summer months. Melting is identified when backscatter decreases below a threshold (dashed-line), set at 3 dB below the winter mean (solid-line). (**D**) At the upper reaches of the Khumbu Glacier (7,128 m a.s.l.), S1-SAR observes melting during ascending passes (18:00 local time) but not during descending passes (06:00 local time) except for a brief period during late June., (**F**) Timing of surface melt from observation and SEB modeling are compared to S1 ascending and descending observations at (**E**) Camp II and (**F**) South Col AWS. The cumulative number of melting days from the SEB model and S1-SAR are shown for (**G**) Camp II and (**H**) South Col.

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3.3 Comparison to temperature elevation lapse rates

Melting on glacier surfaces across the HKH is controlled by the ~~surface energy balance (~~SEB~~)~~ between the atmosphere and underlaying snow, firn or ice. We explore the relationship between the S1-~~Sentinel-1~~ SAR derived surface melting record and air temperature-elevation lapse rates within ~~since measurements of SEB components like radiant energy fluxes are scarcely measured in the HKH and difficult to extrapolate [66]. Air temperature across elevations in~~ the Central Himalayas ~~are determined~~ during 2018 using data~~from temperature-elevation lapse rates derived~~ from two meteorological stations within the Langtang Valley (*Table 2*). Temperature-elevation lapse rates were determined using three-day averages of hourly

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air temperature measurements ~~that were~~ interpolated to fill gaps using methods identical for the calculation of temperature elevation lapse rates in numerical model studies of snowmelt and glacier wasting in the HKH (Baral et al., 2014).~~[67].~~ We calculated the difference between three-day average air temperatures and divided by the difference in elevation (1,148 m~~148m~~) between the two stations in the Langtang River Valley, Nepal. Lapse-rates ranged from 5ºC km^{-1} in July of 2018 to -13.7ºC km^{-1} in December of the same year. Temperature--elevation lapse rates were used to extrapolate the maximum elevation of three isotherms (-10ºC, -5ºC, and 0ºC) for each day of year in 2018 in order to compare extrapolated temperatures with melt retrievals from Sentinel-1.

Table 2. Sources of air temperature data used to calculate 3-day average temperature-elevation lapse rates within the Central Himalaya for the 2018 calendar year.

STATION NAME	DATE RANGE (DD/MM/YYYY)	RESOLUTION	ELEVATION (M A.S.L.)	LATITUDE	LONGITUDE	SOURCE
YALA GLACIER	05/08/2012 – 12/31/2018	Hourly	4,950	28.23252	85.61208	ICIMOD ~~[52]~~
KYANGING STATION	03/22/2012 – 12/31/2019	Hourly	3,802	28.21081	85.56169	ICIMOD ~~[61]~~

4 Results and Discussion

A melting signal ($z > 2$) is observed across all mapped glacier area contained in the GAMDAM inventory. Melt retrievals are aggregated across 17 glacio-climate sub-regions within the HKH delineated within the HiMAP dataset (Shean et al., 2020) and averaged across the calendar years 2017-2019 to report summary statistics (*Table 3*). Aggregate statistics of melt onset (MO) and freeze onset (FO) are calculated across 100m elevation bins using the 30m SRTM (Farr, 2007) digital elevation model for each glacio-climate sub-region as presented in *Figure 4*. For all sub-regions, there is a roughly linear relationship of mean MO with elevation over most ranges in elevation. The progression of MO with increasing elevation is consistent with lapse rate temperature controls on surface melting for most elevation ranges. Notably, we find an inflection toward earlier melt onset occurring at higher elevations (>6,500 m a.s.l.). A divergence from lapse-rate driven melting at high elevations suggests that snowmelt onset may have regional triggers, like strong solar insolation (Matthews et al., 2019) or variable regional weather patterns; such as increases in atmospheric moisture, cloudiness, and deep convection (Lau et al., 2010).

In the three years of freeze onset (FO) across sub-regions we do not find the level of elevation dependence as observed in MO (*Fig. 6*). For much of the HKH, FO occurs during a short period of time and over large spans of elevation. For example, in the Central Himalaya sub-region, FO has a range of 33 days while the MO for this region spans 79 days on average. FO across sub-regions does not follow a linear trend with elevation similar to MO (*Fig. 6*). In western sub-regions (Eastern Hindu Kush, Western Pamir, and Karakoram), there is a signal of delayed refreeze apparent in summary statistics at higher elevation ranges within each respective catchment. In the Western Pamir, FO at 6,000 m occurs 22 days later than FO at 5,000m a.s.l (*Supplementary Fig. S2*). Similarly, in the

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Karakoram, FO occurs 10 days later at 7,500 m a.s.l. compared to 6,500 m a.s.l. In the Tanggula Shan, FO at 6,500 m a.s.l. is delayed by 21 days relative to FO at 5,500 m a.s.l.

Signals of delayed refreeze are observed at elevation ranges similar to greatest **z**-score across each sub-region. Complete refreeze across the depth of a percolation zone is delayed relative to percolation zone surfaces because liquid water is retained within a percolation zone media after the surface of the percolation zone has frozen (Paterson, 2016). Completely frozen percolation zones produce some of the largest radar backscatter responses on the terrestrial earth (Jezek et al., 1994). Because frozen snow and percolation facies are essentially transparent, C-band SAR will be sensitive to the presence of liquid water across the volume of a snowpack or firn strata (Fischer et al., 2019). Signals of delayed refreeze across sub-regions are indicative of meltwater storage within the percolation volume due to meltwater retention. A figure illustrating melt timings and **z**-score metric is included as Supplementary materials (*Supplementary Fig. S2*).

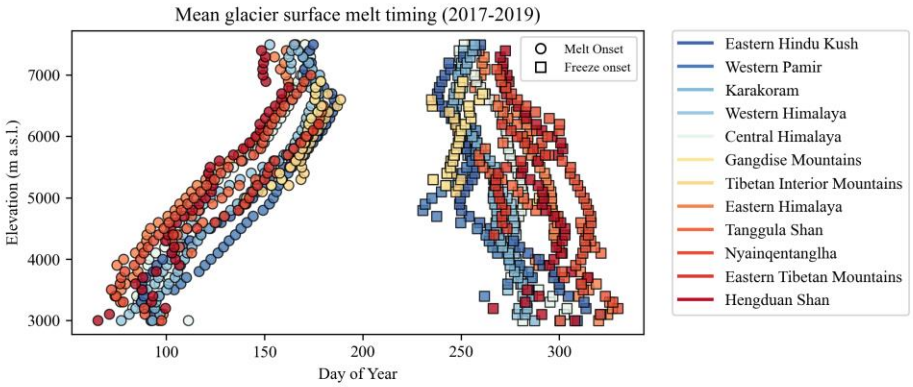

Figure 6. Mean melt onset (MO) and freeze onset (FO) summarized in 100m elevation bins using the 30m SRTM digital elevation model (Farr, 2007) and 12 HiMAP sub-regions (Shean, 2020). The blue to red color scale indicates the longitude of the HiMAP region centroid, where the westernmost regions are shown in dark blue and easternmost shown in dark red.

Table 3. Melt retrieval statistics summarized across HiMAP sub-regions and aggregated over 1km elevation bins from the SRTM 30m DEM. Data for each elevation bin and sub-region are structured where the first row is the melt onset (MO) in day of year (DOY) and associated MO variance in days, freeze onset (DOY) and associated variance (days), and the area of melt retrieved in units of square kilometers.

~~We report melt onset (MO), freeze onset (FO), and the frequency of melt retrievals across each study year, termed the annual melt fraction (AMF), across the HKH cryosphere for the calendar years 2017-2019. A melting signal is retrieved across 97% (62,907km^2) of the mapped glacier area contained in the GAMDAM inventory. Between the Eastern (EH), Central (CH), Western Himalayas (WH) and Karakoram (K) we find similar mean glacier area with elevation, with the EH and CH having slightly higher minimum elevations compared to K and WH (Fig. 4b). In a comparison of the strength of the observed melting signal, we find that the EH and CH show a maximum at close to 6,000m a.s.l. compared to the WH and K at much lower elevations (~5,000m a.s.l.) (Fig. 4c). The maximum **z** indicates the greatest seasonal contrast in C-band backscatter. Since bright radar signatures and strong seasonal contrasts during melting are indicative areas of percolating snowmelt, these results suggest a percolation zone skewed towards higher elevations in the EH and CH relative to the WH and K where these zones appear distributed over a larger range in elevation.~~

~~We detect melt earlier in the year and for a longer portion of each year in the central and eastern Himalaya compared to the western Himalaya and Karakoram regions. Glacio-climatic dynamics characteristic of HKH sub-regions are apparent in summary statistics of melt retrievals: melt onset occurs about one week (6 days) earlier at elevations between 3,500m and 7,000m a.s.l. across the CH and EH relative to the WH and Karakoram (Table 2). Freeze onset in the CH and EH similarly occurs one week (7 days) sooner relative to the WH and Karakoram on average between 3,500m and 7,000 m a.s.l. The AMF is only about 2.5% greater on average in the EH and CH compared to the WH and Karakoram between elevations of 3,500m and 7,000m a.s.l. At elevations below 4,000m a.s.l. across the entire HKH region, melt is retrieved across 79% of mapped glaciers versus 96% of mapped glacier area above 4,000m a.s.l. in elevation. The reduced consistency in glacier melt-area retrievals at elevations where higher temperatures are expected is likely due to a thinner seasonal snowpack and reduced magnitude of the melting signal (reduced **z**). Here seasonal backscatter changes do not have a large volume scattering component. Considering this, records from these elevations that are missing or indicating anomalous frozen conditions at elevations below 4,000m a.s.l. are likely errors rather than actual non-melting conditions. Similar mischaracterization of seasonal melt onset at low elevations (<4,000m a.s.l.) we interpret as a contribution from the debris-covered surfaces of the glacier exhibiting a radiometric response characteristic of freeze/thaw processes in soils [68].~~

