Central Asia's spatiotemporal glacier response ambiguity due to data inconsistencies and regional simplifications

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Abstract. ~~Glacier evolution across~~ We have investigated the drivers behind the observed spatiotemporal mass balance heterogeneity in Tien Shan and Pamir~~is heterogeneous in space and time. This heterogeneity is believed to be mainly driven by contrasting climatic settings and changing atmospheric conditions. However, a systematic and consistent region-wide analysis of the climatic and static morphological drivers remains limited to date. Meteorological~~ , in High Mountain Asia. To study the consistency of the different interpretations derived from the available meteorological reanalysis and remote sensing products, ~~and novel approaches to derive region-wide annual mass balance time series, all provide the basis to investigate the drivers behind the observed heterogeneous glacier response. Here, we investigate the consistency of interpretations derived from available datasets through~~ we used correlation analyses between climatic and static drivers with ~~mass balance estimates in Tien Shan and Pamir~~novel estimates of region-wide annual glacier mass balance time series. These analyses were performed both spatially using different spatial classifications of glaciers and temporally for each individual glacier. Our results show that ~~even~~ the importance of the variables studied depends strongly on the dataset used and which spatial classification of glaciers is chosen. This extends to opposing results using the different products. Even supposedly similar datasets lead to different and partly contradicting assumptions on dominant drivers of mass balance variability. ~~Only when considering all glaciers in the Pamir and Tien Shan together, we find a similar picture of dominant meteorological drivers over space. Using either existing mountain subdivisions or glacier subdivisions based on mass balance variability, no consistencies can be found. Within different mass balance and meteorological datasets the results suggest very different drivers. This conclusion is even more prominent in the temporal correlation analysis where contradicting patterns of dominant drivers result from presumably similar meteorological datasets. Clear non-climatic drivers could not be identified. Even with newly available mass balance and meteorological data, a knowledge gap about the main mechanisms behind the heterogeneous glacier response in Central Asia remains. The results highlight that~~ The apparent but false consistencies across studies using a single dataset ~~might largely relate to~~ are related, according to our results, to the chosen dataset or spatial classification rather than to the processes or involved environmental variables. ~~As long as no~~ Without a glaciological, meteorological, ~~or~~ and hydrological *in situ* observation network ~~provides data for~~ providing data that allow the direct calibration and validation of extensive datasets, ~~we cannot predict a realistic improvement in~~ our understanding of the changing cryosphere at the regional scale for Tien Shan and Pamir cannot improve, neither can our understanding of glacier response to climate change or the assessment of water availability for the region's growing population.

1 Introduction

Glaciers across ~~the~~ Tien Shan and Pamir, ~~part of~~ in High Mountain Asia, have been observed to change heterogeneously ~~(e.g., Barandun et al., 2021; Shean et al., 2020; Brun et al., 2017; Miles et al., 2021). This behaviour is principally driven by their different mass balance sensitivities to the climate (Sakai and Fujita, 2017; Wang et al., 2019). The diverse glacier responses to climate change are thus not only a result of~~ in space (e.g., Barandun et al., 2021; Shean et al., 2020; Brun et al., 2017; Miles et al., 2021). Under the assumption of equal climatology, glacier morphology has been found to explain up to 36% of the mass balance variability for Tien Shan, 20% for Pamir-Alay, and only 8% for Western and Eastern Pamir (Brun et al., 2019). Thus, local topographic and glacier-specific morphological characteristics ~~(Fujita and Nuimura, 2011; Brun et al., 2019), but also relate~~ cannot wholly explain the diverse glacier responses to climate change (Fujita and Nuimura, 2011; Brun et al., 2019); these are also related to sharp contrasts ~~of~~ in the local climatological settings~~. Changes in the weather patterns regarding seasonality and intensities of different meteorological variables, such as precipitation and air temperature for the last two decades are characterized in Gerlitz et al. (2020). Gerlitz et al. (2019) showed that changing regional circulation characteristics led to increased climate variability during the winter season and explained parts of the pronounced warming in Central Asia . Mölg et al. (2014) and Farinotti et al. (2020)~~ , mainly to their different mass balance sensitivities to climate (Sakai and Fujita, 2017; Wang et al., 2019) (responsible for up to 60% of spatially contrasting glacier response in High Mountain Asia (Sakai and Fujita, 2017)). Mölg et al. (2014) and Farinotti et al. (2020) related a spatially heterogeneous glacier response for selected mountain ranges to different weather pattern constellations. ~~Dyurgerov and Dwyer (2000) and Azisov et al. (accepted) reported changes in accumulation and ablation patterns of selected Central Asian glaciers, resembling a shift from continental to more maritime glacier regimes. Such shifts consequently influence the mass balance sensitivity (Wang et al., 2017) and variability(Barandun et al., 2021). In earlier studies, climatic settings were found to be the dominant drivers of the heterogeneous mass balance sensitivity over High Mountain Asia and explained up to 60% of its spatially contrasting glacier response (Sakai and Fujita, 2017). Under the assumption of equal climatology, the glacier morphology was found to explain up to 36% of the mass balance variability for the Tien Shan, 20% for the Pamir-Alay, but only 8% for the Western and Eastern Pamir (Brun et al., 2019).~~

~~The investigation of the~~ These are reported to have changed in the past (Gerlitz et al., 2020), leading to increased climate variability. de Kok et al. (2020) argues that increased evapotranspiration might explain positive mass balances for solid precipitation sensitive glaciers. However, systematic analyses of drivers behind the observed spatiotemporal mass balance heterogeneity ~~has so far only received limited attention . This is~~ have attracted limited attention to date mainly due to ~~three reasons:~~ (1) limited ~~glaciological measurements,~~ direct glaciological and meteorological measurements, (2) large uncertainties about meteorological variables, and (3) ~~a~~ limited understanding of ~~non-climatic~~ nonclimatic effects on glacier mass balance.

(1) Glaciological measurements are conducted predominantly at annual resolution and are limited to a few ~~, well accessible~~ well-accessible glaciers. Geodetic methods, which have become state-of-the-art to assess glacier mass balances, have limited temporal resolution. Remote sensing provides a powerful tool to study inaccessible glaciers from space~~, however~~; however, robust mass change assessments remain limited to intervals of ~~five~~ 5 years or more (e.g., Kääb et al., 2015; Brun et al., 2017; Wang et al., 2017; Shean et al., 2020; Wouters et al., 2019; Hugonnet et al., 2021). ~~Barandun et al. (2018) developed an approach to~~

~~reduce the uncertainties related to conventional mass balance modelling by incorporating observations of transient snowlines. Barandun et al. (2021) has applied this approach in combination with geodetic mass changes and highlight, for the first time, hot-spots of~~ Barandun et al. (2018) highlighted hot spots of spatiotemporal heterogeneity and ~~increasing~~ increased mass balance variability in the different mountain ranges of the Tien Shan and Pamir at annual temporal resolution~~.~~; however, their results were not purely observation based. Meteorological measurements are sparse and often discontinuous even for the most monitored glaciers in Central Asia, such as Abramov or Golubin Glacier (Kronenberg et al., 2021; Azisov et al., accepted). Replacement of old meteorological stations with modern sensors often lacks precise homogenization. Regional extrapolation from station data and use of existing time series as validation datasets for gridded products are thus problematic.

(2) ~~The identification of possible~~ Identification of potential climatic drivers for mass balance variability is ~~strongly complicatedby prevailing~~ highly complicated; uncertainties in climatic state variables ~~due to a lack of~~ prevails due to the abovementioned lack of independent station data in the remote and largely inaccessible terrain. These data are ~~crucially needed~~ crucial for validation and adjustment of gridded datasets (Zandler et al., 2019). Precipitation products, in particular ~~,~~ from reanalysis, interpolation, and remote sensing, can show up to 1000% difference in these remote locations (Palazzi et al., 2013; Pohl et al., 2015; Immerzeel et al., 2015) and can barely cover the large range of orographic processes that affect~~e.g.~~, for example, small scale precipitation events (Roe et al., 2003). ~~Problems in remote sensing snow retrieval, and precipitation in general, over complex topography render reanalysis products in most cases~~Reanalysis products, in most cases, are more suitable for capturing precipitation seasonality and spatial patterns in ~~the Pamir~~ Pamir – albeit overall intensities ~~might not be captured well~~ possibly not being well captured – due to problems in remote sensing snow retrieval, and precipitation in general, over complex topography (Zandler et al., 2019; Pohl et al., 2015). The spatiotemporal comprehensiveness of reanalysis data facilitates ~~including~~ the inclusion of various climatic variables at global scale in correlation analysis that are otherwise not ~~even~~ available from simple meteorological stations or remote sensing/interpolation data products ~~. This allowed, for example Hugonnet et al. (2021) , to derive matching patterns of decadal glacier mass balance variability with precipitation and temperatures in a global scale analysis.~~ (e.g. Hugonnet et al., 2021).

(3) Many glaciers in Central Asia are heavily ~~debris-covered in their ablation areas and debris thickness can range considerably (Kraaijenbrink et al., 2017)~~debris covered with considerably different debris thickness (Kraaijenbrink et al., 2017; McCarthy et al., 2021) . A scale-dependent ~~debris-cover~~ debris cover - mass balance relationship and ~~the lack of~~ limited region-wide debris thickness assessments ~~limit~~ restrict the explanatory power of debris cover for region-wide glacier mass balance patterns in Central Asia (Brun et al., 2019; Miles et al., 2022). Both ~~the~~ Tien Shan and Pamir are known to host numerous surge-type glaciers (Mukherjee et al., 2017; Kotlyakov et al., 2008; Gardelle et al., 2012; Guillet et al., 2022). After a surge, the mass balance regime of ~~the~~ a glacier changes abruptly due to ~~non-climatic~~ nonclimatic reasons. After such a pronounced advance, melt rates might increase ~~strongly~~greatly, uncoupled from current local climate conditions ~~. Guillet et al. (2022) show that there is~~ (Glasser et al., 2022). Guillet et al. (2022) show that no significant difference exists in mass balance between ~~surge-type and non-surge-type glaciers. However, they use two different geodetic~~ surge- and nonsurge-type glaciers. Avalanching represents another nonclimatic factor that influences glacier mass balance through mass redistribution. The quantification of its effect on glacier mass balance at regional scales is, however, not straightforward. As an approximation, Brun et al. (2019) used the avalanche contributing area

as potential morphological control. However, the authors found no significant correlation with their mass balance estimates ~~that already show pronounced differences~~for almost all regions assessed in High Mountain Asia.

~~With the ultimate aim to better understand the climatic and non-climatic induced spatiotemporal~~ The reasons abovementioned outline a lack of consistent understanding regarding the climatic and nonclimatic drivers of glacier mass balance variability ~~for the~~ in Tien Shan and Pamir~~previously reported in literature (e.g., Brun et al., 2017, 2019; Barandun et al., 2021; Hugonnet et al., 2021), we aim to provide~~. Therefore, a more comprehensive and rigorous analysis of the available datasets is indispensable to provide more conclusive and accurate results and interpretations on the drivers of ~~the~~ glacier response to climate change ~~for~~ in Central Asia. Therefore, we aim in this study for a rigorous analysis of different datasets to identify similarities and differences in the drivers found to explain the glacier mass balance changes in Pamir and Tien Shan, with the ultimate goal of advancing the understanding of the drivers behind heterogeneous mass balance changes in Central Asia. Our analysis benefits from newly available and advanced ~~high~~ highly temporally resolved mass balance estimates and new reanalysis products. Given the often unconstrained uncertainties in climatological / meteorological datasets for ~~data sparse~~ data-sparse regions, we ~~consider the analysis of the~~ analyze (1) the consistency of the different meteorological and mass balance ~~data sets as a fundamental and eminently needed first step. In this study, we therefore rigorously analyse different products to pinpoint similarities and differences in the identified drivers behind the glacier mass balance changes in Pamir and Tien Shan.~~datasets and (2) which variables can explain in a statistically significant manner the variability found in mass balance datasets.

We follow a systematical approach ~~for testing~~ to test three different reanalysis products that are or have been used extensively in the region. Additionally, due to existing differences in glacier mass balance ~~time-series, we also incorporate two~~ time series, we incorporate the two available annual mass balance estimates ~~. One are the~~ for the region: the snowline-aided estimates by Barandun et al. (2021) ~~, and one are~~ and the geodetic mass balances by Hugonnet et al. (2021). ~~These~~ Mass balance time series are related to the most commonly used climatic variables temperature ~~and precipitation~~ (T) and precipitation (P) from the reanalysis datasets, ~~and to the glacier specific~~ snow cover (SC) from a remote sensing product, and glacier-specific topographic and morphological characteristics. Finally, to account for possible regional data issues or arbitrarily chosen regional divisions, the analyses are performed at different spatial subsets.

~~In short, our analysis follows the objectives 1) to reveal dominant drivers for glacier mass balance and associated uncertainties resulting from dataset choices, and 2) to reveal the limitations connected to the use of gridded climate data products as only estimates in the absence of ground truthing.~~

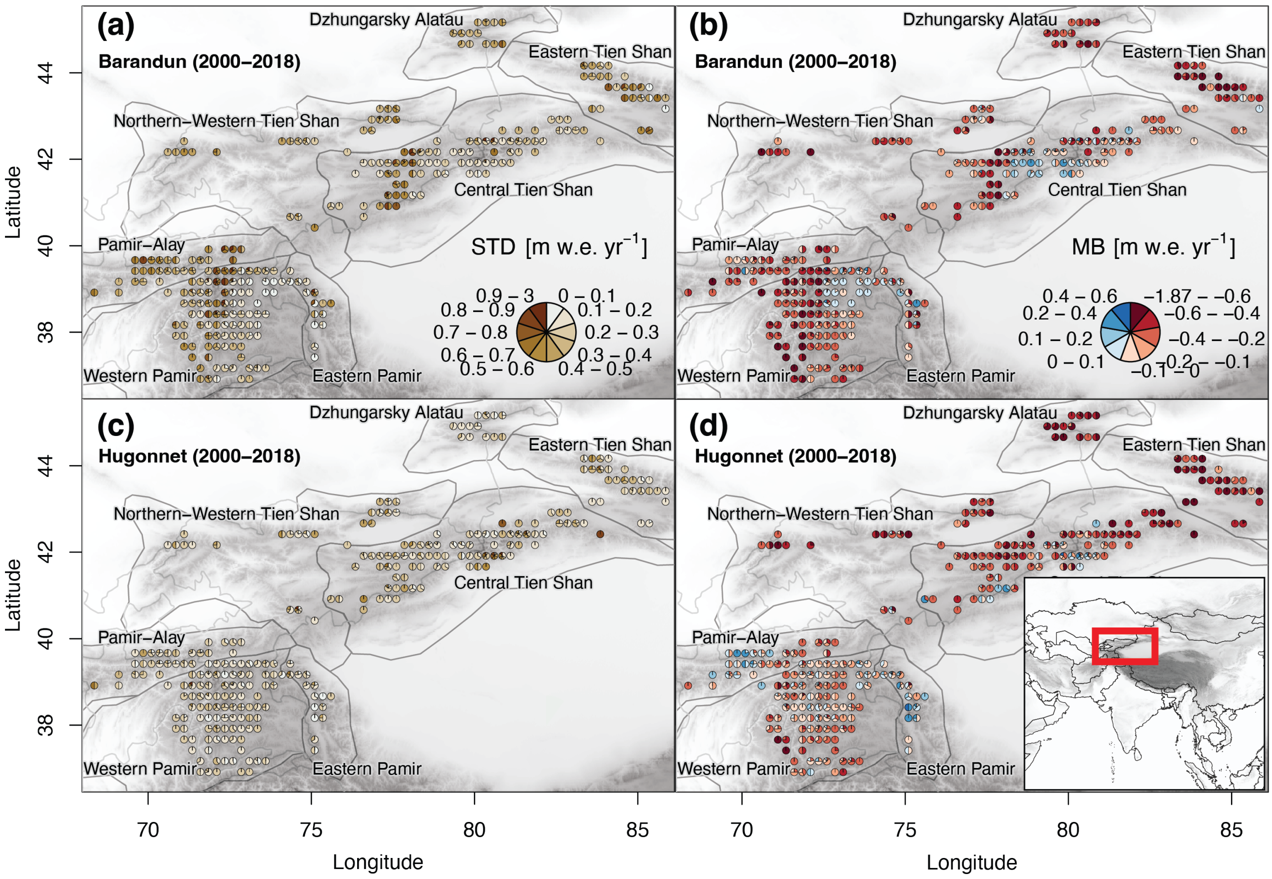

Figure 1. Overview map of the study region. (a,~~the glacier~~ c) Glacier mass balance variability in terms of standard deviation (STD~~; left~~) and (b, d) average ~~surface~~ glacier mass balance estimates (~~SMB; right~~MB) ~~from the work of Barandun et al. (2021) (top~~a, b) from Barandun et al. (2021) and ~~Hugonnet et al. (2021) (bottom~~c, d) Hugonnet et al. (2021). Estimates from Hugonnet et al. (2021) ~~only~~ include only the glaciers for which the transient snowline constrained modelling of Barandun et al. (2021) provides estimates. The pie charts aggregate values per glacier into classes and the relative class frequencies. Pies are not scaled to glacier area. The seven subregions of the Hindu Kush Himalayan Monitoring and Assessment Programme (HiMAP) classification (Bolch et al., 2019) are shown in grey outlines.