~~A summary of glacier melt timing with elevation averaged across study years is shown across 100m elevation bins in Figure 5 and tabulated across 1km elevation bins in Table 2. Due to errors in melt classification at elevations below 3,500m a.s.l., we will summarize our observations across elevations >3,500m a.s.l. and assume that the relatively small glaciated area at elevations at or below 3,500m a.s.l. is negligible for the purposes of identifying trends across regions and elevation. We find an earlier MO at lower elevations, as expected from temperature-elevation lapse rates, beginning in mid-March in the eastern Himalaya and progressing to the Western, Central and Karakoram regions into late April (Fig. 5). Above 5,000m a.s.l. there is less variability in MO timing with elevation, but there is distinct regional variability where melt onset occurs on average 5 days sooner in the CH and EH regions compared to the WH and K regions. MO in the EH and CH between elevation ranges of 3,500m – 5,000m a.s.l. occurs one week~~

sooner (7 days) than the WH and K regions. Freeze onset shows greatest regional variability at elevation ranges between about 5,000m and 6,500m a.s.l., occurring nine days later on average in the CE and EH compared to the WH and Karakoram. At elevations greater than 7,000m a.s.l., both melt and freeze onset appear to occur contemporaneously across glacio-climate subregions; with less than three days of difference between the WH/Karakoram and the CE/EH.

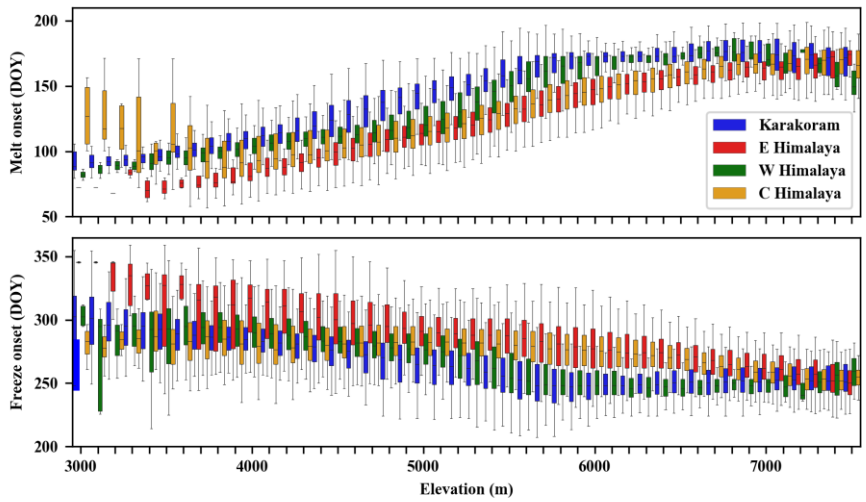

Figure 5. Boxplots of melt onset and freeze onset averaged over 2017-2019 in 100m elevation bins across four glacio-climatic domains of study region (Karakoram, western, central, and eastern Himalaya). **(Top)** Melt onset for each sub-region. Within elevation ranges of significant glacier area (3,500-7,000m a.s.l.), melt onset occurs later in the year in the western Himalaya and Karakoram relative to the central and eastern Himalaya. **(Bottom)** Freeze onset for each glacio-climatic subregion. Freeze onset occurs later on average in the central and eastern Himalaya relative to the western Himalaya and Karakoram, most pronounced within elevations between 5,000m-6,800m a.s.l.

Table 2. Melt onset (MO), freeze onset (FO), and annual melt fraction (AMF) averaged over all three study years (2017-2019) across glacio-climatic sub-regions identified in the Randolph Glacier Inventory summarized across 1000m elevation bins. Melt retrieval generally increases with elevation due to the homogeneity and strong frozen scattering across regions of glacier percolation. Standard deviation for melt and freeze statistics could not be reported at elevations greater than 7,000m due to limited sampling frequency and are instead reported as missing data (N/A).

HKH Sub-Region	Elevation (m a.s.l.)	Glacier Area (km²)	Melt Area Detected (km²)	MO (DOY)	MO (std)	FO (DOY)	FO (std)
Central East Himalaya	3000 90 (21)	277 (22) 24	492 23	104 (17) 93	274 (14) 3	1492 309	134 (20) 8
							274 (17) 34%
							7374 5
							156 (12) 2
							268 (15)
	4000	587	557	109	7	292	

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Western Pamir	117 (20) 6000	275 (28) 1946	602 1881	141 (16) 172	255 (23) 2	5271	159 (12)	250 (16)	4103	177 (13)	243 (12)
Western Himalaya	94 (9)	280 (22)	156	113 (14)	275 (15)	3651	138 (20)	263 (22)	6135	163 (11)	247 (13)
Tibetan Interior	-5000	- 1151	- 1105 9	136 (1) 152	299 (11) 16	<1 259	166 (11)	249 (14) 26	3109	172 (12)	249 (12) 1
Tangg-ula Shan	-	-	-	120 (13)	290 (14)	17	161 (13)	265 (20)	2184	169 (9)	284 (29)
Nyainqe-ntanglha	79 (19) 400 0	300 (38) 573	145 553 1	105 (13) 117	310 (18) 8	2637 28 4	131 (18) 5	302 (24) 38	5253	150 (11)	294 (22)
Karakoram	3000			968		946	96		6		293
	7000			8		8	159		10		253
	6000			333		316	173		2		248
Karako-ram	105 (19) 50 00	278 (23) 50	955 48 08	128 (20) 14	268 (19)	5889 26 0	152 (15)	262 (19)	15060	170 (17)	249 (13)
	4000			3616		3437	113		4		284
Hengduan Shan **Western Himalaya**	90 (27) 3000	294 (39) 205	11 195	113 (17) 93	294 (21) 7	231	121 (24)	289 (24)	1245 7	146 (15) 33%	289 (16) 6
	7000			50		49	168		6		252
	6000			1053		1019	170		4		255
Gangdise	-5000	-4476	-4264	-143	-16	-267	164 (14)	247 (11)	1123	166 (10)	250 (9)
Eastern Tibetan	-4000	-1493	-1418	136 (10) 109	268 (12)	26	151 (10)	275 (15)	381	173 (7)	280 (5) 284
Central Himalaya	3000			63		59	94		4		293
	7000			61		59	169		4		254
Eastern Hindu Kush	6000 101 (13)	276 (42) 1340	89 1293	131 (17) 169		257 (27)	2179 2	152 (12)	253 (16)	1333	180 (13)
Eastern Himalaya	5000 75 (17)	293 (46) 395	25 3774	102 (20) 144	292 (24) 16 4	353 272	129 (18) 9	290 (20) 29	2621	152 (13)	279 (18)

Elevation Range (m a.s.l.)	3000 - 3999	4000 - 4999	5000 - 5999	6000 - 6999

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4.1 Percolation Meltwater Hydrology

Delayed freeze-up apparent in summary statistics at unique elevation ranges across glacio-climate sub-regions is an important illustration of how melt retrievals from Sentinel-1 are sensitive to the presence of liquid water within the snowpack and/or firn subsurface (Brangers et al.; Fischer et al., 2019). At the Khumbu glacier on Mount Everest, Sentinel-1 retrieved refreeze occurs over thirty days later at ~6,000m a.s.l. compared to elevations below 5,400m a.s.l. and above 6,200m a.s.l., indicating that liquid meltwater was retained at elevation ranges between ~5,400-6,2000m a.s.l. during a month when elevations both above and below this range were recorded as completely frozen within Sentinel-1 retrieved melt signals. The time series of mean Sentinel-1 SAR backscatter for descending orbital nodes from two 250m buffered points on the Khumbu glacier show a rapid increase in SAR backscatter magnitude for the higher elevation location, whereas backscatter time series extracted from within the elevation range of delayed melt offset show a gradual increase in radar backscatter. We interpret this gradual backscatter increase to be indicative of gradually decreasing liquid water content in the snowpack (or firn) as refreeze progresses from the glacier surface and into the depth of the percolation zone (*Fig. 7*) (Forster et al., 2014; Miège et al., 2016). This elevation range (~5,400-6,200 m a.s.l.) is similar to known elevation ranges of percolation zones on the Khumbu glacier as detailed in recent field work (Matthews et al., 2019; Matthews et al., 2020). SAR backscatter time series showing a gradual increase in backscatter within regions of known percolation suggest that a relationship between frozen percolation zone depth and the rate of C-band backscatter change across refreeze cycles. It has been shown that C-band backscatter gradually increases with frozen percolation zone depth and decreasing percolation zone wetness during a refreeze process (Ashcraft and Long, 2005).

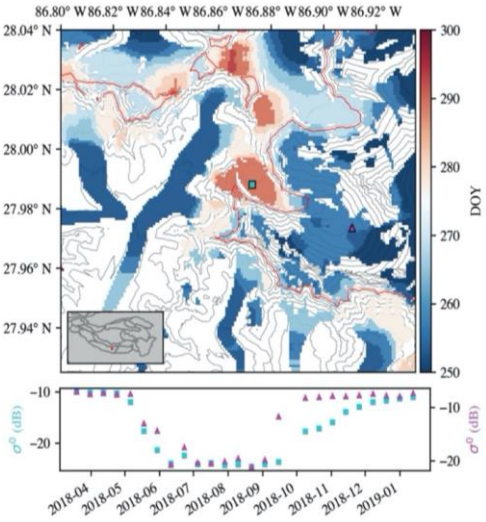

Figure 7. (Top) Refreeze timing over Khumbu glacier region of Mount Everest in the Central Himalaya. Red regions of freeze onset occur at mid-elevations, indicative of delayed refreeze due to meltwater retention in percolation zones. **(Bottom)** Sentinel-1 backscatter time series from two points on the Khumbu glacier, one within known elevations of glacier percolation facies (teal square, 6,000 m a.s.l.) and another point at elevations where temperatures likely do not exceed 0ºC annually (pink triangle, 6,600 m a.s.l.).