2 Study sites and data

3 ~~Study Site and Data~~

2.1 Study sites

2.1.1 Climate setting and variability

~~The following shall provide some insights on the complex climate settings of High Mountain Asia that reanalysis products are expected to depict. These settings range from humid, maritime, to continental and hyper-arid (Bohner, 2006; Schiemann et al., 2007; Yao et~~ ~~.~~ Central Asia is a mostly arid to ~~semi-arid~~ semiarid region (Barry, 1992) with high seasonal precipitation variability due to its continentality (Haag et al., 2019). Synoptic large-scale meteorological conditions ~~over Central Asia are the result of the~~ in Central Asia respond to the main direction of the zonal flow of the air masses from west to east. A deflection of westerly trade winds (~~Westerlies~~westerlies) to the north and south at the western orogen margin of Tien Shan and Pamir ~~cause~~ causes intense precipitation in the west~~and the~~ , and a barrier effect creates increasingly arid conditions towards the central and eastern part of the main mountain ranges (Pohl et al., 2015; Aizen et al., 2009, 1995). Meridional airflow can occur when tropical air masses enter from south and south-west or when north-westerly, northerly, and sometimes even north-easterly cold air masses intrude into Central Asia (Schiemann et al., 2008, 2007). These mechanisms can provide some insights on the complex climate settings of High Mountain Asia that reanalysis products are expected to depict. These settings range from humid, maritime, to continental and hyperarid (Bohner, 2006; Schiemann et al., 2007; Yao et al., 2012; Maussion et al., 2014).

~~The climate~~ Climate variability depends strongly on how and when the different weather types interact (Zhao et al., 2014; Wei et al., 2017; Gerlitz et al., 2020), guided principally by the position and strength of the jet stream. ~~Schiemann et al. (2008)~~ Schiemann et al. (2008) investigated in detail the seasonal cycle of ~~the~~ Central Asian climate to show that the jet stream is situated over the north of Central Asia during the summer months and ~~that it~~ moves towards the south in autumn, creating atmospheric instabilities. Resulting precipitation occurs mainly at the western margin until mid-January. Subsequently, the influence of the jet stream weakens over Central Asia and the Siberian high-pressure system creates clear and calm winter weather, especially reducing winter precipitation in the north and east (Aizen et al., 1997). By the end of February, the jet stream returns northwards and reaches the southern edge of Central Asia carrying warm and moist air. This creates ~~a~~ temperature contrasts between the north and the south and strengthens the cyclonic activity over Central Asia (Schiemann et al., 2008). Consequently, the highest amount of precipitation, ~~characterised~~ characterized by heavy showers and thunderstorms, occurs in March and April~~and culminates in~~ , culminating at the western parts of ~~the~~ Tien Shan and ~~the~~ Pamir. While the jet stream continues northwards during May, precipitation maxima are reached in ~~the~~ Northern Tien Shan in June (Aizen et al., 2001). At the beginning of the summer, the cyclonic activity weakens, and heat lows start to form again. During summer, the Siberian anticyclonic circulation provides cold and moist air masses in Northern, Central, and Eastern Tien Shan, resulting in frequent spring or summer precipitation (Aizen et al., 1997). The most dominant moisture source at the southern margins of ~~the Pamir are~~ Pamir is the heavy rainfalls provided by the Indian Summer Monsoon ~~(e.g., Cadet, 1979)~~(e.g., Cadet, 1979). Orographic shielding at the south and south-eastern margin of Central Asia's mountain ranges ~~however~~ strongly reduce this moisture supply and lead to very dry conditions in the central parts of ~~the~~ Pamir (Boos and Kuang, 2010; Haag et al., 2019). The Tibetan anticyclone ~~influences additionally~~ additionally influences the local climate along the eastern margin of ~~the~~ Pamir (Archer and Fowler, 2004), leading to summer cooling (Forsythe et al., 2017) and summer rainfall (Aizen et al., 1997).

2.1.2 Topography and glaciation

~~The~~ Tien Shan and Pamir are the two main mountain ranges of Central Asia in the ~~North~~ north of the Karakoram and Hindu Kush. ~~Here, we chose~~ In the present work, we choose a subdivision of the regions based on the ~~commonly-used HiMAP~~commonly used Hindu Kush Himalayan Monitoring and Assessment Programme (HiMAP) regional division suggested in ~~Bolch et al. (2019) into~~Bolch et al. (2019): Western / Northern Tien Shan, Eastern Tien Shan, Central Tien Shan, Dzhungarsky Alatau, Pamir-Alay, Western Pamir, and Eastern Pamir (Fig. 1). ~~The~~ Tien Shan hosts almost 15~~,~~ 000 glaciers, covering a surface area of $\approx 12' \, 300\,km^2$ (~~according to the Randolph Glacier Inventory Version 6.0 (RGIv6.0,~~ RGI, 2017). ~~The Pamir~~Pamir, including Pamir-Alay (also Hissar-Alay), hosts around 13~~,~~ 000 glaciers, covering similarly a surface area of ~~,~~$\approx 12 \, *0000\,km^2$. ~~Highest~~ The highest mountain ranges are found in ~~the~~ Central Tien Shan and Western and Eastern Pamir ~~. Barandun e~~

2.2.1 Annual mass balance ~~time-series~~time series

~~We use two annually-resolved and glacier specific~~ In the present study, we use the two existing annually resolved glacier-specific datasets for glacier mass balance estimates ~~;~~ covering the entire Tien Shan and Pamir: one based on transient ~~snow line observations and the other o~~ digital elevation model (DEM) differences ~~.~~(Fig. 1).

MB$_{Barandunetal}$ ~~are~~) comprises the annual time series provided by ~~Barandun et al. (2021)~~ Barandun et al. (2021), who used a mass balance model ~~combining transient snowlines ,~~ calibrated simultaneously with transient snowlines (as a proxy for surface mass balance~~, together with derived~~) and geodetic mass changes~~to provide annual mass balance time series. 255,000 automatically mapped snowline observations (Naegeli et al., 2019) from 2000 to 2018 for the Tien Shan and Pamir were used for model calibration. The snowlines were mapped for each glacier individually on over 3,000 Landsat surface reflectance scenes with cloud cover of <50%. The transient snowlines are used to directly calibrate a temperature-index and distributed accumulation~~ . The model driven with ERA-interim reanalysis ~~(Dee et al., 2011) data~~ data (Dee et al., 2011) for each glacier and year separately (Barandun et al., 2021, 2018). ~~In a second step, semi-decadal to decadal geodetic mass balances were integrated into the model calibration (Barandun et al., 2021). The geodetic mass balances were derived from Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER)scenes and High Mountain Asia DEMs (Girod et al., 2017; Shean et al., 2017) . A total of over 25, 000 individual geodetic estimates were homogenized to a common reference period from 2000 to 2018 using long-term glaciological measurements (Zemp et al., 2019). These glacier-specific decadal to semi-decadal geodetic mass changes were then used to constrain the modelled mass balance time series in order to reach agreement between the two observational datasets. Thus, Barandun et al. (2021)~~ ERA-interim was chosen because, unlike other reanalysis products (e.g., ERA5), *in situ* observations in mountain regions are assimilated (Orsolini et al., 2019). Barandun et al. (2021) provided annual mass balance ~~time-series~~time series, closely tied to direct observations, with low sensitivity to meteorological input for roughly 60% of the glaciers larger than 2 km^2 in the data-sparse Tien Shan and Pamir. For more details on the methodological approaches for mass balance determination and model sensitivity the reader is referred to ~~Barandun et al. (2018, 2021),~~ Barandun et al. (2018) and Barandun et al. (2021); for the automatic snowline mapping~~to Naegeli et al. (2019), ~~, to Naegeli et al. (2019) ; and for the geodetic estimates~~to Girod et al. (2017) and McNabb et al. (2019). ~~, to Girod et al. (2017) and McNabb et al. (2019) . Differences in ERA-interim and ERA5 performance and output at high altitudes are highlighted in Orsolini et al. (2019) and Liu et al. (2021), showcasing the independence of the two datesets.

The second dataset (MB$_{Hugonnet et al}$~~are~~) comprises the geodetic mass balance estimates by Hugonnet et al. (2021)~~. Their estimates~~, which rely on DEM differences and filtering techniques. The predominant input is the 20-year-long archive of stereo images from the ~~ASTER~~ Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER) used to derive ~~time-series~~ time series of DEMs. Their estimates were validated at all glaciers world-wide with intersecting laser altimetry and ~~optical elevations and show~~ elevations derived from high resolution optical imagery data. The approach shows good agreement at the global scale although ~~at local and regional scale biases can persist~~having varying uncertainties at the regional scale (Hugonnet et al., 2021) due to a sometimes limited performance of the method for individual glaciers (Hugonnet et al., 2021). Geodetic methods are more accurate at longer ~~time-scales~~ time scales as the signal-to-noise ratio improves. However, Hugonnet et al. (2021) also provide annual estimates connected to much higher uncertainties pointed out by the authors, which we use in this work. We select only the ~~same~~ glaciers from this dataset for which ~~we have~~ estimates from Barandun et al. (2021) are available. This serves for a consistent analysis of dominant drivers and ~~at the same time highlight~~ to highlight the differences between the two mass balance estimates ~~.~~ (Fig.2).

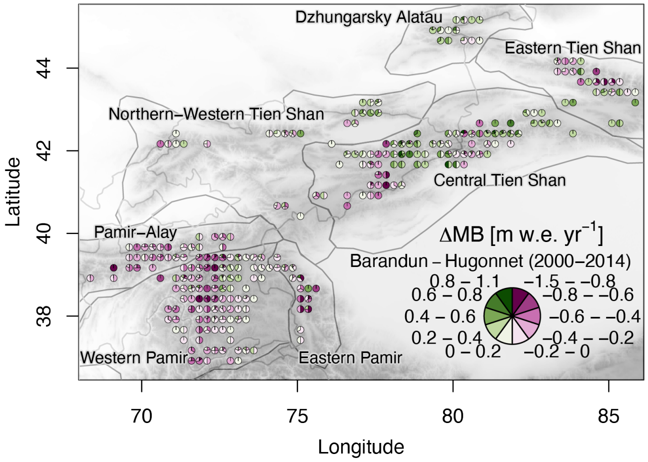

Figure 2. Difference in mean annual glacier mass balance between Barandun et al. (2021) and Hugonnet et al. (2021) for the period 2000–2014 (see Fig. A1 for period 2000–2018). Estimates from Hugonnet et al. (2021) only include the glaciers for which the transient snowline constrained modelling of Barandun et al. (2021) provides estimates. The pie charts aggregate values per glacier into classes and the relative class frequencies. Pies are not scaled to glacier area.

Both datasets are tied to elevated uncertainties of the annual mass balance estimates. Barandun et al. (2021) adopted mean uncertainties provided in Barandun et al. (2018) (±0.32 m w.e. yr^{-1}) associated with the snowline-constrained mass balance modelling and combined them with the error estimate from the geodetic surveys. This resulted in a rather conservative uncertainty of ±0.37 m w.e. yr^{-1} and does not assume independence of the errors from year to year. Hugonnet et al. (2021) reported uncertainties of up to ±0.1 m w.e. yr^{-1} for mean annual mass balance values of 5-year periods. Hugonnet et al. (2021)

provide uncertainties in mass changes for periods shorter than 5 years only for the global or near-global estimates. Global annual mass balance uncertainties are reported to be around ±0.2 m w.e. yr^{-1} (Hugonnet et al., 2021), and we expect higher ones for the mass balance time series of individual glaciers.

2.2.2 Glacier morphological characteristics

We use glacier outlines and areas from the Randolph Glacier Inventory (RGI) version 6 (RGIv6~~(RGI, 2017), which were~~, RGI, 2017), kept unchanged over time, and the freely available ~~,~~void-filled Shuttle Radar Topography Mission (SRTM, Jarvis et al., 2008) digital elevation model ~~to derive glacier topography, aspect and slope as morphological parameters~~as topographic input. We use ~~further~~ the information provided in Scherler et al. (2018) on percentage of ~~debris-cover~~ debris cover on individual glaciers for ~~the~~ Tien Shan and Pamir and the data on surge activity from (Guillet et al., 2022). The latter work provides multiple statistics on surge activity. We ~~chose to simply~~ use occurrence of surge activity provided in this dataset to test ~~if there is~~ whether a significant difference ~~between surge and non-surge type~~ exists between surge- and nonsurge-type glacier mass balances in MB$_{Hugonnetetal}$ and MB$_{Barandunetal}$. We do not include other variables such as avalanche processes due to insufficient data availability.

2.2.3 Meteorological data

~~In order to investigate possible relationships of the~~ We use precipitation and air temperature of three different reanalysis datasets to identify similarities and differences in the relationships of mass balance with ~~the~~ key meteorological drivers ~~, precipitation and air temperature, we use three different reanalysis dataset and a remote sensing snow cover product~~(Fig. 3 and A2). The reanalysis products are (1) the European Centre for Medium Range Weather Forecast (~~ECWMF~~ECMWF) fifth generation atmospheric reanalysis ERA5 (Hersbach et al., 2020), (2) the Climatologies at High resolution for the Earth's Land Surface Areas (CHELSA) ~~time-series~~ time series version 2.1 (Karger et al., 2017, 2021), and (3) the High Asia Refined analysis (HAR) in 30 km spatial resolution HAR30 version 1.4 (Maussion et al., 2011). The ~~snow cover product is the Moderate resolution Imaging Spectroradiometer (MODIS) monthly snow cover product MOD10CM version 6 (Hall and Riggs, 2015). We chose the time period~~ study time period is 2000–2018 ~~, as well as~~ ("long"), and 2000–2014 ~~for all dataset~~ ("short") for all datasets to match the limited temporal availability of HAR30 v1.4 (Maussion et al., 2011), for which only the second period was ~~analysed~~analyzed.

ERA5 monthly averaged data on single levels from 1979 to present is an atmosphere reanalysis dataset (Hersbach et al., 2020) with a 0.25° × 0.25° (≈21 km) native spatial resolution. ERA5 incorporates a multitude of *in situ* and remote sensing data in an integrated forecasting system to produce hourly outputs of atmospheric variables. We obtained the monthly means (sums) product from the ECMWF data store for temperature (precipitation). ERA5 data have not been thoroughly validated in hydrological ~~and~~ or glaciological model applications in Pamir ~~and~~ or Tien Shan. A significant overestimation of snow depth (Wang et al., 2021; Orsolini et al., 2019) is problematic for these applications and is also assumed to alternate the energy fluxes related to overestimated albedo (Wang et al., 2021). This renders the parameters for in- and outgoing energy fluxes

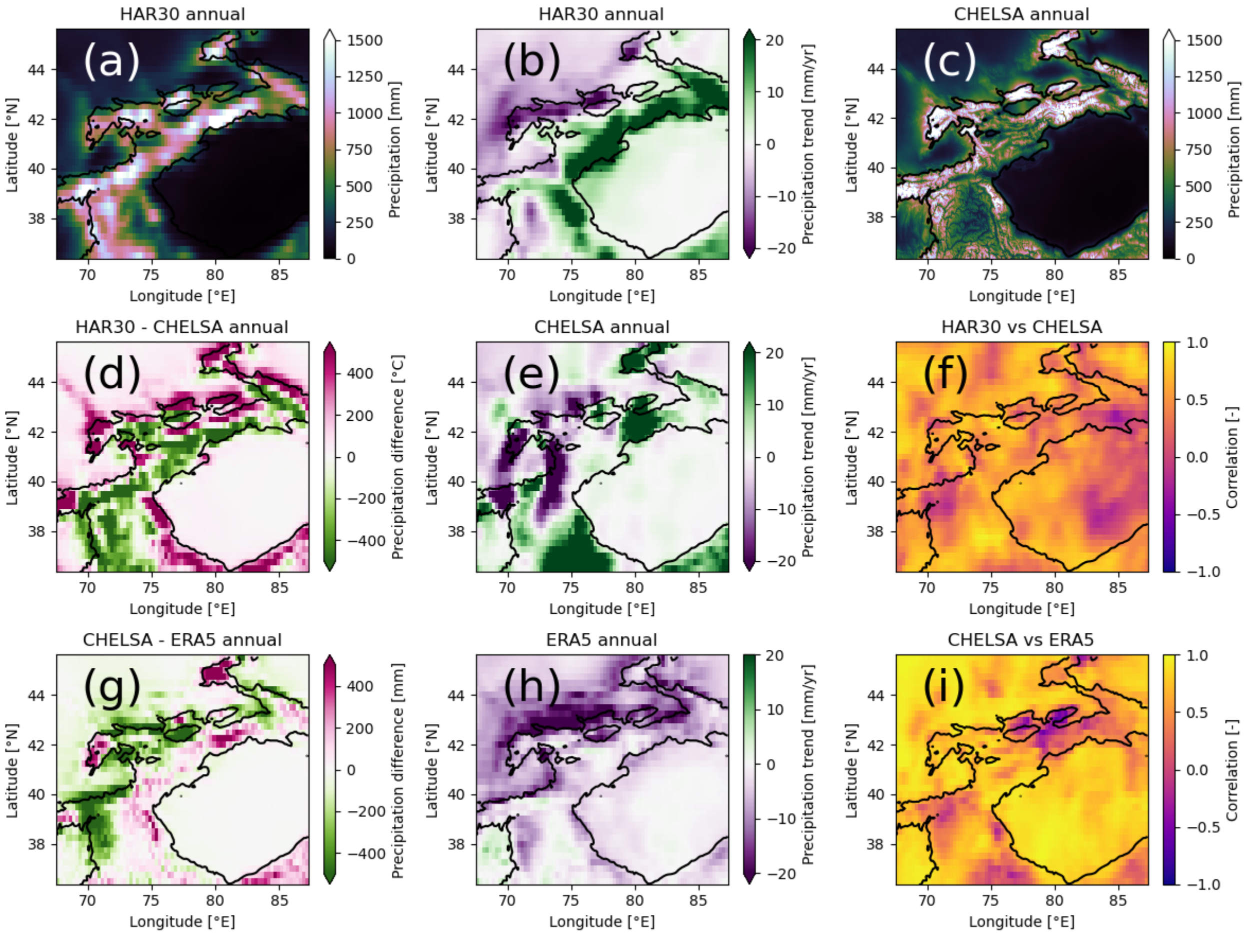

Figure 3. Mean annual precipitation sums for (a) HAR30 and (c) CHELSA. Trends for (b) HAR30, (e) CHELSA, and (h) ERA5. Differences between (d) HAR30 and CHELSA and (g) CHELSA and ERA5 and correlation between (f) HAR30 and CHELSA and (i) CHELSA and ERA5. CHELSA and ERA5 were spatially resampled bilineraly to the resolution of HAR30 for the differences and correlation. Black outlines correspond to 2000 m a.s.l. altitude. The same figure for temperature is provided in the Annex (A2).

problematic, nor are they consistently measured at the few meteorological stations in High Mountain Asia, and we focus only on the two variables ~~precipitation (P)~~ P and 2 m ~~air temperature (T).~~ T. For our correlation analysis, a systematic and linearly scaled over-/underestimation does not pose a problem. Consequently, we focus on P and T for the other datasets ~~as well~~too.

CHELSA ~~time-series~~ time series version 2.1 is a processed and downscaled version of the ERA5 dataset ~~. It~~ which incorporates directional wind speeds and cloud cover observations to address precipitation biases ~~, as well as wind- and~~ and wind and leeward distributions (Karger et al., 2017). The final downscaled product ~~has~~ presents a ≈1 km spatial and monthly temporal resolution. By incorporating the CHELSA data, we provide a means to determine how a state-of-the-art downscaling affects the correlation analysis.

HAR30 version 1.4 (Maussion et al., 2011) ~~has~~ presents a 30 km spatial and a daily temporal resolution. ~~The data resulted~~ Data result from a dynamical downscaling of global analysis data (Final Analysis data from the Global Forecasting System (National Centers for Environmental Prediction, National Weather Service, NOAA, 2000); ~~data set~~ dataset ds083.2) using the Weather Research and ~~Forecasting~~ Forecasting–Advanced Research WRF (WRF-ARW) model (Skamarock and Klemp, 2008). The ~~data set shows~~ dataset has shown high consistency with temperature, precipitation, and snow cover measurements in several regions of High Mountain Asia, where uncertainties are ~~particularly~~ especially large due to limited or ~~non-existent~~ nonexistent meteorological stations. ~~It~~ This dataset has captured climatic extremes in the greater Pamir region that lead to floods and droughts (Pohl et al., 2015)~~. It was~~ , has been used for glacier studies in the greater Himalayan region (Maussion et al., 2011; Mölg et al., 2013; Curio et al., 2015), and ~~it was~~ has been applied in hydrological studies (Pohl et al., 2015, 2017; Biskop et al., 2016). ~~While there was a~~ Despite the need to bias-correct HAR precipitation intensities in ~~the~~ Pamir (Pohl et al., 2015) and ~~the~~ Tibetan Plateau (Biskop et al., 2016), the dataset ~~showed~~ has shown superior correlation with *in situ* measurements than interpolated and remote sensing ~~dataset~~ datasets in Pamir (Pohl et al., 2015). Due to large uncertainties in gridded meteorological ~~dataset~~datasets, we believe that the HAR dataset, ~~which has been~~ validated at least to some degree in High Mountain Asia in several previous studies (e.g. Pohl et al., 2015, 2017; Biskop et al., 2016; Maussion et al., 2014), should be included in our analysis. We do not use HAR version 2 because ERA5 is used as input to downscale the version 2 output and shows strong differences with the validated HAR version 1 dataset.

2.2.4 Snow cover data

The snow cover product used in the present work is the Moderate resolution Imaging Spectroradiometer (MODIS) monthly snow cover product MOD10CM version 6 (Hall and Riggs, 2015). **MOD10CM** is a monthly average snow cover dataset on a regular climate modelling grid with approximately 5 km spatial resolution (Hall and Riggs, 2015). The snow cover is calculated using the normalized differences snow index (NDSI) constrained to positive values, providing snow cover values in the range between 0 to 100%. From the original snow cover fraction values, we also derive the temporal changes between consecutive time steps as a measure for snow accumulation or depletion events. ~~The two variables are simply referred to as snow cover (SC) in the following~~Here, we refer to both variables as SC.

3 Methods

The mass balance estimates of Hugonnet et al. (2021) and Barandun et al. (2021) ~~,~~ provide average long-term values for the two study periods (2000–2014 and 2000–2018) ~~, but~~ and, more importantly, ~~also annual time-series~~ annual time series for individual glaciers that are only available from the year 2000 onwards. In turn, this allows us to run two kinds of ~~analysis to determine possible drivers explaining the~~ analyses to determine potential drivers of mass balance variability: (1) a temporal individual analysis for each glacier ~~individually by correlating the~~ correlating mass balance and meteorological time series ~~,~~ ~~and~~ and (2) a spatial analysis relating mean glacier mass balance with statistics of meteorological and morphological data, e.g., long-term averages, trends, or the standard deviation as a measure for mass balance or meteorological variability. Both types of analysis are based on multiple linear regression analysis to identify significant predictors in the group of meteorological or morphological variables ~~. An overview of this workflow is given in~~ (Fig. 4). In this study, we focus strictly on the determination of significant predictors in multiple linear regression analysis and do not report, nor discuss, obtained model coefficients or coefficients of determination in detail. ~~Our reasoning is based on the very different~~ This decision responds to the large uncertainties present in the outcomes of the analyses, ~~based on the choices of meteorological dataset and mass balance estimates questioning the decisiveness of the results, and to streamline the scope of the work.~~ as shown in the results. Focusing on whether variables show or do not show significant correlations allow for a streamlined highlighting of important variables and seasons.

~~In order to~~ For the correlation, each glacier provides a data point in the spatial analysis, and each time step of an individual glacier time series provides a data point in the temporal analysis. To systematically identify all significant (always at a significance level α=0.05) ~~and~~ independent variables while accounting for some complexity in glacier accumulation and ablation processes, we use all possible combinations of two independent predictors for each meteorological and morphological dataset~~, respectively~~. For the spatial analyses we report the number of identified singificant predictor variables over the total number of variable combinations and refer to this as "relative importance"; for the temporal analyses, we identify all occurences of singificant predictor variables and present their frequency in pie chart maps. For the meteorological analysis, we constrain ~~these combinations to individual dataset products, e.g. only~~ the variable combinations separately to each individual dataset product, i.e., only combinations from ERA5, ~~but~~ or HAR, or CHELSA. However, we also extend this analysis ~~also to include the MODIS snow cover data~~ by adding the MODIS SC data to each reanalysis datasets in a second step. This allows ~~exploring if the observational snow cover~~ to explore whether the observational SC dataset adds more explanatory power than the reanalysis. The coarse spatial resolution of HAR30 and ERA5 can prevent the finding of correlations in the spatial analysis if the mass balance intergrid variability is lower than or equal to the variability within a grid cell. Using ERA5 and its downscaled version CHELSA for comparison provides a means to assess whether this effect occurs. In the temporal analysis, the spatial resolution does not affect the identification of significant correlations. A linearly downscaled (e.g., fixed temperature or precipitation lapse rate) higher resolution independent variable yields the same result in a correlation analysis as the data with a coarser resolution. This is because a determined significance is independent from a scale factor applied to a variable. The temporal component is also included to some degree in the spatial analysis by using derived statistics from the meteorological time series, such as standard deviation and trend, which also yield the same results in the correlation analysis if adjusted linearly.

We do not run a separate collinearity test to identify and remove correlating predictors even though this is expected, for example, in the case of different temporal temperature aggregates or snow cover and precipitation data (Fig. 4). As our ~~focus is to show~~ goal is to reveal possible inconsistent outcomes depending on the chosen glacier mass balance and meteorological dataset, we focus only on identifying significant predictors rather than model coefficients. A possible impact in case of collinearity is a ~~non-significance of one , or both of the two~~ nonsignificance of one or both correlating predictors (Vatcheva et al., 2016)~~.~~; thus, an anticipated effect of collinearity is the concealing (removing) of significant variables, rather than the inclusion of more. The results can thus be interpreted as a more conservative identification of significant variables when not accounting for collinearity. Due to the large number of combinations for the meteorological dataset (~~n~~n = 1480 for the spatial analysis including MODIS ~~snow cover~~SC), we expect ~~that~~ randomly omitted predictors ~~would, however,~~ to show up in a different combination and not to be completely omitted.

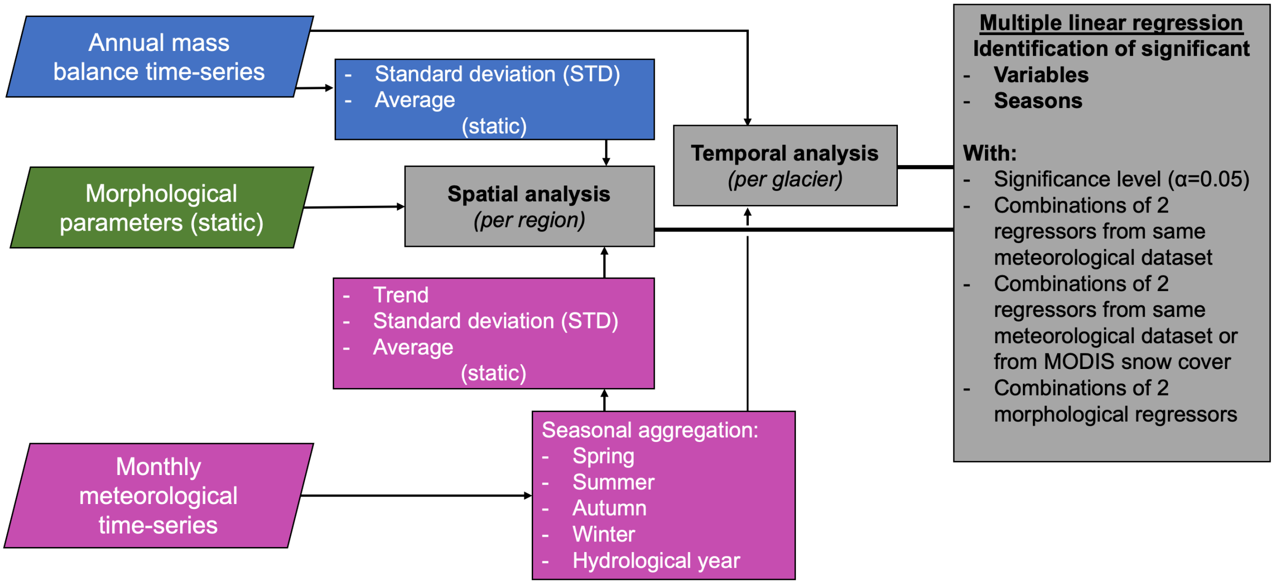

Figure 4. Workflow of spatial and temporal ~~analysis~~ analyses using the mass balance estimates from Barandun et al. (2021) and Hugonnet et al. (2021) ~~,~~ and the meteorological data from the three different reanalysis products and MOD10CM snow cover ~~,~~ (SC) as explained in the data section. Focus in this study is ~~the identification of~~ to identify significant relationships rather than ~~explained~~ explain variance or other statistics. Therefore, identification of important variables and seasons is solely based on derived *p-values* from multiple linear regression analyses. All significant correlations of a variable are used to produce the maps for the temporal analyses, and the reported "Relative Importance" in the spatial analysis is defined as the number of significant variables over the total number of tested variable combinations (see also Section3).

3.1 Spatial correlation

The spatial correlation ~~is using~~ uses the derived average ~~mass balances~~ annual mass balances for each of the 1220 glaciers ~~, either in their entirety~~ and provides results either for the entire Tien Shan and Pamir or divided into different regions according to two different classifications~~; 1)~~ : HiMAP after Bolch et al. (2019) according (1) to main mountain range names (Fig. 1) ~~, and~~ and (2) to the mass balance variability found in Barandun et al. (2021). The latter is determined using a k-means clustering with ~~3 fixed classes(~~three fixed classes, where points are classified by minimizing their squared distance to the iteratively determined cluster centers (Pedregosa et al., 2011; Fig. 5). ~~This division is done to see if there are~~ The k-means clustering is based on the standard deviation of the mass balance time series of Barandun et al. (2021) and relies on an unsupervised classification that avoids a precise association of a class with, for example, a process. We arbitrarily chose a number of three clusters that would highlight the regions of high mass balance variability (hot spots) identified in Barandun et al. (2021). The division is performed to determine whether different dominant predictors ~~for these "hot spots" of glacier mass balance variability~~exist for these regions and, in general, to assess the effect of arbitrarily subdividing glaciers into different groups.

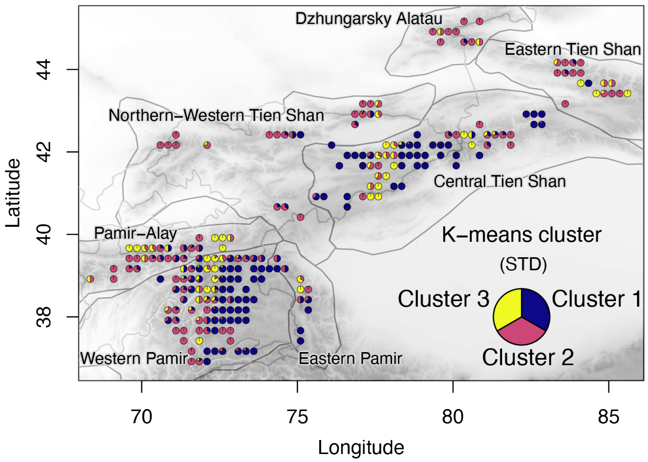

Figure 5. K-means clusters according to mass balance variability (standard deviation - STD) for the 2000–2018 period from Barandun et al. (2021). Classes represent glaciers with different variability.