Spatial Variability:

~~4.~~14.2 Radar Scattering and Glacier Facies

Imaging radar backscatter intensity, and response to surface melting, is linked with glacier facies (Ramage et al., 2000; Rau et al., 2000; Zhou and Zheng, 2017). Snow melting on the glacier surface produces a strong decrease in radar backscatter across all glacier facies. In the accumulation zone the refreeze signal is also pronounced as the dissipation of strongly absorbing wet snow at the surface is followed by volume scattering from deep snowpack and stratified ice layering. The scattering response to refreeze in the ablation zone is more complex and not well characterized. Here, supra-glacier ~~meltwater~~ features like crevasses, sun-cups, debris-cover, and other heterogeneities are likely to cause highly variable radar scattering mechanisms over short distances upon the disappearance of snow from the ablation surface. (Rott and Mätzler, 1987). We use the **z**-score metric to select areas where radar backscatter increases substantially during the refreeze process. However, since scattering response during the transition from wet snow will differ with various surface features (e.g. bare ice, debris and supra-glacier ponding) it is difficult to isolate the refreeze response. ~~[27]~~ Average **z** is minimum in the HKH across the lowest elevation glacier surfaces (2~~3~~,000m-4,000m a.s.l.) whereas **z** is maximum at unique elevation ranges within sub-regions (*Fig. 4, Supplementary Fig. S2.*). Ablation zone surfaces (at lower elevations) do not exhibit the magnitude of backscatter intensity of percolation zones and therefore lower glaciated elevations show lesser seasonal contrast

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than higher elevations.~~and we subsequently retrieve valid melt signals at the lowest rate over elevations below 4,000m a.s.l. There is much greater density of valid retrievals in fields above 4,000m a.s.l. (Table 2).~~ These differences are also apparent in the spatial granularity of melt retrievals from the S1-SAR product, as shown in *Fig. ~~8~~6*. Ablation zone surfaces on valley glaciers ~~are well resolved and~~ show spatial heterogeneity in MO indicative of supraglacial~~meltwater~~ features, like ~~and~~ debris cover, rather than randomly distributed noise. There exists uncertainty in the FO signal on glacier ablation surfaces that will require further investigation. In ablation areas with ~~We attribute missing retrievals in these areas to~~ lower sensitivity to melting, we hypothesize that snow-off conditions result in brightening of the radar signal due to surface scattering contributions from wet debris, bare ice, or other ablation surface heterogeneities. For this reason, at lower elevations where annual air temperatures exceed 0ºC (i.e. where temperature-elevation lapse rates hold), lapse rate estimates of elevation might be more robust estimates of FO using this approach. Overall, surface melting signals ~~from a lack of winter-season volume scattering due to differences in snow depth and/or morphology. We find these are more likely to occur in some regions of the HKH like the EH. Conversely, there are surface-area fractions highly sensitive to surface melting that~~ appear to be consistent with expectations of temperature lapse rates (i.e. earlier melting and later refreeze at lower elevations) across elevations where annual air temperatures likely exceed 0ºC (<6,000 m a.s.l.). ~~).~~ We ~~obtain more robust estimates of melting onset and refreeze by spatially aggregating results of the glacier surface melt timing (*Eq. 1*) using a median window filter of 9x9 pixels after melt classification and z-score validation.~~ have illustrated the spatial granularity of melt retrievals in *Fig. 8* in addition to average melt onset and offset by sub-region in *Fig. 9*~~In this way, we select signals within those areas that are indicative of seasonal melting. All spatiotemporal characteristics we report herein are after median window filtering of melt retrievals from 10m native resolution to 90m resolution~~.

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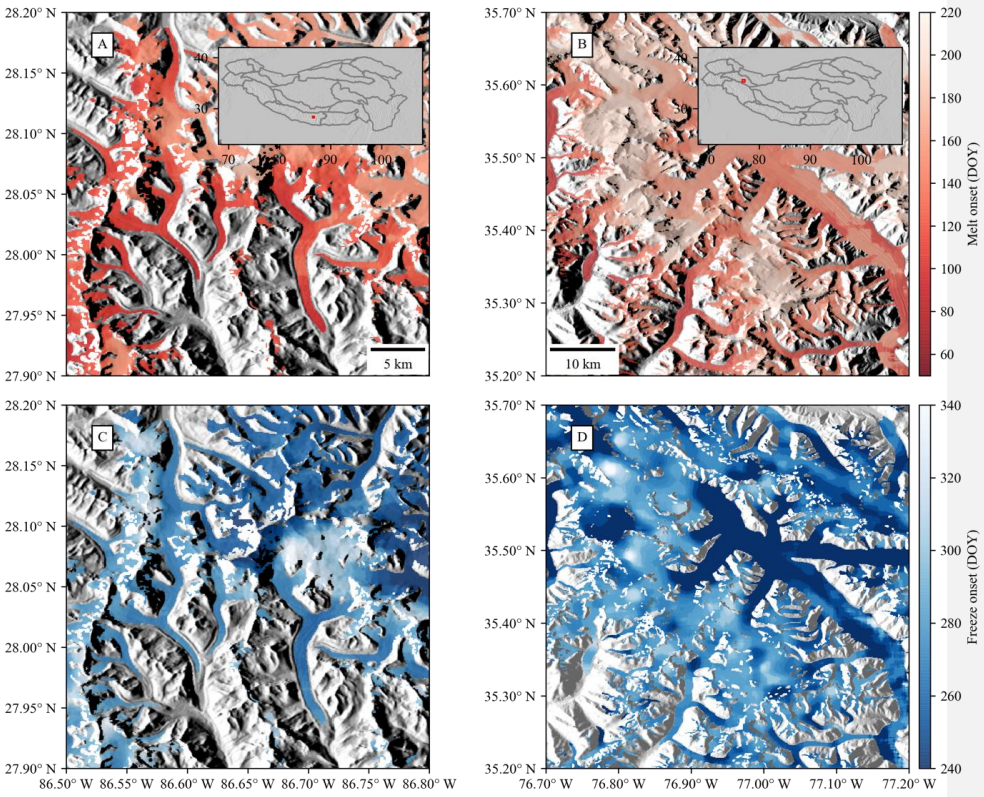
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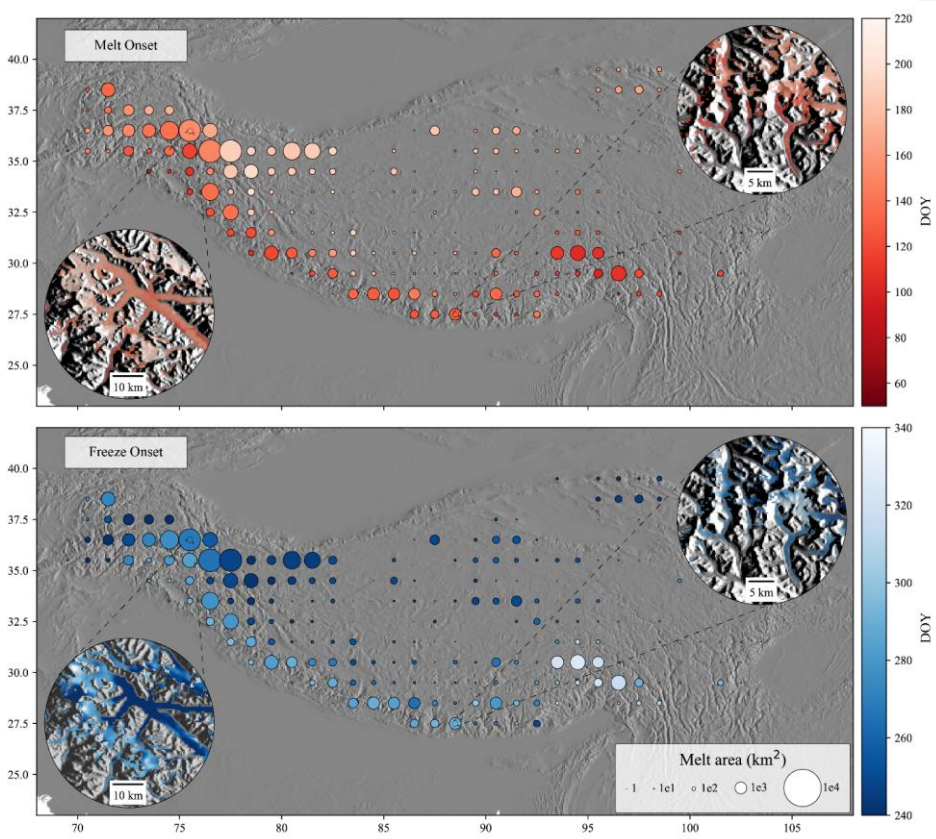

Figure 8. Melt retrievals averaged over the calendar years 2017-2019 in the Central Himalaya and Karakoram regions. **(A)** Mean melt onset (DOY) in the Central Himalaya. **(B)** Mean melt onset (DOY) over the Siachen glacier in the Karakoram region. **(C)** Mean melt offset (DOY) in the Central Himalaya. **(D)** Mean melt offset (DOY) over the Siachen glacier in the Karakoram region.