We use either meteorological or morphological parameters as predictors. For meteorological predictors, we use calculated average, standard deviation, and trend or tendency (derived slope from a temporal regression), each for the different seasons (spring, summer, autumn, winter~~,~~) and the entire hydrological year (~~October-September~~October–September) (Fig. 4). As static morphological predictors, we include the variables latitude, longitude, slope over glacier tongue, median elevation, aspect, and glacier area from ~~the RGI , as well as~~ RGI and debris cover from Scherler et al. (2018). For aspect, we use the sine and cosine of the original values ~~given~~ in the range between 0 and 360° to ~~have~~ obtain consistent value ranges in zonal and meridional directions. We showcase, additionally, any possible relationship with surge activity using separate histograms and boxplots where we simplify the complex information on surge activity ~~given in Guillet et al. (2022) as either~~ provided in Guillet et al. (2022) as either (1) having experienced surge activity or (~~1) or not (~~0) ~~during the 2000 to 2018~~ not during the 2000–2018 study period.

3.2 Temporal correlation

~~In addition to the spatial analysis, we also~~ We run multiple linear regression analysis on the glacier mass balance ~~time-series~~ time series per glacier to identify significant predictors over the time domain. ~~The annual~~ Annual glacier mass balance time series ~~are~~ represent the dependent variable~~and~~ ; combinations of meteorological variables from individual reanalysis datasets

~~are~~ represent the predictors. As this yields one result per glacier, we aggregate the results visually in form of maps. We identify both ~~, significant variables , as well as significant seasons in this way~~ significant variables and significant seasons to identify possible patterns and differences resulting from the use of a particular reanalysis or mass balance dataset.

4 Results

4.1 Comparison of reanalysis datasets

A comparison of the different reanalysis datasets is shown for precipitation in Figure 3 and for temperature in Figure A2. Only CHELSA provides a spatial resolution to resolve intramountain range variability. Differences in precipitation amount and different trends exist independently of the spatial resolution (Fig. 3). However, for temperature, CHELSA is the temperature-conserving downscaled ERA5 product with matching trends and a correlation of one (Fig. A2i). For precipitation, CHELSA and ERA5 show deviating distribution patterns and trends, highlighting the nonlinear downscaling method (Fig. 3). The use of the datasets in their original spatial resolution in consecutive analyses allow for an assessment of how downscaling affects the correlation with mass balance data.

4.2 Spatial correlation

Despite a ~~relatively~~ high number of significant correlations between mass balances and meteorological variables (70-90%), the variability between the different ~~dataset~~ datasets is high, leaving ~~an~~ uncertain the interpretation on dominant drivers for ~~the~~ Tien Shan and Pamir ~~uncertain~~ (Fig. 6). Obtained coefficients of determination (R^2) are in the range of 5% for the entire Pamir and Tien Shan per variable and increase to up to 20% for ~~sub-regions~~ subregions (Fig. A3). When including remote sensing ~~snow cover (SC)~~ SC in addition to the reanalysis meteorological variables (T and P), SC ~~constitutes about half of~~ represents about half the significant correlations. Without SC, an akin number of significant correlations indicates that SC ~~is likely explaining~~ explains a similar portion of the variance in ~~the mass balance ,~~ mass balance but slightly more significantly than the variables from the reanalysis. The R^2 remains low (Fig. A3). No dominant season can be identified in the analysis for ~~the Tien Shan and Pamir. The variability~~ Tien Shan or Pamir. Variability in the meteorological variables within each season ~~or~~ and for the hydrological year are equally important (Fig. 6; ~~middle~~b, d).

Of the tested morphological parameters, 60 to 70% ~~showed~~ show a significant correlation with ~~the~~ mass balances for the entire Tien Shan and Pamir (Fig. 6; ~~bottom~~e-f), and no individual morphological variable stands out as the most dominant one (Fig. 6). Each ~~was determined in around~~ parameter is determined in 10% of combinations as a significant predictor. Debris cover is not identified ~~in any of the cases using either mass balance dataset for~~ as an important variable in any case using mass balance datasets for either the short or long time period. This only changes in the regional division ~~where debris cover is identified for some sub-regions.~~ for some subregions (Fig. A4). However, depending on the mass balance estimates and ~~sub-region~~subregion, the identified morphological parameters can change entirely~~(Fig. A4).~~. The mass balance distribution indicates no significant difference between ~~surge and non-surge type~~ surge- and nonsurge-type glaciers (Fig. A5). The small

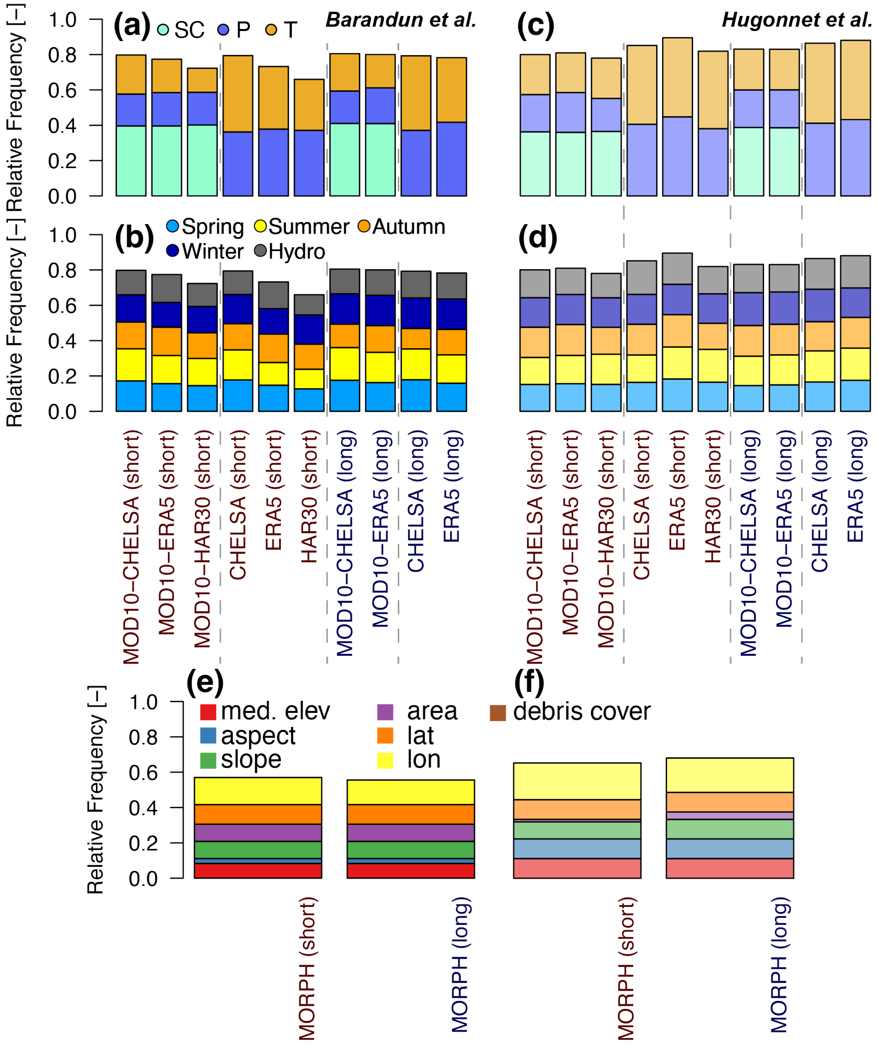

Figure 6. Importance of ~~climatic variables (top~~a,c) climatic variables, ~~season (middle~~b,d) season , and ~~morphological parameters~~ (~~bottom~~e-f) morphological parameters for the entire Tien Shan and Pamir. Solid colors (left) refer to MB$_{Barandunetal}$, and ~~semi-transparent~~ semitransparent colors (right) refer to MB$_{Hugonnetetal}$. Labels "short" and "long" refer to the periods 2000–2014 and 2000–2018, respectively. For the morphological analysis this refers to the glacier mass balance data.

number of ~~surge type glaciers and~~ surge-type glaciers and the uneven distribution across the regions (Fig. A6) ~~prevents~~ prevent a conclusive result.

Considering the different HiMAP regions (Bolch et al., 2019), the number of significant correlations between mass balance and meteorological variables varies strongly ~~, and is depending also~~ and depends on the mass balance dataset (Fig. 7). Overall, the total number of identified important variables ~~are similar between the two~~ is similar in both mass balance estimates. However, strong differences are apparent regarding which variable and temporal aggregation (seasons) is dominant. Likewise, the choice of a different reanalysis dataset results in different variable and temporal aggregation importance. For example, ~~there are many significant correlations for the~~ a large amount of significant correlations are present for Western Pamir and Northern / Western Tien Shan for MB$_{Barandunetal}$ and for Central Tien Shan for MB$_{Hugonnetetal}$ ~~;~~ whereas a medium amount of significant correlations ~~for the~~ are present for Eastern and Central Tien Shan for MB$_{Barandunetal}$ and for ~~the~~ Western Pamir and Pamir-Alay for MB$_{Hugonnetetal}$ (Fig. 7). For all other regions, the importance of meteorological variables is low and very variable from one dataset to another. For the majority of cases ~~,~~ according to the HiMAP classification and for the entire region (Fig. 7,6), the number of significant correlations is ~~higher for~~ somewhat higher for the spatially higher resolved CHELSA than for ERA5, despite CHELSA being based on ERA5 data as input. ~~Regardless of contributing to at least half of the significant combinations for most regions, snow~~ However, using the division according to the k-means clusters, this effect is not perceived (Fig. 8).

Snow cover increases the total amount of significant correlations only for ~~the~~ Central Tien Shan for MB$_{Barandunetal}$ and for ~~the~~ Eastern Tien Shan, Pamir-Alay, and Western and Eastern Pamir for MB$_{Hugonnetetal}$, despite contributing to at least half the significant combinations for most regions. For all other regions, ~~temperature and precipitation~~ T and P provide more significant correlations when ~~not considering snow cover~~SC is not considered. Combinations with ~~snow cover barely showed~~ SC barely show significant correlations in ~~the~~ Eastern Pamir and ~~the~~ Dzungarsky Alatau (Fig. 7). ~~Overall, we~~ Thus, incorporation of SC does not notably increase the number of significant correlations overall. Instead, a shift of important variables from P and T to SC occurs. This distinct shift from P and T to SC suggests that potential collinearity does not bias the general outcome.

We found clearly more significant combinations including ~~precipitation than temperature for the Western Pamir , and the~~ P than those including T for Western Pamir and Pamir Alay. ~~Temperature seemed more important for the~~ T seems more significant for Eastern and Northern / Western Tien Shan and, to some degree~~also for the ,~~ , for Central Tien Shan. For ~~the Dzhungarsky Alatauthe results varied~~ Dzhungarsky Alatau, the results vary strongly between the different datasets, ~~and prevented~~ preventing a conclusion on ~~a~~ the dominance of one of the meteorological variables. For ~~the~~ Western Pamir and ~~the~~ Eastern Tien Shan, winter and spring changes ~~contributed~~ contribute to most of the significant combinations. ~~For the Pamir Alay , the autumn season, and for the~~ The autumn season for Pamir Alay and the summer and autumn seasons for Central and Northern / Western Tien Shan ~~, the summer and autumn seasons showed~~ show the most significant correlations. For ~~the~~ Eastern Pamir and ~~the~~ Dzhungarsky Alatau, the different seasons ~~contributed more or less~~ contribute nearly equally to the amount of significant combinations.

Besides the importance of the meteorological variables, the morphological parameter importance is relatively high for ~~the~~ Western Pamir (approx. 50%; Fig. A4). However, no dominant morphological parameter could be identified~~and the ,~~ , and variability across the different HiMAP regions ~~as well as~~ and for the different mass balance estimates is ~~relatively~~ high (Fig. A4). The only region in which both morphological and meteorological parameters ~~showed~~ show a high frequency of significant correlations is ~~the~~ Western Pamir. In contrast, for Dzungarsky Alatau and Eastern Pamir, ~~neither category of parameters showed~~ none of these two categories of parameters show a high number of significant correlations with ~~either~~ any of the mass balance estimates.

~~Within the k-means derived "hot spot" regions of different mass balance variability, there is always~~ In contrast to the results for the regional HiMAP classification, a high number of significant correlations is always present within the k-means derived hot-spot regions of different mass balance variabilities (Fig. 8~~), different to the regional HiMAP classification~~; a-b). We found significant correlations for over 80% of meteorological variables ~~significant correlations~~ in cluster 1, slightly less in cluster 3 (60–80%), and the lowest amount, with high variability depending on the meteorological dataset used, for cluster 2 (40–70%). Including ~~snow cover~~ SC did not increase the overall number of significant combinations for any of the ~~3~~ three clusters, but ~~it~~ this is the most important (relative highest number of correlations) variable for clusters 1 and 3. For cluster 1 (mainly positive and more balanced ~~"hot spot " and low glacier~~ hot spot and low mass balance variability in $MB_{Barandunetal}$), ~~precipitation~~ P seems slightly more important than ~~air temperature, and vice-versa~~ T; for cluster 2 (average mass balance with low variability, mainly along western / north-western margins) T is dominant, and SC shows the lowest number of significant correlations compared with that of the other clusters; for cluster 3 (negative ~~"hot spot "~~ hot spot and high mass balance variability in $MB_{Barandunetal}$), ~~temperature~~ T is slightly more dominant (Fig. 8). ~~Cluster 2 (average mass balance with low variability, mainly along the Western/North-Western margins) is temperature dominated, and snow cover showed the lowest number of significant correlations among all clusters.~~

For cluster 1, no clear dominance of either season is visible (Fig. 8; c-d). In contrast, for ~~cluster~~ clusters 2 and 3~~there are~~ , some dominant seasons ~~, however,~~ are apparent although dependent on the mass balance dataset. Generally, ~~there is~~ a more even distribution in seasonal importance is present for $MB_{Hugonnetetal}$ than for $MB_{Barandunetal}$. The highest variability of dominant seasons was found for cluster 2 based on the reanalysis dataset used, with ~~particularly~~ especially strong variability in the importance of spring and winter~~importance~~. Regarding the two mass balance estimates, $MB_{Barandunetal}$ ~~showed~~ shows dominance of summer and autumn, ~~contrasting~~ while $MB_{Hugonnetetal}$ shows dominance of winter and spring~~dominance for $MB_{Hugonnetetal}$~~. The morphological variables ~~showed~~ show less significant correlations than the meteorological variables, especially for $MB_{Barandunetal}$ in ~~cluster~~ clusters 2 and 3 (Fig. A4).

4.3 Temporal correlation

The explanatory power of the meteorological variables for the glacier-wide mass balance time series per individual glacier is between 30 and 50% (Fig. A7). However, similar to the spatial analysis, regional and dataset-dependent differences are apparent.

The importance of the variables depends strongly on the dataset used, and our ~~analysis~~ analyses led to opposing results using the different products. This concerns the different reanalysis products but also the different mass balance time series. As an example, for ~~the~~ Pamir-Alay~~snow cover~~ , SC is the dominant variable for $MB_{Hugonnetetal}$ ~~, whereas temperature and precipitation seem more important~~ whereas T and P are the more important ones for $MB_{Barandunetal}$. A similar discrepancy ~~is~~ was found for the different reanalysis datasets (Fig. 9)~~. For~~ ; for example, for $MB_{Hugonnetetal}$, the central and southern parts of ~~the Western~~ western Pamir are dominated by ~~temperature~~ T using the HAR dataset, by ~~snow cover~~ SC using ERA5, and by ~~precipitation when~~ P using CHELSA. ~~Even stronger visible is this discrepancy when excluding snow cover in the analysis , only using temperature and precipitation as predictor~~ This discrepancy is even clearer when SC is excluded from the analysis and only T and P are used as predictors for the mass balance time series (Fig. A8).

Similarly, for the seasonal importance, results vary largely for the different glaciers depending on the dataset used and provide a more detailed view than that of the spatial analysis (Fig. 10). No consistency ~~could be~~ was found either for the same mass balance time series with different reanalysis products ~~,~~ or for different mass balance time series with the same reanalysis product. When including ~~snow cover~~SC, the pattern of variable importance becomes slightly more consistent in regions where ~~snow cover~~ SC replaces other variables as the most important variable (Fig. 10) without any apparent change in explained variance (Fig. A7).

5 Discussion

~~The~~ Our temporal and spatial analyses (Section 4.2 and Section 4.3) offer radically different conclusions on the climatic drivers behind glacier mass balance response, independently of the mass balance estimate used or time period considered. According to our correlation analyses between the two mass balance estimates and different reanalysis products~~show foremost that~~ , in Pamir and Tien Shan, a clear identification of ~~dominant drivers of glacier evolution is not possible in Pamir and Tien Shan with the currently available reanalysis datasets. Even slight differences in P and T, for example, between CHELSA and ERA5, where the former is a result of downscaled ERA5, lead to partly opposing results (Fig. 9 and Fig. A8). This finding is independent of what mass balance estimate is used or if the short (2000–2014) or long period (2000–2018) is considered. Even though the two utilized~~ glacier evolution dominant drivers is impossible. Regional subdivision can influence significantly the outcome of a spatial analysis (Section 4.2), and aggregation or division of the total number of glaciers into regional clusters for comparison, although often required to summarize extensive study results (e.g. Brun et al., 2019), is somehow arbitrary. Use of temporal analysis based on annual mass balance time series can improve both the subregions definition and the aggregation process; however, this analysis depends strongly on the accuracy of the mass balance estimates ~~mainly agree at the regional scale, the differences at local scale amplify the inconsistencies. Different conclusions can also be drawn depending on whether the spatial or temporal domain builds the basis for the analysis as presented in Sections 4.2 and 4.3. The temporal analysis presents a very detailed overview of where and which meteorological variables correlate with~~ at annual time scales, which are often highly uncertain, not observation based, or simply not available. In the present study, we discuss the uncertainty and danger of misinterpretations related to correlation analysis relying on individual data products.

5.1 Spatial resolution and downscaling

CHELSA is a processed and downscaled version of the ERA5 dataset. When using these two products, differences appear in the correlation analyses due to different spatial resolutions in the predictor variables; however, these differences only become striking when using the regional subdivision (Fig. 6). This might respond to a low number of data points with high mass balance variability within areas of encompassing meteorological grid cells, while the mass balance ~~time-series. On the other~~

~~hand, long-term average mass balance estimates, which are the standard output from geodetic mass balance studies, prevent such an analysis. Consecutive aggregation or dividing the total number of glaciers into adequate regional clusters are somehow arbitrary and can significantly influence the outcome as shown in Section 4.2. However, the presented results, in particular from the~~ variability between the different encompassing grid cells in the regional subdivision is rather low. The nonlinearly downscaled precipitation of CHELSA (Fig. 3) compared with the conserving values for T (Fig. A2) can explain the higher number of significant correlations of this product compared with that of ERA5. As we use two predictor variables, the original P fields of CHELSA can change the significance of T. In the temporal analysis, ~~also allow to find similarities that suggest consistent meteorological representations in some regions by identifying the same variable and seasonal importance and their associated glaciological processes.~~ the effect is even clearer, leading to partly opposing results (Fig. 9 and Fig. A8). We do not answer here how exactly any downscaling method can affect results but we show that advanced downscaling methods (CHELSA's precipitation) can severely impact driver interpretation. Different outcomes can be expected depending on the downscaling technique used, adding subjectivity to the results.

5.2 ~~Spatial Analysis~~Correlation analysis

Our results reveal ~~, largely independent of mass balance estimate and reanalysis products,~~ a high number of significant correlations between T, P, and mass balance for the entire Pamir and Tien Shan region (Fig. 6), largely independent of mass balance estimate or reanalysis product. The relative number of significant correlations remains similar when introducing SC, suggesting that the meteorological parameters from the reanalysis and ~~snow cover relate in the same way~~ SC relate similarly to the spatial variability in glacier mass balances.

When dividing ~~the~~ glaciers regionally, ~~either according to the HiMAP classification or according to the k-means temporal mass balance variability found in Barandun et al. (2021), the~~ the amount of significant correlations between T, P, ~~snow cover~~ SC, and mass balance ~~drops. It can also be seen that identified variables~~ decreases, and the identified variables are shown to depend strongly on the datasets used (Fig. 7 and 8). ~~Using the division based on the k-means clustering shows consistently more significant correlations , which might be related to the more even~~ The low number of significant correlations for certain subregions can respond to (1) data availability, (2) data quality and scale issues, and (3) process representation.

(1) Due to the lower number of glaciers ~~per division class in comparison to the HiMAP regions. The decreasing number of significant correlations for certain subregions can have multiple reasons. (1) The provided meteorological variables are not sufficient to represent~~ with mass balance time series available, especially for Eastern Pamir and Dzhungarsky Alatau, the robustness of the statistical analysis is reduced, making difficult to find a significant correlation with the meteorological variables. (2) The meteorological variables used cannot represent on their own the relevant processes responsible for the mass balance variability. For example, at high elevations, the relevance of temperature and long-wave radiation can decrease in favor of short wave radiation, which could likewise explain lower numbers of significant correlations for T in Eastern Pamir, where the highest glaciers are located (Sicart et al., 2011; Yang et al., 2011). The larger changes in meteorological forcing needed for a glacier response in areas with lower mass balance sensitivity (~~2) Especially in Eastern Pamir and Dzhungarsky Alatau, a relatively low number of modelled glaciers adds to the difficulty to find a correlation with the meteorological variables.~~

~~(3) Varying mass balance variability, sensitivity or mass balance gradients and regimes that are not well represented within one subregion can further complicate finding consistent relationships. Typically, the Tien Shan and Pamir are classified as subcontinental (western and northern part of the Tien Shan, and the Pamir-Alay) to continental glacier regimes(central part of the Tien Shan, and central and eastern part of the Pamir) (Wang et al., 2019). Under ongoing climate change, glacier response to meteorological conditions are undergoing important changes due to a changing mass balance sensitivity and variability (Azisov et al., accepted; Dyurgerov and Dwyer, 2000), partly related to a shift from continental to more sub-continental conditions. Small ~~regions with more continental climate regimes) are easier to capture in reanalysis than the small changes that can make glaciers react in areas with higher sensitivity (subcontinental regions). For example, small scale processes (e.g. changes in pore space) close to the equilibrium line altitude can change accumulation patterns to which such glaciers react sensitively (Kronenberg et al., 2022). This ~~adds to the heterogeneous mass balance response and renders finding direct correlations with climatic drivers difficult~~can explain the lower number of significant correlations found for more subcontinental settings. Such scale-related issues can also explain some of the contrasting patterns in the correlation analysis resulting from the different reanalysis products due to their different spatial resolution. (3) Changing mass balance variability, sensitivity, response times, or mass balance gradients and regimes can further complicate finding consistent relationships under climate change at a subregional scale. Based on station data, ~~Wang et al. (2019) ~~Wang et al. (2019) showed that subcontinental glaciers react mostly to air temperature variability, whereas ~~the ~~continental glaciers, generally located at higher elevations, are sensitive to both air temperature and precipitation. ~~Faster changing accumulation and ablation processes or a rotation and steepening of the mass balance gradients (increased ablation and accumulation) will change the mass balance ~~Under ongoing climate change, glacier response to meteorological conditions undergo important changes due to changing mass balance sensitivity and variability ~~on the short to long term (Kronenberg et al., 2022; Dyurgerov and Dwyer, 2000; Kuhn, 1980, 1984). This will, hence, shift ~~(Azisov et al., accepted; Dyurgerov and Dwyer, 2000), partly related to a shift from continental to more subcontinental conditions, thus shifting the dependence on specific meteorological variables. ~~In addition to these changes, already slight uncertainties in meteorological estimates might complicate finding a relationship with sensitive glacier responses. This is especially important in sub-continental regions, where sensitivity is highest and small variations at various spatial scales over a glacier are invisible in the coarsely resolved reanalysis products. In contrast, at high altitudes and more continental climate regimes, larger changes are needed for a glacier response. These more important changes are easier to capture in reanalysis datasets and could explain the higher number of significant correlations found. ~~Changes in mass balance gradient such as rotation (simultaneous increase of ablation with decreasing elevation and increase of accumulation with increasing elevation or vice-versa) or parallel shifts of the mass balance gradients (simultaneous increased ablation and decreased accumulation or vice-versa) have been observed for the region (Kronenberg et al., 2022; Dyurgerov and Dwyer, 2000; Azisov et al., accepted; Kuhn, 1980,
. Such shifts, in return, influence the mass balance sensitivity (Wang et al., 2017) and variability (Barandun et al., 2021).

~~The clusters roughly coincide with a gradient from a sub-continental (cluster 2) to a more continental climate regime (cluster 1) and higher glacier elevations from the north-western to the central and south-eastern parts of the study region . Cluster 2 with medium temporal mass balance variability and average mass balances describes most of the outer orogene margins~~

~~(~~Our analysis reflects all of the above issues. Glaciers in cluster 2 (subcontinental climate regime) are more heterogeneously distributed spatially (Fig. 5)~~and glaciers within this cluster are spatially more heterogeneously distributed. This is the cluster with the lowest amount~~ , and this cluster shows the lowest number of significant correlations. In combination with the high variability within the datasets, our results suggest that glacier mass balance variability does not result from the investigated meteorological drivers ~~. In other words, this finding suggests~~ for this cluster, suggesting that a similar mass balance variability is a response to different drivers within this cluster. ~~In contrast, anomalous high (cluster 3) and low (cluster 1)~~ Conversely, glaciers in clusters 1 (continental climate regime) and 3 (hot spots of mass balance variability~~are better correlated. Cluster 1 and cluster 3 are spatially~~) are much more aggregated spatially, and the investigated meteorological and morphological parameters ~~represent better~~ better represent the subregional mass balance variability.

~~What is responsible for the high variability within cluster 2 remains speculation in this data scarce region at the moment. It could be imprecise precipitation estimates~~ At this point especially precipitation estimates are imprecise in general (Palazzi et al., 2013) , and at the glacier scale ~~, resulting e.g. from the coarse resolution of reanalysis products,~~ as a result of e.g. coarse resolution or insufficiently represented localized precipitation events such as orographic precipitation effects (Roe et al., 2003)~~, or different microclimatic settings.~~ . What is responsible for the high variability within the data-scarce region of cluster 2 remains unclear. An interesting finding is the lower number of correlations when including ~~snow cover~~ SC for both mass balance estimates. This is especially pronounced for cluster 2 (Fig. 8), where a low fraction of variable combinations identifies ~~snow cover~~ SC in combination with MB$_{Barandunetal}$. This ~~could~~ can indicate that a crucial meteorological component is missing in our analysis and that ~~the~~ T and P estimates are a surrogate for a process not related to snow dynamics. For these cases, glacier response might be more related to radiation, physical snow properties ~~,~~ (e.g. albedo, grain size), or the amount of snow, which in total are better represented by simply using T and P ~~, rather than~~ than with the qualitative information of SC. In contrast, a similar number of correlations would indicate that T and P explain processes ~~similar~~ similarly to SC.

~~We have not identified a strong seasonal importance of the meteorological variables in our spatial analysis (Fig. 7 and Fig. 8).~~ Our results indicate a tendency of stronger summer and autumn influence along the northwestern margin and~~to some extend also~~ , to some extent, for the negative ~~"hot spot "~~hot spot that could be linked to either summer snowfall events or changing melt rates due to changes in air temperature. This contrasts the autumn to spring importance for the positive mass balance anomalies in ~~the~~ Western Pamir and Central Tien Shan~~. We suggest that the latter might~~ , which can relate to changing snow cover dynamics and / or changes in ~~solid-liquid~~ solid–liquid precipitation ratios, supported by the high ~~amount~~ number of significant correlations including ~~precipitation. In contrast, the summer and autumn importance could be linked to either summer snowfall events or changing melt rates due to changes in air temperature.~~ P. However, we have not identified a strong seasonal importance of the meteorological variables in our spatial analysis (Fig. 7 and Fig. 8).

5.3 ~~Temporal Analysis~~What are the dominant climatic drivers?

~~From our results , a very~~ Our results show a heterogeneous picture of dominant variables and seasons from 2000 to 2014(2018) ~~becomes apparent, that is~~ strongly dependent on the choice of datasets. ~~Looking at~~ An interpretation based on an individual dataset ~~might allow interpreting patterns backed-up by literature. At the same time the interpretations are contradicted by~~ can contradict a different interpretation based on another set of data, ~~which is similarly~~ both of them well supported by literature. ~~In the following,~~ Here we show two ~~,~~ somewhat contradicting but plausible interpretations ~~about~~ of meteorological drivers for glacier mass balance changes based on the ~~here presented temporal analysis. With this we aim~~ results of our temporal and spatial analysis to highlight the persistent difficulty to shed light onto the ~~glacier-climate~~ glacier–climate interaction in a heterogeneous and ~~data sparse~~ data-sparse region such as Central Asia.

~~Summary of dominant drivers found for (a) analysis I (using MB$_{Barandunetal}$ and HAR dateset) and (b) analysis 2 (using MB$_{Hugonnetetal}$ and ERA5 dateset). P denotes precipitation, T air temperature and SC snow cover. A negative sign indicates a decrease and a positive sign an increase.~~

5.3.1 Analysis I: HAR dataset and MB$_{Barandunetal}$

~~All mass balances in this section are~~ Mass balance data are based on MB$_{Barandunetal}$, and all drivers refer to the identified HAR meteorological variables ~~(limited to the 2000 to 2014 period)~~ in our results ~~. From the combined analysis of these data and previous studies, significant trends towards warmer annual air temperatures for large parts of Central Asia from 1950~~ (Fig. 11a).

Air temperature increased by about 0.1 to ~~2016 (Haag et al., 2019) seem to be reflected by the overall negative mass balance throughout the Tien Shan and Pamir~~0.2° C per decade in Tien Shan from 1960 to 2007 (Aizen et al., 1996; Kutuzov and Shahgedanova, 200 . Air temperature is the dominant driver for ~~most glaciers in the~~ the mass balance of most glaciers located in Tien Shan, most dominantly in spring and autumn (Fig. 9). ~~This is possibly related to a strong increase in temperatures by about 0.1 to 0.2° C per decade from 1960 to 2007 (Aizen et al., 1996; Kutuzov and Shahgedanova, 2009; Kriegel et al., 2013).~~

~~A pronounced winter warming and an increase in winter and autumn precipitation in the northern and eastern parts of the Tien Shan have been reported (Haag et al., 2019). Snow cover and air temperature~~ In Eastern Tien Shan and Dzungarsky Alatau, air temperature and snow cover in spring and summer are the dominant drivers identified for the high mass loss ~~in the Eastern Tien Shan and Dzungarsky Alatau~~ (Fig. 9~~, 10~~c, 10c). This might relate to a pronounced snow cover decrease ~~reported for the~~ in Eastern Tien Shan ~~Notarnicola (2020),~~ (Notarnicola, 2020) as a result of increased air temperatures causing faster snow depletion in late spring and early summer. In line with that, ~~Sakai and Fujita (2017)~~ Sakai and Fujita (2017) concluded that climatic settings represented by the three factors (i) summer temperature, (ii) temperature range, and (iii) summer precipitation ratio, are the most important factors for mass balance variability.

~~Precipitation trends for Central Asia are less significant and play a minor role for the mass balance evolution in Tien Shan. Haag et al. (2019)~~ Although Haag et al. (2019) reported a slight positive trend in summer, winter~~and autumn~~ , and autumn precipitation for Tien Shan from precipitation anomaly ~~time-series~~ time series for the period 1950 to 2016 for entire Central Asia~~. However, in our analysis most of these changes were not identified~~ , our analysis did not identify these changes as individually dominant drivers for ~~the~~ mass balances at the regional scale (Fig. 6a,b). More locally, increasing spring and summer precipitation in combination with an autumn and summer cooling in ~~the~~ Central Tien Shan (e.g. Li et al., 2022) align with the cluster of ~~slightly positive /~~ close-to-zero and slightly positive mass balances.