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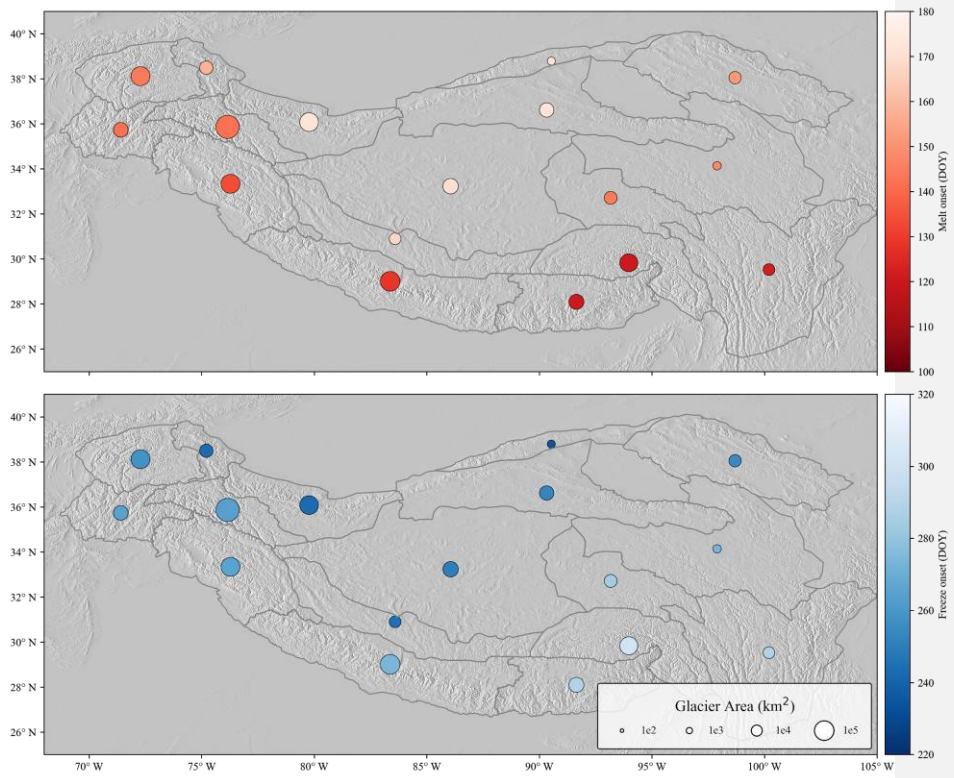

Figure 9~~6~~. Melt onset (top) and freeze onset (bottom) averaged over 2017-~~for the calendar year~~ 2019 plotted over a SRTM 30m DEM hillshade (Farr, 2007). Melt retrievals are averaged across HiMAP glacio-climate sub-regions (Bolch et al., 2019a; Shean et al., 2020) ~~hill shade. Each point represents the mean melt onset~~ and ~~offset within a 1°x1° grid cell and the size of each point is~~ scaled by the mapped glacier area within each sub-region. ~~of melt detected. (Top) Mean melt onset across the HKH with two inset maps highlighting the Karakoram region over the Siachen glacier (lower left inset map) and over Mount Everest (upper right inset map). (Bottom) Mean freeze onset by 1° grid cell across the HKH with insets over the Siachen glacier in the Karakoram region (bottom left) and in over Mount Everest (upper right).~~

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~~4.2~~4.3 Considerations of Temperature-Elevation Lapse Rates

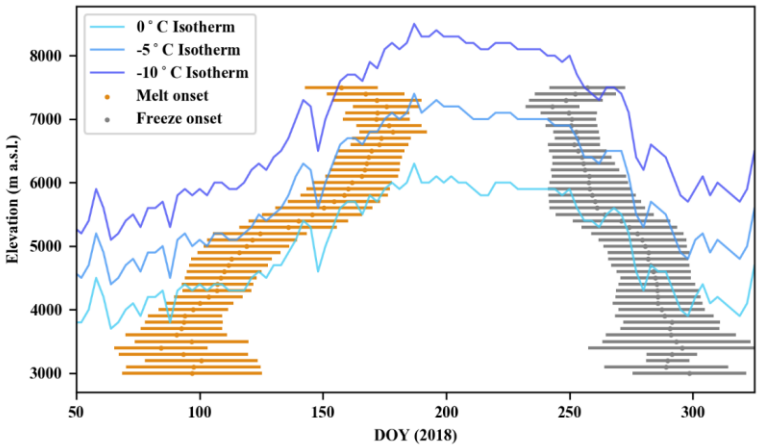

Figure 7. Sentinel-1 SAR retrieved melt onset (orange) and freeze onset (gray), with spatial variability at ±1 standard deviation, across the Central Himalaya region. The elevations of the 0ºC, -5°C, and -10ºC isotherms from 2018 are overlaid for comparison. Melt signals are recorded in excess of three months at elevations extending >1km above the maximum elevation of the 0ºC isotherm, indicative of a sustained presence of liquid water within the snow matrix across these high elevation ranges.

We compare SAR retrievals of MO and FO to temperature-elevation lapse rates derived within a catchment in the Central Himalaya to investigate SAR retrievals alongside lapse-rate assumptions of glacier melt status; using methods and AWS data for the construction of lapse-rates from prior studies in the Langtang valley, Central Himalaya (Baral et al., 2014). In 2018, we ~~We~~ observe that the average MO is found to follow the 0º and -5ºC isotherms for elevations ~4,500~~4500~~ to 6,500m~~6500 m~~ a.s.l. Below and above these elevations, and for FO, we find episodic melting events occurring over a range of elevations. This is especially apparent in the FO around day of year 270 where FO occurs within a roughly two week period across glaciers between 5,000m-7,500m a.s.l. MO and FO signals are retrieved on days and at elevations where lapse-rate derived temperatures do not exceed ~~-~~ -10ºC, which strengthens and expands recent *in situ* observations on glacier melt at the Khumbu glacier in the Mount Everest region showing incident shortwave radiation drives melt at these temperatures and elevations (Matthews et al., 2019).~~longwave incident radiation driving melt at these temperatures and elevations [17].~~ Here we observe that, even at these extreme elevations (>7,000m a.s.l.) melt signals persist for over three months on

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average across the Central Himalaya, which suggests that liquid water is retained at these high elevations across a seasonal melt cycle and may not be hydrologically negligible. In radar-derived observations there is a discrepancy between SAR and lapse-rate estimated ~~we find surface~~ melting records that occurs ~~to occur~~ at elevations extending ~~over~~ 1km above the maximum ~~elevation of~~ 0ºC isotherms in the Central Himalaya. Glaciated ~~We observe melting over the vast majority of glacier surfaces; signals are retrieved across all elevation ranges of the HKH region, indicating that any~~ areas ~~of snow accumulation are experiencing some degree of surface melting during the summer months, purely melt-free, "dry snow" areas may not currently exist~~ in the Central Himalaya at elevations greater than 6,000m a.s.l. – the approximate maximum elevation of the 0ºC isotherm for 2018 – account for 21.58% (2,453 km^2) of total glaciated area within the region. ~~HKH.~~

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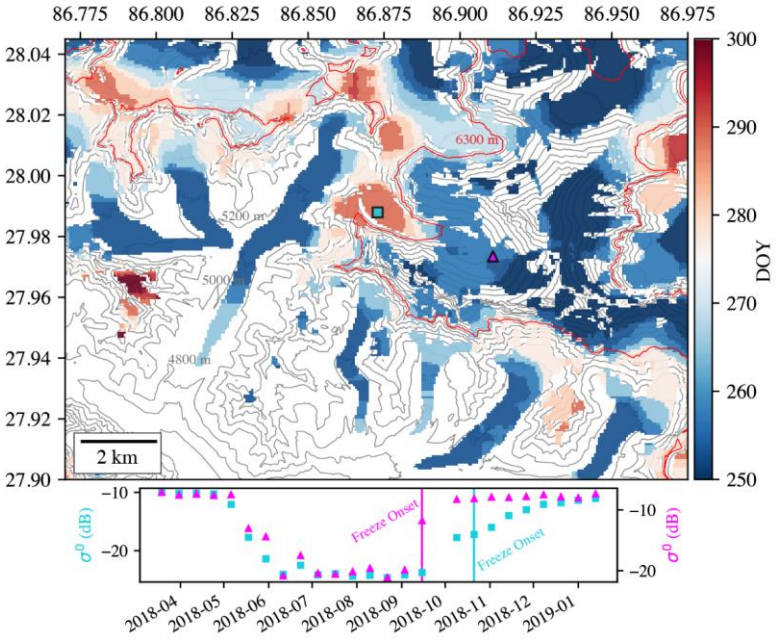
4.4 Melt Retrievals and Glacio-Climate Sub-regions

The three-year record of Sentinel-1 SAR retrievals of glacier melt status represent a baseline measurement for the HMA. The summary melt statistics are aggregated over HiMAP sub-regions in order to compare melt retrievals and sub-regional estimates of glacier mass wasting (Bolch, et al. 2019a; Shean, et al., 2020). Overall, the HMA sub-regions with the most rapid mass wasting between 2000-2010 tabulated in Shean, et al. (2019a) (Eastern Himalaya, Hengduan Shan, Nyainquntanglha) exhibit the greatest number of melt days on average in 2017-2019 from Sentinel-1 retrievals. Sub-regions with slower mass wasting, in steady state, or with mass slight gain (Eastern Hindu Kush, Western Pamir, Karakoram, Tibetan Interior) show on average one month less of melt duration relative to regions with accelerated mass wasting. Interestingly, the Gangdise sub-region, with one of the higher post-2000 rates of glacier wasting in the HKH, shows annual melt durations of less than three months on average, which appears more characteristic of western regions with slower mass wasting (i.e. Tibetan Interior Mountains). Although Sentinel-1 retrievals of glacier melt status for three calendar years does not make-up a climatic record, we observe that between 2017-2019 there was on average less duration of melting in regions where *in situ* data and climate models indicate that frozen winter precipitation contributes to glacier accumulation despite warming global climate (Karakoram, Hindu Kush, Eastern Pamir, Western Himalaya) (Kääb et al., 2015; Kapnick et al., 2014; Palazzi et al., 2013). We interpret shorter duration of annual melt days in the western regions of the HKH as a potential indicator of the "Karakoram Anomaly" reflected in the Sentinel-1 data record. Because the meteo-climatic drivers of the Karakoram Anomaly are still under debate (Farinotti et al., 2020), Sentinel-1 retrievals of melt duration may be useful for interrogating meteo-climatic drivers of heterogeneity in glacier wasting dynamics across the HKH.

5 Conclusion

~~Percolation Zone Meltwater Hydrology~~

~~We observe a delayed freeze-up over zones of known and apparent accumulation, indicating percolation and seasonal storage of subsurface meltwater at high elevations. An example of this is given in Figure 8, where refreeze occurs over thirty days later at 6,000m. a.s.l. compared to elevations around 6,600m a.s.l. The time series of mean Sentinel-1 SAR backscatter for descending orbital nodes from two 250m buffered points on the Khumbu glacier show a more rapid brightening for the higher elevation location, whereas backscatter time series extracted from the point of lower elevation show a gradual increase in radar backscatter, indicative a gradually decreasing liquid water content in the snowpack (*Fig. 8*) [69, 70]. Sentinel SAR backscatter time series at the Khumbu Glacier on Mount Everest indicate similar spatial trends at higher (>6,500 m) and lower (<5,300m) elevations, but a refreeze anomaly is apparent within known elevations of regions of meltwater percolation [17]. These data show gradual increase in backscatter at a lower elevation point (teal square, ~6,000m a.s.l.) and a point at higher elevation, above the maximum elevation of a three-day mean 0ºC summer isotherm (pink triangle, ~6,600m a.s.l.). This observation indicates that there exists a relationship between frozen percolation zone depth and C-band backscatter intensity across refreeze cycles wherein C-band backscatter gradually increases with frozen percolation zone depth during a refreeze process.~~



~~Figure 8.~~ ~~(Top) Map of the day of year (DOY) of freeze onset in the Mount Everest region of the Central Himalaya. Two points on the Khumbu glacier (teal square and pink triangle) mark the locations where Sentinel-1 descending backscatter time series are sampled and plotted (bottom). The maximum elevation of the 0ºC isotherm for the year 2018 is highlighted with a red contour~~

~~line at 6300m. This figure illustrates two important observations from this study: (1) that melt signals are pronounced above the maximum elevation of the 0ºC isotherm extrapolated from meteorological stations within the Central Himalaya and (2) that melt signals persist for over one month at elevations of known meltwater percolation on the Khumbu glacier within ranges of ~5400–6300m a.s.l. relative to both higher and lower elevations. We hypothesize this observed delay in refreeze is due to the retention of liquid water in the glacier percolation zone and a gradual freeze up process.~~

~~5 Summary and Conclusions~~

Synthetic aperture radar time series backscatter images and glacier extent maps derived from optical imagery have long been proposed to inform hydrologic and glaciologic research across the global cryosphere, however a harmonized dataset of glacier surface melt does not exist. We retrieve glacier surface melt timing and duration for the study years 2017-19 across the HKH region using time series C-band SAR from the Sentinel-1 A/B satellites and an inventory of 105,432~~76,831~~ glaciers spanning 83,102 km^2~~65,108km^2~~ of ice-covered area. We quantify the magnitude of the seasonal melt signal by comparing mean summer and winter backscatter using a **z**-score metric and retrieve constraints on seasonal melt characteristics across all glaciated elevations of HKH at 90m spatial and 12-day temporal resolution. Melt conditions in surface energy balance models of glacier melt driven by *in situ* meteorological data from Mount Everest are constrained by Sentinel-1 SAR melt retrievals.~~apply a mask for areas with little confidence in seasonal melt signal (**z** < 2). We subsequently retrieve melt characteristics across the vast majority 97% (62,907km^2) of HKH glacier area at 90m spatial and 12-day temporal resolution. Across elevations of the HKH region, melt onset generally increases with elevation, beginning in the first week of April at 3,000m a.s.l. and extending with increasing elevation into the second week of June at some of the highest elevations across the HKH (>7,000m a.s.l.). Across glacio-climatic regions of the HKH, melt onset occurs about one week earlier on average in the Central and Western Himalaya compared to melt onset in the Western Himalaya and Karakoram. Freeze onset similarly occurs one week sooner in the Western Himalaya and Karakoram compared to the Eastern and Central Himalaya at elevations with encompassing the majority of the glaciated area (4,000m-6,000m a.s.l.). Regional variations in melt timing and duration resemble known characteristics of regional glacio-climatic regimes. Importantly, where the presence of liquid water is likely driven by incident solar radiation driving melt at elevations where air temperatures do not exceed 0ºC, the methods presented in this study can provide observational data on the presence of liquid water across data sparse regions for use in development and assessment of surface energy balance models of glacier ablation.~~ Comparison of melt retrievals to temperature-elevation lapse rates calculated using two high-elevation meteorological stations in the Central Himalaya reveal~~reveals~~ that melt onset persists for over three months at elevations where extrapolated air temperature fields do not exceed -10ºC. Melt is retrieved across all elevation ranges of HKH glaciers, which suggests~~. Additionally, we report observations and propose~~ that a dry snow

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accumulation zone in the HKH region does not exist. Meltwater ~~meltwater~~ retention is indicated within ~~detectable in regions of~~ known glacier percolation zones on Mount Everest through signals ~~retrievals~~ of delayed refreeze. Delayed refreeze occurs across the HKH at elevations with the greatest seasonal contrast in ~~and that there may be a scaling relationship between SAR~~ backscatter intensity, attributable to radar scattering in ~~, frozen~~ percolation facies. Melt signals persist for a greater portion of the year in regions known for rapid contemporary glacier wasting (i.e. Central and Eastern Himalaya sub-regions) whereas regions with stable glacier mass balance (i.e. Karakoram) exhibit a shorter duration of annual melt. ~~zone depth and liquid water content.~~ We produce a geospatial data product of melt onset (DOY) and ~~),~~ freeze onset (DOY) ~~), and fraction of Sentinel-1 observations classified as melt~~ spanning glaciers of the HKH region at 90m spatial resolution for the calendar years 2017-2019 and plan to release annual updates to this dataset ~~database~~ each calendar year ~~. Melt is retrieved~~ across ~~all elevation ranges of HKH glaciers, which suggests that a dry snow accumulation zone in~~ the mission duration of Sentinel-1. ~~HKH region is largely absent.~~ The methods presented in this study can provide the basis for an operational monitor of glacier surface melt dynamics and aid the development and assessment of surface energy balance models of glacier ablation across the global cryosphere.

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Author Contribution

N. C. Steiner and K. C. McDonald devised the project and the main conceptual ideas. C. Scher developed and executed the 425 final methodological approach and authored the computer code. C.S contributed most of the writing to the manuscript with major contributions from N.C.S. K.C.M supervised the project and manuscript.

Competing Interest

The authors declare no competing interests.

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Code and Data availability

The code and data will be available on in the NASA Distributed Active Archive Center, the National Snow and Ice Data Center, as part of the High Mountain Asia Data archive.

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~~6~~7 References

Abdalati, W. and Steffen, K.: Greenland Ice Sheet melt extent: 1979-1999, Journal of Geophysical Research: Atmospheres, 106, 33983-33988, 2001.

Adam, S., Pietroniro, A., and Brugman, M. M.: Glacier snow line mapping using ERS-1 SAR imagery, Remote Sensing of Environment, 61, 46-54, 1997.

Alexander, P., Tedesco, M., Koenig, L., and Fettweis, X.: Evaluating a regional climate model simulation of Greenland ice sheet snow and firn density for improved surface mass balance estimates, Geophysical Research Letters, 46, 12073-12082, 2019.

Anthwal, A., Joshi, V., Sharma, A., and Anthwal, S.: Retreat of Himalayan glaciers–indicator of climate change, Nature and Science, 4, 53-59, 2006.

Ashcraft, I. S. and Long, D. G.: Comparison of methods for melt detection over Greenland using active and passive microwave measurements, International Journal of Remote Sensing, 27, 2469-2488, 2007.

Ashcraft, I. S. and Long, D. G.: Differentiation between melt and freeze stages of the melt cycle using SSM/I channel ratios, IEEE transactions on geoscience and remote sensing, 43, 1317-1323, 2005.

Baghdadi, N., Gauthier, Y., and Bernier, M.: Capability of multitemporal ERS-1 SAR data for wet-snow mapping, Remote sensing of environment, 60, 174-186, 1997.

Bahr, D. B., Meier, M. F., and Peckham, S. D.: The physical basis of glacier volume-area scaling, Journal of Geophysical Research: Solid Earth, 102, 20355-20362, 1997.