The positive mass balance anomaly in Barandun et al. (2021) can be explained by a positive snow cover change matching its location (Notarnicola, 2020). A localized temperature decrease ~~over parts of the~~ in Central Tien Shan in summer increases the frequency of solid precipitation events ~~at the location of the positive "hot spot". Such summer snowfalls can contribute to the mass gain and more importantly~~ that lower melt rates due to a positive albedo effect of fresh snow ~~(e.g., Kronenberg et al., 2016)~~ (e.g., Kronenberg et al., 2016). This is reflected by the importance of a changing snow cover and the seasonal importance ~~ranging~~ from spring to autumn ~~for the positive "hot spots" in the Central Tien Shan~~ (Fig. 10c, 9c), ~~9). This is~~ in line with the heterogeneous and sharply contrasting snow cover changes reported by ~~Notarnicola (2020), showing a positive snow cover change matching the location of the positive mass balance anomaly in Barandun et al. (2021). The neighbouring~~ Notarnicola (2020). The neighboring negative mass balance anomaly in ~~the~~ Central Tien Shan ~~shows predominantly a spring and air temperature importance, where~~ reflects the air temperature and spring importance, with a sharp decrease in snow cover duration ~~was reported (Notarnicola, 2020). Hence elevated spring temperature enhances the snow depletion in the region, favoring an early start of the ablation period.~~ (Notarnicola, 2020).

~~Seasonal temperature trends are heterogeneous for the Pamir . Knoche et al. (2017) indicated a~~ Mass balances of the glaciers located in the eastern part of Western Pamir can respond to the north-to-south gradient (summer cooling for ~~the Northern Pamir but detected a~~ northern Pamir and warming trend for ~~the Southern Pamir. This North to South gradient is reflected in the mass balance of the glaciers located in the eastern part of the Western Pamir, driven mainly~~ southern Pamir) reported by Knoche et al. (2017). These mass balances are therefore mainly driven by air temperatures (Fig. 9c).

Despite ~~non-significant~~ the nonsignificant precipitation trends for the entire Pamir (Pohl et al., 2017), ~~the Pamir-Alay received an increase in winter precipitation~~ winter precipitation increased since 1950 in Pamir-Alay (Haag et al., 2019; Kronenberg et al., 2021). Winter precipitation changes, however, play a subordinate role for the glacier mass balance of ~~the~~ Pamir-Alay, whereas spring and summer changes dominate (Fig. 9~~, 10~~c, 10c). Fig. 9~~and 10 also~~ c and 10c suggest that only glaciers with less negative mass balances show a relation with winter precipitation~~and that most glaciers in the region relate to temperature, and more to the eastern part of the Pamir-Alay, also to snow cover changes.~~, whereas the driver for the mass balance of most glaciers in the region is temperature (also snow cover changes in the eastern part of Pamir-Alay).

~~The negative mass balance "hot spot" in the Western Pamir is dominated by winter and spring precipitation and snow cover . At this location, where year-to-year mass balance variability is high, temperature seems to play a minor role. This, however, changes for the positive "hot spot" in the Western Pamir, with low year-to-year variability, were the mass balance is clearly controlled by the autumn temperature and snow covers (Fig. 9, 10). The positive and negative mass balance clusters in Western Pamir agree well with decreasing and increasing snow cover fractions reported by Notarnicola (2020), respectively.~~

5.3.2 Analysis II: ERA5 dataset and MB$_{Hugonnetetal}$

~~The interpretation presented in section 5.3.1 is strongly contrasted by the following analysis (II), where mass~~ Mass balance data are based on MB$_{Hugonnetetal}$, and all drivers refer to the identified ERA5 meteorological variables in our results ~~.~~ (Fig. 11b).

Air temperature increased by about 0.1 to 0.2° C per decade in ~~the Tien Shan during~~ Tien Shan from 1960 to 2007 (Aizen et al., 1996; Kutuzov and Shahgedanova, 2009; Kriegel et al., 2013). ~~Precipitation trends for Central Asia are less significant~~

~~than temperature trends.~~ However, precipitation and snow cover are more important drivers than temperature for the mass balance of glaciers located in the entire Tien Shan (Fig. 7, 9). Whilst in the southwestern part, spring is the most important season, winter is more important in the northeastern part of Tien Shan, where glacier mass loss is especially pronounced (Fig. 10e). In the Eastern Tien Shan, ~~the main driver~~ decreasing precipitation and snow cover are the main drivers identified for the negative mass ~~balance seems to be precipitation and snow cover~~ balances (Fig. 9~~). In contrast, for the~~ e). For Dzhungarsky Alatau, ~~the~~ however, mass loss seems mainly driven by temperature and snow cover (Fig. 9e).

~~At the western margin of the Central Tien Shan, less negative mass balances are in line with reported positive precipitation changes (Aizen et al., 1996; Kutuzov and Shahgedanova, 2009; Kriegel et al., 2013). Haag et al. (2019) reported~~ Haag et al. (2019) reported a slightly positive trend in summer, winter, and autumn precipitation for ~~the~~ Tien Shan that ~~might influence~~ influences the close-to-zero and slightly positive mass balances at the southern margin of ~~the~~ Tien Shan. This ~~is in agreement~~ agrees with the increase of snow cover fraction reported in ~~Notarnicola (2020).~~ Notarnicola (2020).

At the western margin of Central Tien Shan, less negative mass balances are in line with reported positive precipitation changes (Aizen et al., 1996; Kutuzov and Shahgedanova, 2009; Kriegel et al., 2013). Therefore, the main ~~driver seems~~ drivers seem to be precipitation and snow cover in spring and summer (Fig. 9~~, 10~~e, 10e).

~~For the Pamir-Alay, summer and autumn are the dominant seasons for the positive mass balances found at the~~ Positive mass balances of the glaciers located in the western margin of ~~the subregion. Notarnicola (2020)~~ Pamir-Alay can be related to increased snow cover (Notarnicola (2020) reported a longer snow cover duration from 2000 to ~~2018. Thus, the observed changes seem to be related to increased snow cover~~ 2018) and decreasing temperatures during the transition from winter to summer~~, allowing~~ ; this allows snow to persist longer ~~, and~~ and an earlier snowfall in autumn ~~shortens~~ to shorten the ablation season, acting favorable on the glacier mass balances.

~~Haag et al. (2019) showed thatdespite a non-significant~~ Haag et al. (2019) showed that, despite the nonsignificant trend of annual precipitation amounts, summer precipitation had significantly increased by around 5 mm per decade for ~~the~~ Western and Eastern Pamir. ~~In combination with an important cooling in summer reported for the nearby Karakorum during the past decadesFowler and Archer (2006); Mölg et al. (2014); Forsythe et al. (2017), summer~~ Summer and early autumn precipitation ~~becomes~~ represents the most important driver for the positive mass balances in ~~the Eastern Pamir. The summer snowfall acts~~ Eastern Pamir, in combination with an important summer cooling reported for the nearby Karakorum during the past decades (Fowler and Archer, 2006; Mölg et al., 2014; Forsythe et al., 2017). Summer snowfall, on the one hand, acts directly as mass contributor and, on the other~~hand~~ , lowers melt rates due to a positive albedo effect ~~(e.g. Kronenberg et al., 2016).~~ (e.g., Kronenberg et al., 2016). de Kok et al. (2020) suggests that low temperature sensitivities in combination with an increase in snowfall, largely due to increases in evapotranspiration from irrigated agriculture, explain the positive mass balances in this region.

5.4 Implications from the spatial and temporal ~~analysis~~analyses

The resulting importance of the seasons and meteorological variables from the temporal and spatial ~~analysis are~~ analyses is strongly dependent on the dataset ~~, and suggest sometimes~~ used, sometimes suggesting even a contradicting relationship with glacier response. ~~In addition to that, clear non-climatic drivers can not~~ Clear nonclimatic drivers cannot be identified. ~~The interpretation and analysis is made more difficult because derived~~ Derived interpretations (from Analysis I and II) align with other reported findings in ~~the~~ these regions, as shown in Section 5~~. Unfortunately, available time series are also rather short to provide more~~ , rendering the interpretation and analysis even more difficult. Available time series fall short of robust evidence in the correlation analysis ~~. This is due to a~~ due to high meteorological and mass balance variability compared ~~to~~ with rather slight trends and tendencies in these time series. ~~Independent of the different results, using different meteorological ,~~ Using different meteorological and mass balance estimates, our study highlights in all cases a highly complex glacier response to climate variability and change. The current lack of sufficiently detailed and qualitatively satisfying data prevents elucidating the complex relationship between glacier mass balance and ~~especially~~ climatic drivers in ~~the~~ Tien Shan and Pamir.

~~At the current stage of research, we are not able to rate the different, partly contrasting products. Due to the lack of~~ Lack of regional-wide systematic cryospheric and atmospheric monitoring ~~, validation of these~~ limits the validation of the available datasets for scientific applications~~is strongly limited. This results~~ , resulting in an elevated uncertainty for mass balance modelling and interpretation on the underlying processes of ~~the~~ glacier response to climate change. We cannot rate the different products. Cryological, hydrological, and meteorological monitoring at high elevation throughout the different subregions of Tien Shan and Pamir need to improve to better understand glacier response to climate change. ~~Highlighted with the two scenarios~~ In several subregions, no glaciers are systematically monitored (Barandun et al., 2020), *in situ* snow monitoring is not established, and hydrological monitoring is very limited (Unger-Shayesteh et al., 2013; Hoelzle et al., 2019). Meteorological measurements are underrepresented at high elevation and, for certain subregions, completely lacking (Unger-Shayesteh et al., 2013; Sorg et . Most existing data are inaccessible. The needed long-term systematic monitoring of the different components of the water cycle often lacks financial support, know-how, and man(woman)power (Hoelzle et al., 2019; Barandun et al., 2020). When using only one specific dataset, differences in reanalysis products and elevated uncertainties tied to the available annual mass balance time series for Tien Shan and Pamir underpin the ambiguity in the interpretation of the results of a correlation analysis. As highlighted by the two scenarios presented in Section 5, any derived understanding of ~~the glacier-climate~~ glacier–climate interactions depends strongly on the dataset used. ~~The limitations of these datasets cascade to an increase of uncertainties when~~ When a thorough quality assessment of the different reanalysis products for further application cannot be assured~~. This concerns in particular~~ , the limitations of these datasets cascade into an increase of uncertainties. This especially affects the modelling of future glacier response, hydrological modelling, and the equifinality problem related to too many unknowns in the ~~cryo-hydrological cycle (e.g. Beven, 2006; Farinotti et al., 2015) ,~~ cryohydrological cycle (e.g. Beven, 2006; Farinotti et al., 2015) or reconstruction of glacier mass change ~~. Many studies are typically~~ without a good calibration dataset. Traditionally, many studies have been based on a single reanalysis dataset, either used for bias correction or directly as model input~~directly. Direct~~ , and direct calibration data are generally limited to a few individual ~~location, which is~~ locations, insufficient for regional applications. Remote sensing can partly bridge the gap in observational data, and progress is made to increase temporal resolution of geodetic mass balance estimates (Beraud et al., 2022). Furthermore, integration of different and sometimes unconventional datasets with information on the atmospheric conditions, the Earth surface energy balance, glacier response, and other water storage changes (Farinotti et al., 2015; Pohl et al., 2017; Naegeli et al., 2022; Key et al., 1997) is valuable to asses and possibly quantify uncertainties related to the presented datasets and, eventually, to rate their quality. Modern downscaling techniques such as those provided in Fiddes and Gruber (2014, 2012) facilitate the inclusion of small-scale topographic effects. Standardizing sophisticated downscaling methods can improve the spatial representations of the reanalysis datasets. Despite potential improvements (remote sensing (Beraud et al., 2022), integration of unconventional datasets (Farinotti et al., 2015; Pohl et al., 2017; Naegeli et al., 2022; K , and modern downscaling technics (Fiddes and Gruber, 2014, 2012)), we recommend not to rely on a single product for either correlation analysis or cryohydrological modelling.

6 Conclusions

The extreme scarcity of ~~in situ~~ *in situ* observations for both meteorological variables and glacier mass balance in Central Asia leaves much space for different interpretations on how glaciers may evolve in this region within a changing-climate scenario. As a result, water availability assessment for the growing population is uncertain. Our study shows ~~in particular~~ that even supposedly similar datasets such as ERA5 and its derivative CHELSA lead to different and partly contradicting assumptions on drivers for mass balance variability. Ease of use and great availability of datasets such as ERA5 might lead to a one-sided use of certain datasets in disfavor of those less comprehensive but more thoroughly validated ones such as HAR v1.4, whose shortcomings are better known of. Our study points to a trend in which apparent but false consistencies across studies using a single dataset ~~might~~ can largely relate to the chosen dataset rather than to the processes or involved environmental variables. We ~~accordingly showcase how determined~~ showcase how important variables change with the use of the two different mass balance datasets even though said datasets agree at ~~regional scale:~~ the regional scale; differences at individual glacier scale are stark. ~~Obviously, regionally~~ Regionally aggregated mass balance estimates are useful for summarizing and reporting results, e.g., following the HiMAP classification or our glacier mass balance ($\mathrm{MB}_{Barandunetal}$) standard deviation-based k-means clusters. However, ~~the downside is that~~ derived interpretations about important drivers carry a large subjective and arbitrary aspect, as these interpretations ~~will~~ can change significantly based on the chosen clustering. This effect is largely remediated in the temporal analysis~~where each glacier–meteorological~~ , where each glacier–meteorological relationship is preserved. Such analysis, however, requires mass balance time series that geodetic methods cannot provide by default, and with the ~~trade-off~~ trade off of increasing uncertainty at short time scales.

~~In summary, we find that the aspects~~The aspects, from highest to lowest impact, on deriving conclusive results are:

- Differences in meteorological data
- Differences in mass balance data
- Regional classifications and aggregations

~~Finally, for~~ In the present work, we ~~were completely unable to arrive to~~ cannot reach a conclusion on the driving meteorological and morphological variables ~~for~~ of mass balance variability in Tien Shan and Pamir. In this data-scarce region, where meteorological or mass balance datasets cannot be rigorously validated with ground truth data, ~~we believe~~ the only honest option from a scientific point of view is to “suggest” rather than “state” the existence of found relationships and inferred dependencies.

Code and data availability. The meteorological data for HAR (Maussion et al., 2011) can be obtained from the Technical University of Berlin via https://data.klima.tu-berlin.de/HAR/V1/[Last access:2022-06-09], CHELSA data (Karger et al., 2021) can be obtained via https://doi.org/10.16904/envidat.228.v2.1[last access:2022-06-09], and ERA5 data (Hersbach et al., 2020) via the Copernicus Climate Data Store (Hersbach et al.)[Last access:2022-06-09].

The mass balance data MB$_{Barandunetal}$ is published in Barandun et al. (2021), and annual mass balance time series are provided via zenodo open-access repository https://doi.org/10.5281/zenodo.4782116[Last access:2022-06-09]. The mass balance data MB$_{Hugonnetetal}$ is published in Hugonnet et al. (2021), and annual mass balance are publicly available at https://doi.org/10.6096/13[Last access:2022-06-09].

Debris cover information (Scherler et al., 2018) was obtained via http://doi.org/10.5880/GFZ.3.3.2018.005[Last access: 2022-06-09]. Surge-type glaciers inventory from Guillet et al. (2022) is available at https://doi.org/10.5281/zenodo.5524861 [Last access:2022-06-09]. Glacier outlines and glacier morphological characteristics have been taken from the Randolph glacier inventory accessible here https://www.glims.org/RGI/[Last access:2022-06-09].

The code to reproduce the results can be found on github (https://github.com/pohleric/barandun_pohl_tsl-correl). The required main input files containing the morphological and meteorological data are deposited on a zenodo repository (https://doi.org/10.5281/zenodo.6631963).

Author contributions. Both authors have contributed equally to the manuscript.

Competing interests. We declare no competing interest.