Baral, P., Kayastha, R. B., Immerzeel, W. W., Pradhananga, N. S., Bhattarai, B. C., Shahi, S., Galos, S., Springer, C., Joshi, S. P., and Mool, P. K.: Preliminary results of mass-balance observations of Yala Glacier and analysis of temperature and precipitation gradients in Langtang Valley, Nepal, Annals of glaciology, 55, 9-14, 2014.

Bhattacharya, I., Jezek, K. C., Wang, L., and Liu, H.: Surface melt area variability of the Greenland ice sheet: 1979–2008, Geophysical Research Letters, 36, 2009.

Bindschadler, R., Jezek, K., and Crawford, J.: Glaciological investigations using the synthetic aperture radar imaging system, Annals of Glaciology, 9, 11-19, 1987.

Bogardi, J. J., Dudgeon, D., Lawford, R., Flinkerbusch, E., Meyn, A., Pahl-Wostl, C., Vielhauer, K., and Vörösmarty, C.: Water security for a planet under pressure: interconnected challenges of a changing world call for sustainable solutions, Current Opinion in Environmental Sustainability, 4, 35-43, 2012.

Bolch, T., Shea, J. M., Liu, S., Azam, F. M., Gao, Y., Gruber, S., Immerzeel, W. W., Kulkarni, A., Li, H., and Tahir, A. A.: Status and change of the cryosphere in the Extended Hindu Kush Himalaya Region. In: The Hindu Kush Himalaya Assessment, Springer, 2019a.

Bolch, T., Kulkarni, A., Kääb, A., Huggel, C., Paul, F., Cogley, J. G., Frey, H., Kargel, J. S., Fujita, K., and Scheel, M. J. S.: The state and fate of Himalayan glaciers, 336, 310-314, 2012.

Bolch, T., Bhattacharya, A., King, O., and Allen, S.: Characteristics and changes of glaciers, rock glaciers and glacial lakes in High Mountain Asia since the 1960s, 2019b.

Brangers, I., Lievens, H., Miège, C., Demuzere, M., Brucker, L., and De Lannoy, G.: Sentinel-1 detects firn aquifers in the Greenland Ice Sheet, Geophysical Research Letters.

Brock, B. W., Willis, I. C., and Sharp, M. J.: Measurement and parameterization of aerodynamic roughness length variations at Haut Glacier d'Arolla, Switzerland, Journal of Glaciology, 52, 281-297, 2006.

Brown, L. E., Hannah, D. M., and Milner, A. M.: Vulnerability of alpine stream biodiversity to shrinking glaciers and snowpacks, Global Change Biology, 13, 958-966, 2007.

Brun, F., Berthier, E., Wagnon, P., Kaab, A., and Treichler, D.: A spatially resolved estimate of High Mountain Asia glacier mass balances, 2000-2016, Nat Geosci, 10, 668-673, 2017.

Carrivick, J. L. and Tweed, F. S.: A global assessment of the societal impacts of glacier outburst floods, Global and Planetary Change, 144, 1-16, 2016.

Engeset, R., Kohler, J., Melvold, K., and Lundén, B.: Change detection and monitoring of glacier mass balance and facies using ERS SAR winter images over Svalbard, International Journal of Remote Sensing, 23, 2023-2050, 2002.
ESA: https://sentinel.esa.int/web/sentinel/user-guides/sentinel-1-sar/acquisition-modes/interferometric-wide-swath, last access: February 13, 2020.

Farinotti, D., Immerzeel, W. W., de Kok, R. J., Quincey, D. J., and Dehecq, A.: Manifestations and mechanisms of the Karakoram glacier Anomaly, Nature Geoscience, 13, 8-16, 2020.

Farr, T. G., Rosen, P.A., Caro, E., Crippen, R., Duren, R., Hensley, S., Kobrick, M., Paller, M., Rodriguez, E., Roth, L., Seal, D., Shaffer, S., Shimada, J., Umland, J., Werner, M., Oskin, M., Burbank, D., and Alsdorf, D.E.: The shuttle radar topography mission: Reviews of Geophysics, v. 45, no. 2, RG2004, at https://doi.org/10.1029/2005RG000183., Reviews of Geophysics, 45, 2007.

Fischer, G., Jäger, M., Papathanassiou, K. P., and Hajnsek, I.: Modeling the Vertical Backscattering Distribution in the Percolation Zone of the Greenland Ice Sheet with SAR Tomography, IEEE Journal of Selected Topics in Applied Earth Observations and Remote Sensing, 12, 4389-4405, 2019.

Fujita, K. and Nuimura, T.: Spatially heterogeneous wastage of Himalayan glaciers, Proc Natl Acad Sci U S A, 108, 14011-14014, 2011.

Gardelle, J., Berthier, E., and Arnaud, Y.: Slight mass gain of Karakoram glaciers in the early twenty-first century, Nature geoscience, 5, 322, 2012.

Google: Sentinel-1 Preprocessing, last access: Novermber 30, 2020 2020.

Gorelick, N., Hancher, M., Dixon, M., Ilyushchenko, S., Thau, D., and Moore, R. J. R. S. o. E.: Google Earth Engine: Planetary-scale geospatial analysis for everyone, 202, 18-27, 2017.

Hallikainen, M., Ulaby, F., and Abdelrazik, M.: Dielectric properties of snow in the 3 to 37 GHz range, IEEE transactions on Antennas and Propagation, 34, 1329-1340, 1986.

Huang, L., Li, Z., Tian, B.-S., Chen, Q., Liu, J.-L., and Zhang, R.: Classification and snow line detection for glacial areas using the polarimetric SAR image, Remote Sensing of Environment, 115, 1721-1732, 2011.

Huang, W., DeVries, B., Huang, C., Lang, M., Jones, J., Creed, I., and Carroll, M.: Automated Extraction of Surface Water Extent from Sentinel-1 Data, Remote Sensing, 10, 2018.

ICIMOD: Outline Boundary of Hindu Kush Himalayan (HKH) Region. ICIMOD (Ed.), ICIMOD.

Jacobsen, D., Milner, A. M., Brown, L. E., and Dangles, O.: Biodiversity under threat in glacier-fed river systems, Nature Climate Change, 2, 361, 2012.

Jezek, K. C., Gogineni, P., and Shanableh, M.: Radar measurements of melt zones on the Greenland ice sheet, Geophysical Research Letters, 21, 33-36, 1994.

Kääb, A., Treichler, D., Nuth, C., and Berthier, E.: Brief Communication: Contending estimates of 2003–2008 glacier mass balance over the Pamir–Karakoram–Himalaya, Cryosphere, 9, 2015.

Kapnick, S. B., Delworth, T. L., Ashfaq, M., Malyshev, S., and Milly, P. C.: Snowfall less sensitive to warming in Karakoram than in Himalayas due to a unique seasonal cycle, Nature Geoscience, 7, 834, 2014.
Kayastha, R. B., Steiner, N., Kayastha, R., Mishra, S. K., and McDonald, K.: Comparative study of hydrology and icemelt in three Nepal river basins using the glacio-hydrological degree-day model (GDM) and observations from the Advance Scatterometer (ASCAT), FrEaS, 7, 354, 2019.

Kendra, J. R., Sarabandi, K., Ulaby, F. T. J. I. T. o. G., and Sensing, R.: Radar measurements of snow: Experiment and analysis, 36, 864-879, 1998.

Koskinen, J. T., Pulliainen, J. T., and Hallikainen, M. T.: The use of ERS-1 SAR data in snow melt monitoring, IEEE Transactions on geoscience and remote sensing, 35, 601-610, 1997.

Lau, W. K., Kim, M.-K., Kim, K.-M., and Lee, W.-S.: Enhanced surface warming and accelerated snow melt in the Himalayas and Tibetan Plateau induced by absorbing aerosols, Environmental Research Letters, 5, 025204, 2010.

Lievens, H., Demuzere, M., Marshall, H.-P., Reichle, R. H., Brucker, L., Brangers, I., de Rosnay, P., Dumont, M., Girotto, M., and Immerzeel, W. W.: Snow depth variability in the Northern Hemisphere mountains observed from space, Nature communications, 10, 1-12, 2019.

Litt, M., Shea, J., Wagnon, P., Steiner, J., Koch, I., Stigter, E., and Immerzeel, W.: Glacier ablation and temperature indexed melt models in the Nepalese Himalaya, Scientific reports, 9, 5264, 2019.

Lund, J., Forster, R. R., Rupper, S. B., Marshall, H., Deeb, E. J., and Hashmi, M. Z. U. R.: Mapping snowmelt progression in the Upper Indus Basin with synthetic aperture radar, Frontiers in Earth Science, 7, 318, 2019.
Margulis, S. A., Liu, Y., and Baldo, E.: A joint Landsat-and MODIS-based reanalysis approach for midlatitude montane seasonal snow characterization, Frontiers in Earth Science, 7, 272, 2019.

Matthews, T., Perry, B., Aryal, D., Shrestha, D., and Khadka, A.: New Heights in Glacier-Climate Research: Initial Insights From the Highest Weather Stations on Earth, 2019.

Matthews, T., Perry, L. B., Koch, I., Aryal, D., Khadka, A., Shrestha, D., Abernathy, K., Elmore, A., Seimon, A., and Tait, A.: Going to Extremes: Installing the World's Highest Weather Stations on Mount Everest, B Am Meteorol Soc, 2020. 2020.

Matzler, C.: Microwave properties of ice and snow. In: Solar System Ices, Springer, 1998.

Miles, K. E., Hubbard, B., Quincey, D. J., Miles, E. S., Sherpa, T. C., Rowan, A. V., and Doyle, S. H.: Polythermal structure of a Himalayan debris-covered glacier revealed by borehole thermometry, Scientific reports, 8, 1-9, 2018.

Milner, A. M., Khamis, K., Battin, T. J., Brittain, J. E., Barrand, N. E., Fureder, L., Cauvy-Fraunie, S., Gislason, G. M., Jacobsen, D., Hannah, D. M., Hodson, A. J., Hood, E., Lencioni, V., Olafsson, J. S., Robinson, C. T., Tranter, M., and Brown, L. E.: Glacier shrinkage driving global changes in downstream systems, Proc Natl Acad Sci U S A, 114, 9770-9778, 2017.

Nagler, T. and Rott, H.: Retrieval of wet snow by means of multitemporal SAR data, IEEE Transactions on Geoscience and Remote Sensing, 38, 754-765, 2000.

Nagler, T., Rott, H., Ripper, E., Bippus, G., and Hetzenecker, M.: Advancements for Snowmelt Monitoring by Means of Sentinel-1 SAR, Remote Sensing, 8, 348, 2016.

Nuimura, T., Sakai, A., Taniguchi, K., Nagai, H., Lamsal, D., Tsutaki, S., Kozawa, A., Hoshina, Y., Takenaka, S., and Omiya, S.: The gamdam glacier inventory: a quality-controlled inventory of Asian glaciers, Cryosphere, 9, 2015.

Oza, S., Singh, R., Vyas, N., and Sarkar, A.: Study of inter-annual variations in surface melting over Amery Ice Shelf, East Antarctica, using space-borne scatterometer data, Journal of earth system science, 120, 329-336, 2011.

Palazzi, E., Von Hardenberg, J., and Provenzale, A.: Precipitation in the Hindu-Kush Karakoram Himalaya: observations and future scenarios, Journal of Geophysical Research: Atmospheres, 118, 85-100, 2013.

Paterson, W. S. B.: The physics of glaciers, Elsevier, 2016.

Pritchard, D. M., Forsythe, N., O'Donnell, G., Fowler, H. J., and Rutter, N.: Multi-physics ensemble snow modelling in the western Himalaya, The Cryosphere, 2020. 2020.

Ramage, J. M., Isacks, B. L., and Miller, M. M.: Radar glacier zones in southeast Alaska, USA: field and satellite observations, Journal of Glaciology, 46, 287-296, 2000.

Rau, F., Braun, M., Friedrich, M., Weber, F., and Goßmann, H.: Radar glacier zones and their boundaries as indicators of glacier mass balance and climatic variability, 2000, 317-327.

Rott, H. and Mätzler, C.: Possibilities and limits of synthetic aperture radar for snow and glacier surveying, Annals of Glaciology, 9, 195-199, 1987.

Sakai, A.: Brief communication: Updated GAMDAM glacier inventory over high-mountain Asia, The Cryosphere, 13, 2043-2049, 2019.

Scott, C. A., Zhang, F., Mukherji, A., Immerzeel, W., Mustafa, D., and Bharati, L.: Water in the Hindu Kush Himalaya. In: The Hindu Kush Himalaya Assessment, Springer, 2019.

Shea, J.: Meteorological data from Yala Base Camp automatic weather station. ICIMOD (Ed.), 2016.

Shean, D. E., Bhushan, S., Montesano, P., Rounce, D. R., Arendt, A., and Osmanoglu, B.: A Systematic, Regional Assessment of High Mountain Asia Glacier Mass Balance, Frontiers in Earth Science, 7, 2020.

Shi, J. and Dozier, J.: Inferring snow wetness using C-band data from SIR-C's polarimetric synthetic aperture radar, IEEE transactions on geoscience and remote sensing, 33, 905-914, 1995.

Shi, J., Dozier, J., and Rott, H.: Snow mapping in alpine regions with synthetic aperture radar, IEEE Transactions on Geoscience and Remote Sensing, 32, 152-158, 1994.

Steiner, N. and Tedesco, M.: A wavelet melt detection algorithm applied to enhanced-resolution scatterometer data over Antarctica (2000–2009), The Cryosphere, 8, 25-40, 2014.

Trusel, L. D., Frey, K. E., and Das, S. B.: Antarctic surface melting dynamics: Enhanced perspectives from radar scatterometer data, Journal of Geophysical Research: Earth Surface, 117, 2012.

Winebrenner, D. P., Nelson, E. D., Colony, R., and West, R. D.: Observation of melt onset on multiyear Arctic sea ice using the ERS 1 synthetic aperture radar, Journal of Geophysical Research, 99, 1994.

Winsvold, S., Kääb, A., Nuth, C., Andreassen, L. M., Van Pelt, W., and Schellenberger, T.: Using SAR data time-series for regional glacier mapping, The Cryosphere, 12, 867-890, 2018.

Wiscombe, W. J. and Warren, S. G. J. J. o. t. A. S.: A model for the spectral albedo of snow. I: Pure snow, 37, 2712-2733, 1980.

Wood, L. R., Neumann, K., Nicholson, K. N., Bird, B. W., Dowling, C. B., and Sharma, S.: Melting Himalayan Glaciers Threaten Domestic Water Resources in the Mount Everest Region, Nepal, Frontiers in Earth Science, 8, 2020.

Yao, T., Thompson, L. G., Mosbrugger, V., Zhang, F., Ma, Y., Luo, T., Xu, B., Yang, X., Joswiak, D. R., and Wang, W.: Third pole environment (TPE), Environmental Development, 3, 52-64, 2012.

Zemp, M., Haeberli, W., Hoelzle, M., and Paul, F.: Alpine glaciers to disappear within decades?, Geophysical Research Letters, 33, 2006.

Zemp, M., Huss, M., Thibert, E., Eckert, N., McNabb, R., Huber, J., Barandun, M., Machguth, H., Nussbaumer, S. U., and Gärtner-Roer, I.: Global glacier mass changes and their contributions to sea-level rise from 1961 to 2016, Nature, 568, 382-386, 2019.

Zhou, C. and Zheng, L.: Mapping Radar Glacier Zones and Dry Snow Line in the Antarctic Peninsula Using Sentinel-1 Images, Remote Sensing, 9, 2017.

1. Zemp, M., et al., *Alpine glaciers to disappear within decades?* Geophysical Research Letters, 2006. **33**(13).
2. Brangers, I., et al., *Sentinel-1 detects firn aquifers in the Greenland Ice Sheet.* Geophysical Research Letters.
3. Yao, T., et al., *Third pole environment (TPE).* Environmental Development, 2012. **3**: p. 52-64.
4. Anthwal, A., et al., *Retreat of Himalayan glaciers–indicator of climate change.* Nature and Science, 2006. **4**(4): p. 53-59.
5. Zemp, M., et al., *Global glacier mass changes and their contributions to sea-level rise from 1961 to 2016.* Nature, 2019. **568**(7752): p. 382-386.
6. Brown, L.E., D.M. Hannah, and A.M. Milner, *Vulnerability of alpine stream biodiversity to shrinking glaciers and snowpacks.* Global Change Biology, 2007. **13**(5): p. 958-966.
7. Milner, A.M., et al., *Glacier shrinkage driving global changes in downstream systems.* Proc Natl Acad Sci U S A, 2017. **114**(37): p. 9770-9778.
8. Carrivick, J.L. and F.S. Tweed, *A global assessment of the societal impacts of glacier outburst floods.* Global and Planetary Change, 2016. **144**: p. 1-16.
9. Jacobsen, D., et al., *Biodiversity under threat in glacier-fed river systems.* Nature Climate Change, 2012. **2**(5): p. 361.
10. Bogardi, J.J., et al., *Water security for a planet under pressure: interconnected challenges of a changing world call for sustainable solutions.* Current Opinion in Environmental Sustainability, 2012. **4**(1): p. 35-43.
11. Litt, M., et al., *Glacier ablation and temperature indexed melt models in the Nepalese Himalaya.* Scientific reports, 2019. **9**(1): p. 5264.
12. Fujita, K. and T. Nuimura, *Spatially heterogeneous wastage of Himalayan glaciers.* Proc Natl Acad Sci U S A, 2011. **108**(34): p. 14011-4.
13. Shi, J., J. Dozier, and H. Rott, *Snow mapping in alpine regions with synthetic aperture radar.* IEEE Transactions on Geoscience and Remote Sensing, 1994. **32**(1): p. 152-158.
14. Pritchard, D.M., et al., *Multi-physics ensemble snow modelling in the western Himalaya.* The Cryosphere, 2020.
15. Alexander, P., et al., *Evaluating a regional climate model simulation of Greenland ice sheet snow and firn density for improved surface mass balance estimates.* Geophysical Research Letters, 2019. **46**(21): p. 12073-12082.
16. Miles, K.E., et al., *Polythermal structure of a Himalayan debris-covered glacier revealed by borehole thermometry.* Scientific reports, 2018. **8**(1): p. 1-9.
17. Matthews, T., et al. *New Heights in Glacier-Climate Research: Initial Insights From the Highest Weather Stations on Earth*. in *AGU Fall Meeting 2019*. 2019. AGU.
18. Matthews, T., et al., *Going to Extremes: Installing the World's Highest Weather Stations on Mount Everest.* Bulletin of the American Meteorological Society, 2020.
19. Brun, F., et al., *A spatially resolved estimate of High Mountain Asia glacier mass balances, 2000-2016.* Nat Geosci, 2017. **10**(9): p. 668-673.