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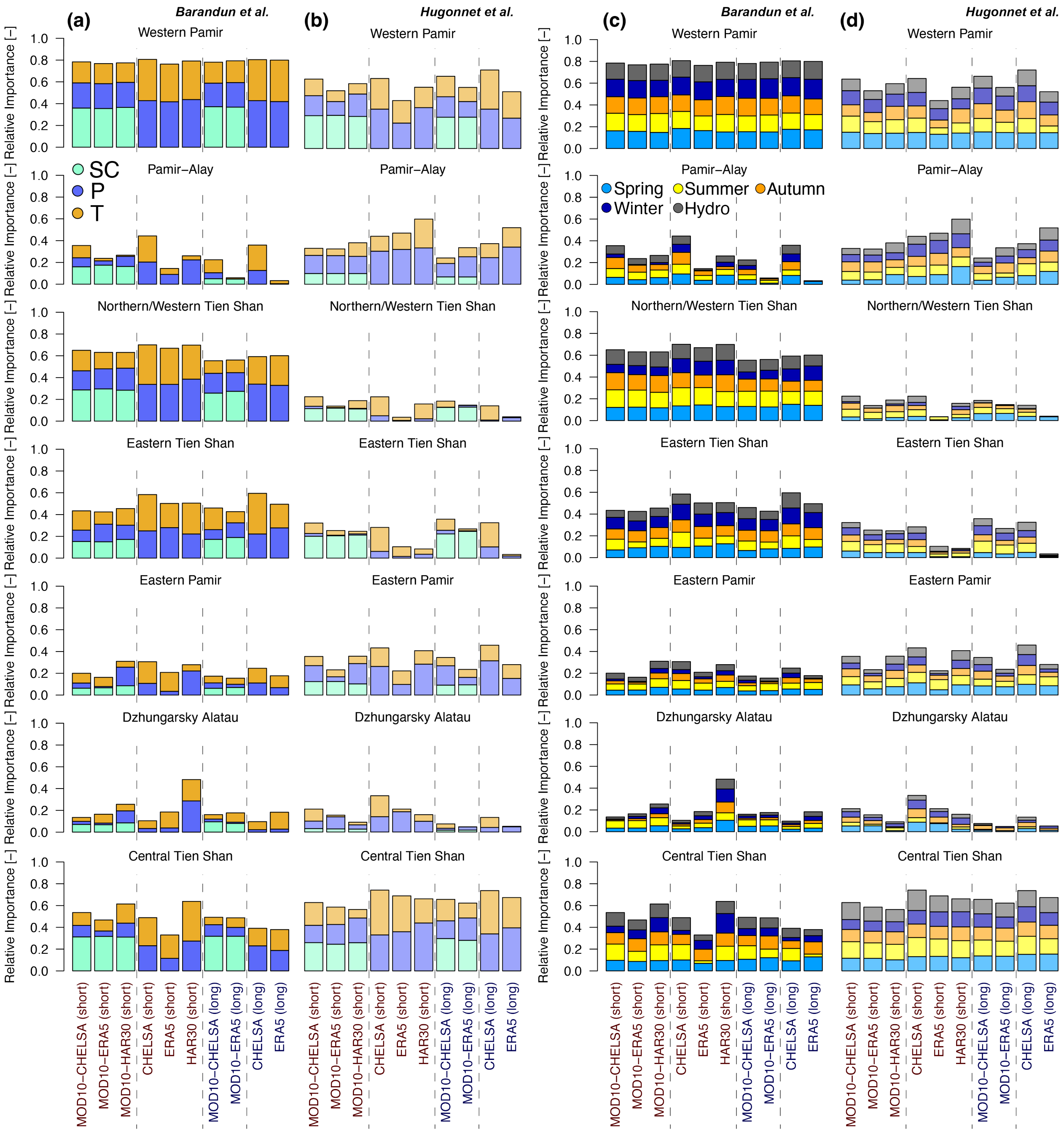

Figure 7. Importance of ~~meteorological variables~~ (~~left~~a-b) meteorological variables and ~~seasons~~ (~~right~~c-d) ~~,~~ seasons as the number of significant correlations ~~,~~identified using mass balance estimates from ~~Barandun et al. (2021)~~ Barandun et al. (2021) (solid color) and from ~~Hugonnet et al. (2021)~~ Hugonnet et al. (2021) (~~semi-transparent~~ semitransparent color) for the HiMAP regions. Labels "short" and "long" refer to the periods 2000–2014 and 2000–2018, respectively.

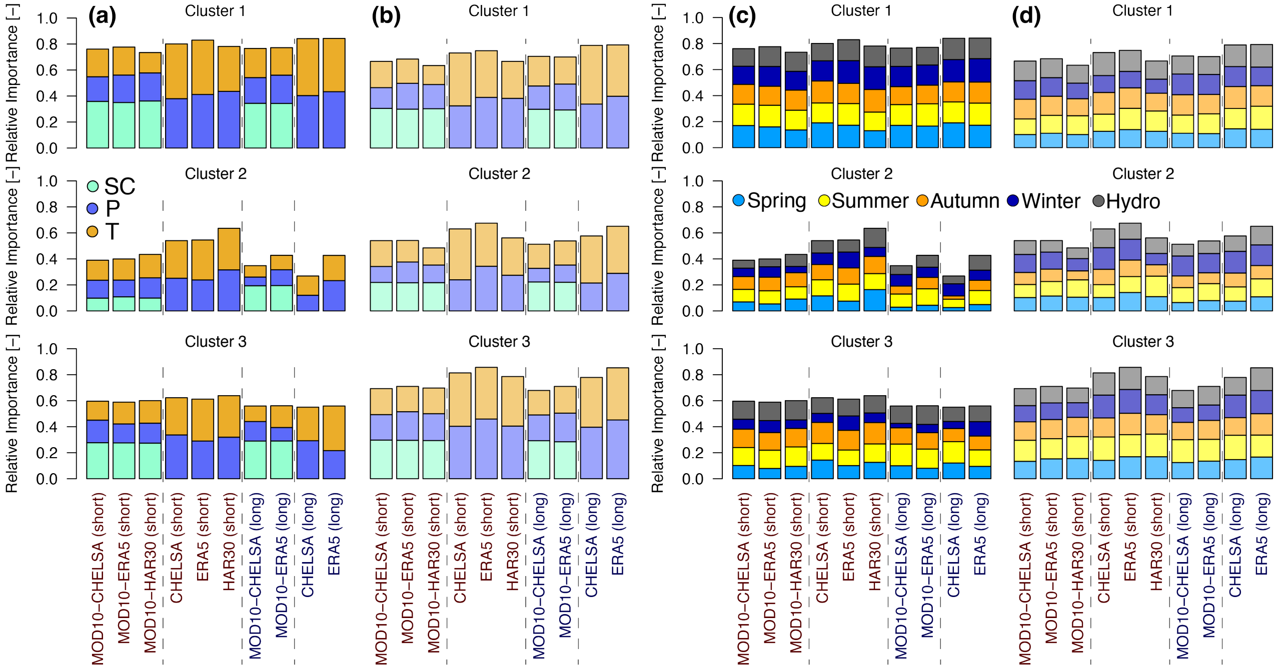

Figure 8. ~~As~~ Same information showed in Fig. 7 but with glaciers aggregated according to similar glacier mass balance standard deviations (k-means clusters) found in Barandun et al. (2021).

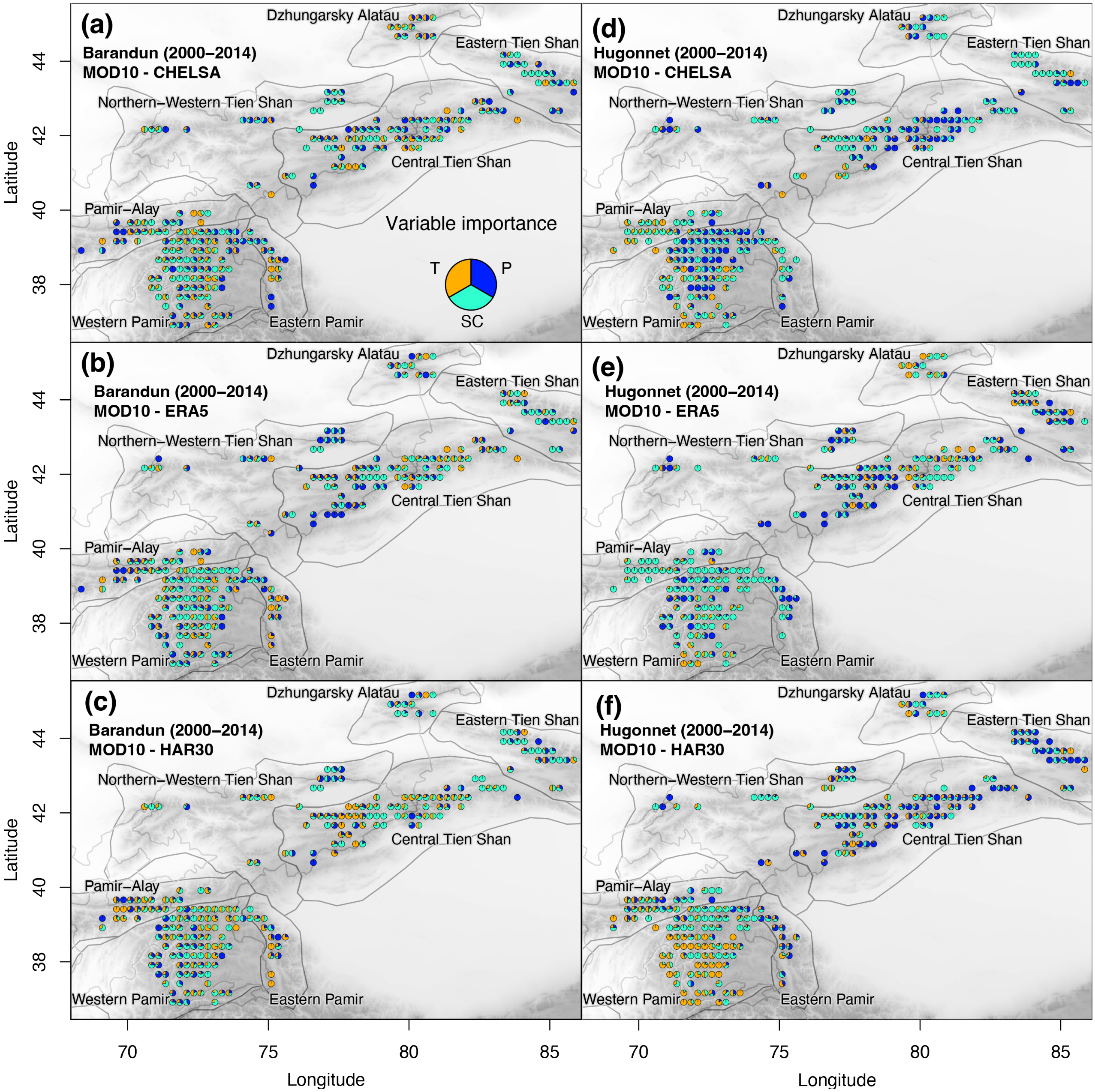

Figure 9. Importance of meteorological variables for the temporal analysis between annual mass balance estimates from ~~Barandun et al. (2021)~~(~~top~~a-c) Barandun et al. (2021) and ~~Hugonnet et al. (2021)~~(~~bottom~~d-f) Hugonnet et al. (2021), and two meteorological variables from the different reanalysis datasets, with and without ~~snow cover~~ SC as indicated in the figure legends.

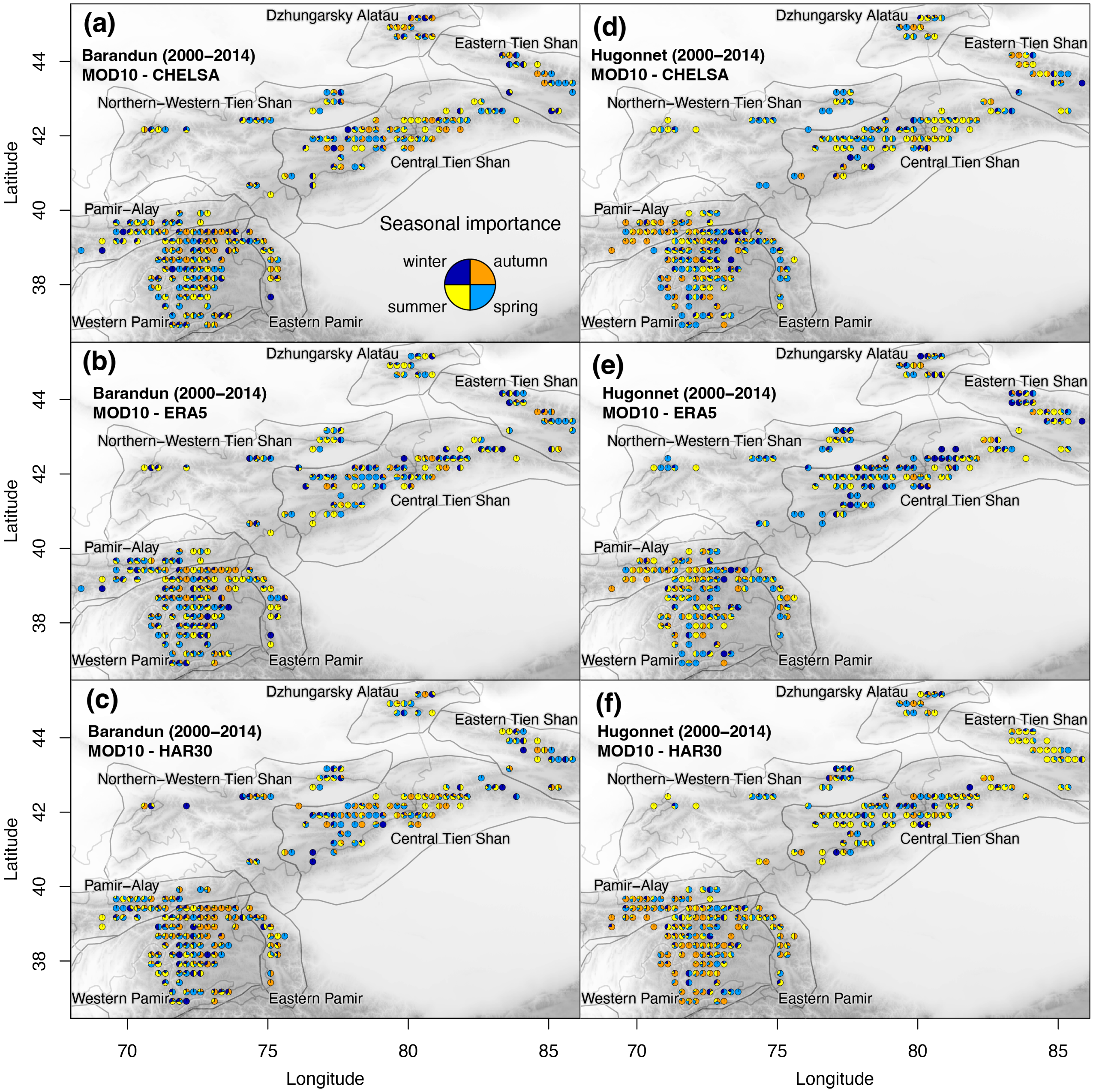

Figure 10. Seasonal importance from the temporal analysis between annual mass balance estimates from ~~Barandun et al. (2021)~~(~~top~~a-c) Barandun et al. (2021) and ~~Hugonnet et al. (2021)~~(~~bottom~~d-f) Hugonnet et al. (2021) and two meteorological variables from the different reanalysis datasets~~and snow cover~~; SC as indicated in the figure legends.

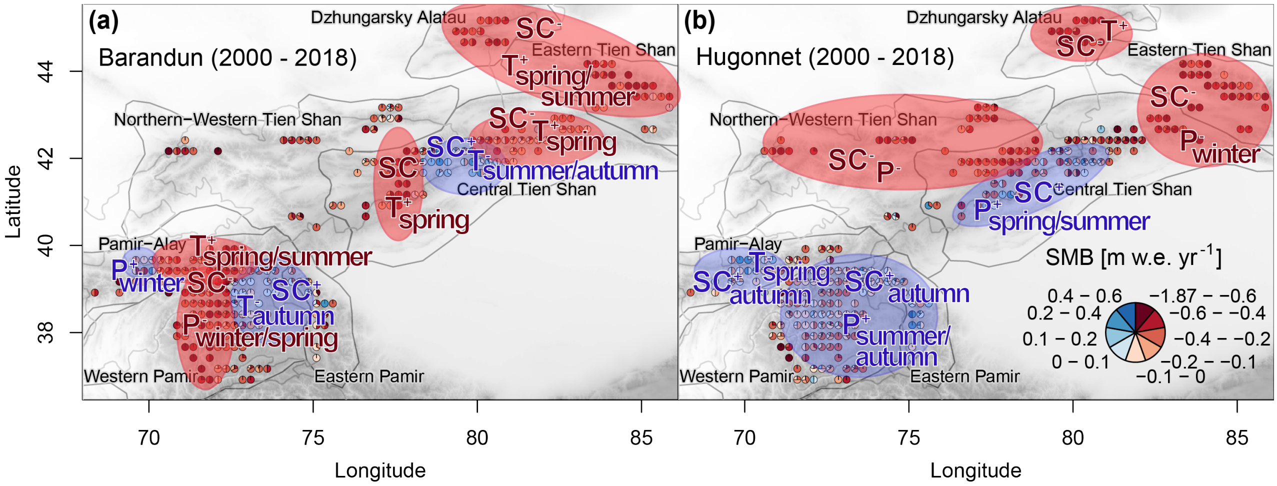

Figure 11. Summary of dominant drivers found for (a) Analysis I and (b) Analysis II. P denotes precipitation, T air temperature, and SC snow cover. A negative sign indicates a decrease, and a positive sign an increase. Effects associated with more positive mass balances, such as increase in precipitation and snow cover or decrease in temperature are highlighted in blue and vice versa in red.