20. Abdalati, W. and K. Steffen, *Greenland Ice Sheet melt extent: 1979-1999*. Journal of Geophysical Research: Atmospheres, 2001. **106**(D24): p. 33983-33988.
21. Mote, T.L., et al., *Passive microwave-derived spatial and temporal variations of summer melt on the Greenland ice sheet*. Annals of Glaciology, 2017. **17**: p. 233-238.
22. Jezek, K.C., P. Gogineni, and M.J.G.R.L. Shanableh, *Radar measurements of melt zones on the Greenland ice sheet*. 1994. **21**(1): p. 33-36.
23. Rawlins, M.A., et al., *Analysis of the Arctic System for Freshwater Cycle Intensification: Observations and Expectations*. Journal of Climate, 2010. **23**(21): p. 5715-5737.
24. Bahr, D.B., M.F. Meier, and S.D. Peckham, *The physical basis of glacier volume-area scaling*. Journal of Geophysical Research: Solid Earth, 1997. **102**(B9): p. 20355-20362.
25. Kimball, J.S., et al., *Radar remote sensing of the spring thaw transition across a boreal landscape*. 2004. **89**(2): p. 163-175.
26. Jezek, K.C., P. Gogineni, and M. Shanableh, *Radar measurements of melt zones on the Greenland ice sheet*. Geophysical Research Letters, 1994. **21**(1): p. 33-36.
27. Rott, H. and C. Mätzler, *Possibilities and limits of synthetic aperture radar for snow and glacier surveying*. Annals of Glaciology, 1987. **9**: p. 195-199.
28. Hallikainen, M., F. Ulaby, and M. Abdelrazik, *Dielectric properties of snow in the 3 to 37 GHz range*. IEEE transactions on Antennas and Propagation, 1986. **34**(11): p. 1329-1340.
29. Matzler, C., *Microwave properties of ice and snow*, in *Solar System Ices*. 1998, Springer. p. 241-257.
30. Wiscombe, W.J. and S.G.J.J.o.t.A.S. Warren, *A model for the spectral albedo of snow. I: Pure snow*. 1980. **37**(12): p. 2712-2733.
31. Winsvold, S., et al., *Using SAR data time-series for regional glacier mapping*. The Cryosphere, 2018. **12**(3): p. 867-890.
32. Kendra, J.R., et al., *Radar measurements of snow: Experiment and analysis*. 1998. **36**(3): p. 864-879.
33. Shi, J. and J. Dozier, *Inferring snow wetness using C-band data from SIR-C's polarimetric synthetic aperture radar*. IEEE transactions on geoscience and remote sensing, 1995. **33**(4): p. 905-914.
34. Lievens, H., et al., *Snow depth variability in the Northern Hemisphere mountains observed from space*. Nature communications, 2019. **10**(1): p. 1-12.
35. Bhattacharya, I., et al., *Surface melt area variability of the Greenland ice sheet: 1979–2008*. Geophysical Research Letters, 2009. **36**(20).
36. Bindschadler, R., K. Jezek, and J. Crawford, *Glaciological investigations using the synthetic aperture radar imaging system*. Annals of Glaciology, 1987. **9**: p. 11-19.
37. Koskinen, J.T., J.T. Pulliainen, and M.T. Hallikainen, *The use of ERS-1 SAR data in snow melt monitoring*. IEEE Transactions on geoscience and remote sensing, 1997. **35**(3): p. 601-610.
38. Winebrenner, D.P., et al., *Observation of melt onset on multiyear Arctic sea ice using the ERS 1 synthetic aperture radar*. Journal of Geophysical Research, 1994. **99**(C11).
39. Koskinen, J.T., et al., *The use of ERS-1 SAR data in snow melt monitoring*. 1997. **35**(3): p. 601-610.
40. Ashcraft, I.S. and D.G. Long, *Comparison of methods for melt detection over Greenland using active and passive microwave measurements*. International Journal of Remote Sensing, 2007. **27**(12): p. 2469-2488.
41. Kayastha, R.B., et al., *Comparative study of hydrology and icemelt in three Nepal river basins using the glacio-hydrological degree-day model (GDM) and observations from the Advance Scatterometer (ASCAT)*. FrEaS, 2019. **7**: p. 354.
42. Lund, J., et al., *Mapping snowmelt progression in the Upper Indus Basin with synthetic aperture radar*. Frontiers in Earth Science, 2019. **7**: p. 318.
43. Rau, F., et al. *Radar glacier zones and their boundaries as indicators of glacier mass balance and climatic variability*. in *Proceedings of the 2nd EARSeL Workshop-Special Interest Group Land Ice and Snow*. 2000.
44. Huang, W., et al., *Automated Extraction of Surface Water Extent from Sentinel-1 Data*. Remote Sensing, 2018. **10**(5).
45. Scott, C.A., et al., *Water in the Hindu Kush Himalaya*, in *The Hindu Kush Himalaya Assessment*. 2019, Springer. p. 257-299.
46. Gardelle, J., E. Berthier, and Y. Arnaud, *Slight mass gain of Karakoram glaciers in the early twenty-first century*. Nature geoscience, 2012. **5**(5): p. 322.
47. Kapnick, S.B., et al., *Snowfall less sensitive to warming in Karakoram than in Himalayas due to a unique seasonal cycle*. Nature Geoscience, 2014. **7**(11): p. 834.
48. Bolch, T., et al., *The state and fate of Himalayan glaciers*. 2012. **336**(6079): p. 310-314.

49. Nuimura, T., et al., *The gamdam glacier inventory: a quality-controlled inventory of Asian glaciers.* Cryosphere, 2015. **9**(3).
50. Sakai, A., *Brief communication: Updated GAMDAM glacier inventory over high-mountain Asia.* The Cryosphere, 2019. **13**(7): p. 2043-2049.
51. Bolch, T., et al. *Characteristics and changes of glaciers, rock glaciers and glacial lakes in High Mountain Asia since the 1960s*. in *AGU Fall Meeting 2019*. 2019. AGU.
52. Farr, T.G., Rosen, P.A., Caro, E., Crippen, R., Duren, R., Hensley, S., Kobrick, M., Paller, M., Rodriguez, E., Roth, L., Seal, D., Shaffer, S., Shimada, J., Umland, J., Werner, M., Oskin, M., Burbank, D., and Alsdorf, D.E., *The shuttle radar topography mission: Reviews of Geophysics, v. 45, no. 2, RG2004, at https://doi.org/10.1029/2005RG000183*. Reviews of Geophysics, 2007. **45**(RG2004).
53. Stiles, W.H. and F.T. Ulaby, *The active and passive microwave response to snow parameters: 1. Wetness.* Journal of Geophysical Research: Oceans, 1980. **85**(C2): p. 1037-1044.
54. Gorelick, N., et al., *Google Earth Engine: Planetary-scale geospatial analysis for everyone.* 2017. **202**: p. 18-27.
55. ESA. [cited 2020 May 23]; Sentinel Application Platform (SNAP)]. Available from: http://step.esa.int/.
56. Baghdadi, N., Y. Gauthier, and M. Bernier, *Capability of multitemporal ERS-1 SAR data for wet-snow mapping.* Remote sensing of environment, 1997. **60**(2): p. 174-186.
57. Nagler, T. and H. Rott, *Retrieval of wet snow by means of multitemporal SAR data.* IEEE Transactions on Geoscience and Remote Sensing, 2000. **38**(2): p. 754-765.
58. Trusel, L.D., K.E. Frey, and S.B. Das, *Antarctic surface melting dynamics: Enhanced perspectives from radar scatterometer data.* Journal of Geophysical Research: Earth Surface, 2012. **117**(F2).
59. Steiner, N. and M. Tedesco, *A wavelet melt detection algorithm applied to enhanced-resolution scatterometer data over Antarctica (2000–2009).* The Cryosphere, 2014. **8**(1): p. 25-40.
60. Engeset, R., et al., *Change detection and monitoring of glacier mass balance and facies using ERS SAR winter images over Svalbard.* International Journal of Remote Sensing, 2002. **23**(10): p. 2023-2050.
61. Oza, S., et al., *Study of inter-annual variations in surface melting over Amery Ice Shelf, East Antarctica, using space-borne scatterometer data.* Journal of earth system science, 2011. **120**(2): p. 329-336.
62. Shea, J., *Meteorological data from Yala Base Camp automatic weather station*, ICIMOD, Editor. 2016.
63. ESA. *User Guides - Sentinel-1 SAR - Interferometric Wide Swath*. Sentinel Online. February 13, 2020]; Available from: https://sentinel.esa.int/web/sentinel/user-guides/sentinel-1-sar/acquisition-modes/interferometric-wide-swath
64. Man, Q.X., et al., *Comparison of different methods for monitoring glacier changes observed by Landsat images.* IOP Conference Series: Earth and Environmental Science, 2014. **17**.
65. Winsvold, S.H., et al., *Using SAR satellite data time series for regional glacier mapping.* The Cryosphere, 2018. **12**(3): p. 867-890.
66. de Kok, R.J., et al., *Measurements, models and drivers of incoming longwave radiation in the Himalaya.* International Journal of Climatology, 2020. **40**(2): p. 942-956.
67. Baral, P., et al., *Preliminary results of mass balance observations of Yala Glacier and analysis of temperature and precipitation gradients in Langtang Valley, Nepal.* Annals of glaciology, 2014. **55**(66): p. 9-14.
68. Entekhabi, D., et al., *The soil moisture active passive (SMAP) mission.* Proceedings of the IEEE, 2010. **98**(5): p. 704-716.
69. Miège, C., et al., *Spatial extent and temporal variability of Greenland firn aquifers detected by ground and airborne radars.* Journal of Geophysical Research: Earth Surface, 2016. **121**(12): p. 2381-2398.
70. Forster, R.R., et al., *Extensive liquid meltwater storage in firn within the Greenland ice sheet.* Nature Geoscience, 2014. **7**(2): p. 95-98.

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