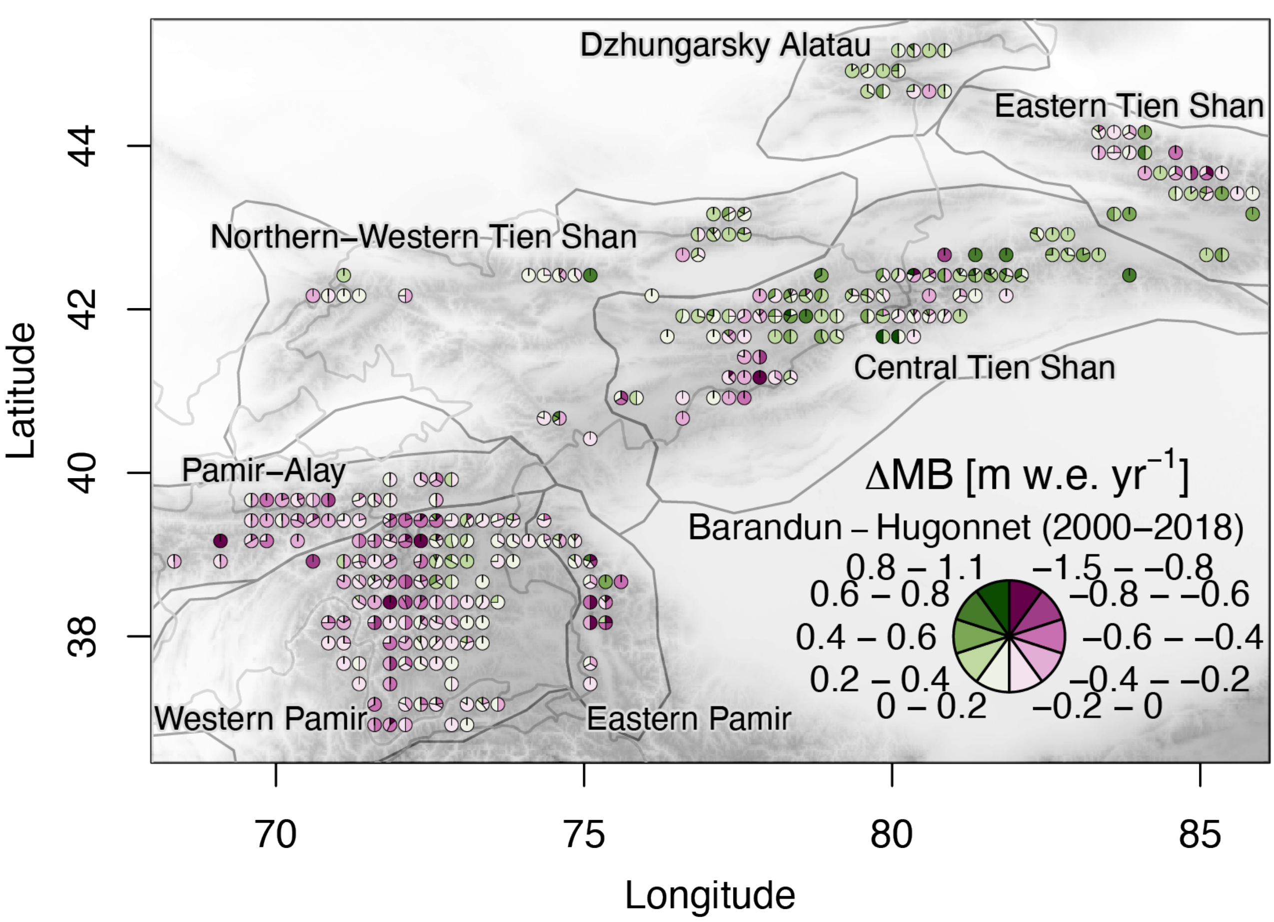

Figure A1. Difference in mean annual glacier mass balance between Barandun et al. (2021) and Hugonnet et al. (2021) for the period 2000–20018. Estimates from Hugonnet et al. (2021) only include the glaciers for which the transient snowline constrained modelling of Barandun et al. (2021) provides estimates. The pie charts aggregate values per glacier into classes and the relative class frequencies. Pies are not scaled to glacier area.

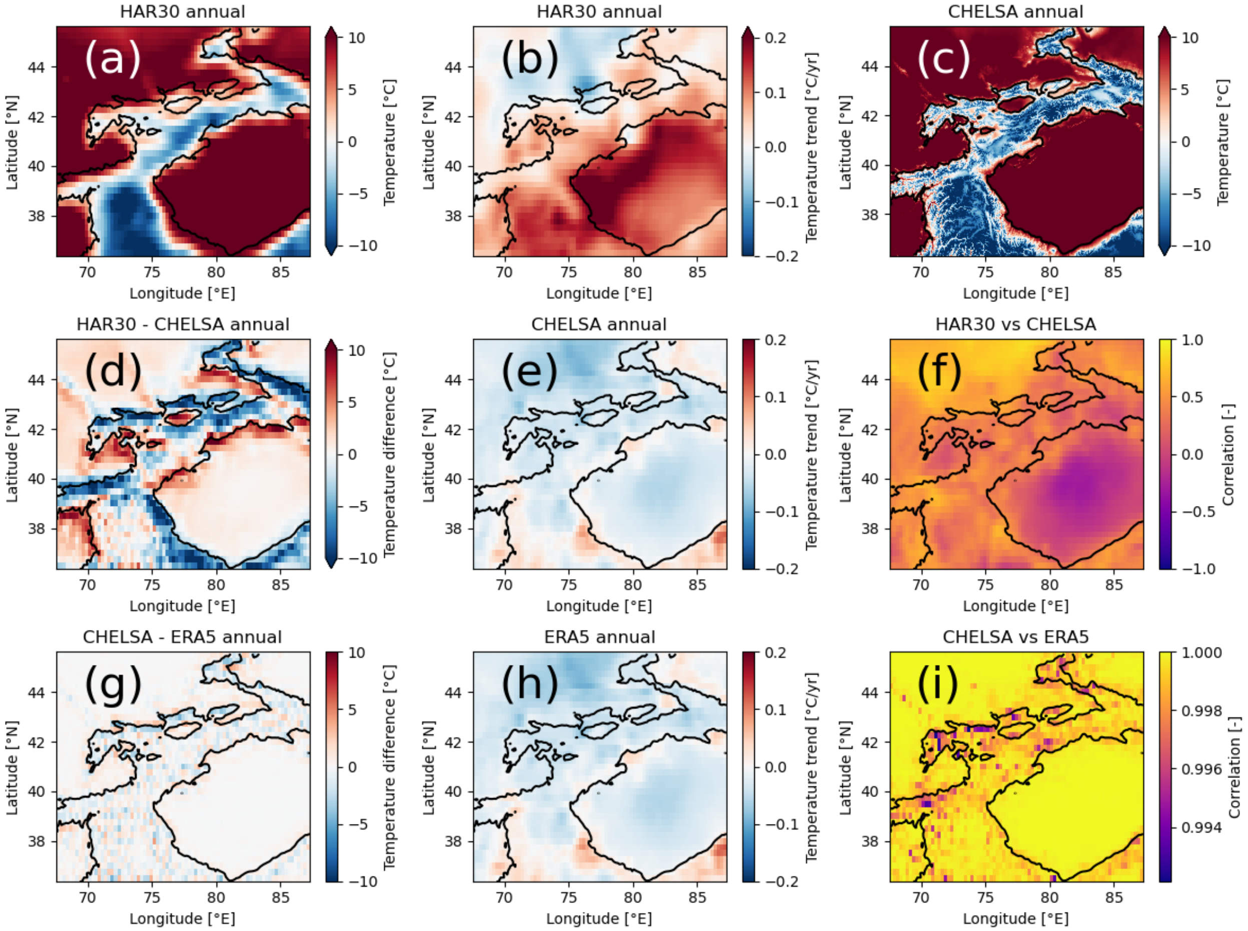

Figure A2. Mean annual temperature for (a) HAR30 and (c) CHELSA. Trends for (b) HAR30, (e) CHELSA, and (h) ERA5. Differences between the datasets (d) HAR30 and CHELSA and (g) CHELSA and ERA5 and correlation between (f) HAR30 and CHELSA and (i) CHELSA and ERA5. CHELSA and ERA5 are spatially resampled to the resolution of HAR30 for the differences and correlation. Note the different scale for the correlation in (i). Black outlines correspond to 2000 m a.s.l. altitude.

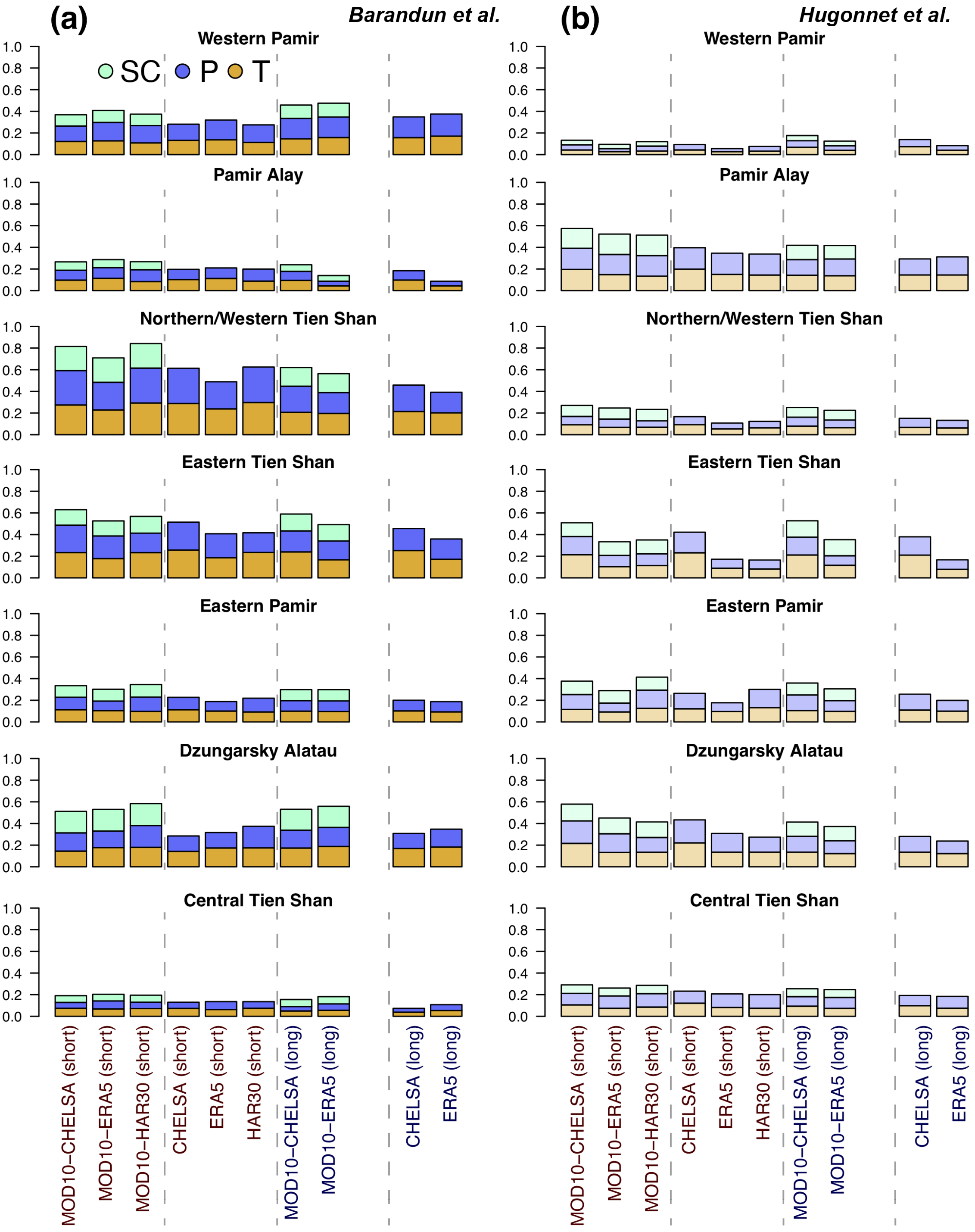

Figure A3. Coefficient of determination (R^2) for variables in the spatial analysis. Shown R^2 is the average for all variable combinations in which the displayed meteorological variable (SC, P, T) is contained. Mass balance estimates of Barandun et al. (2021) (left) and Hugonnet et al. (2021) (right).

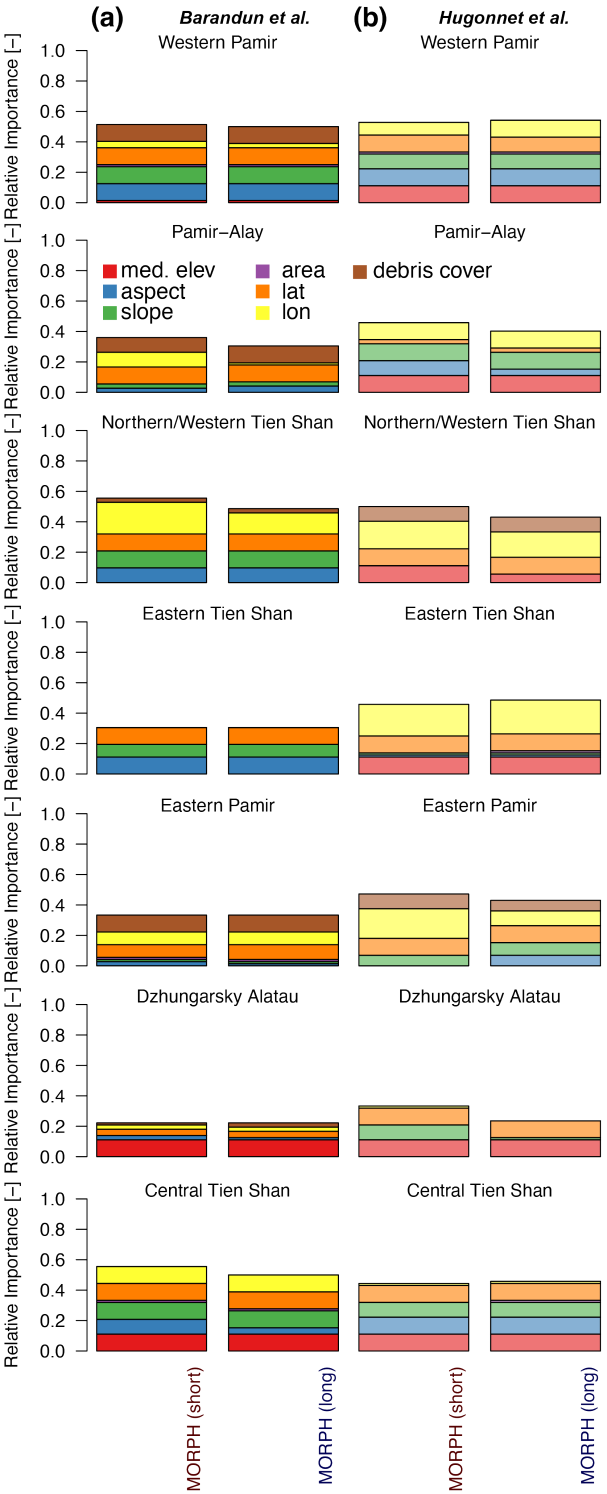

Figure A4. Frequency of significant morphological variables for the HiMAP regions and for the two mass balance estimates by Barandun et al. (2021) (left) and Hugonnet et al. (2021) (right).~~.~~

~~Surge type glacier (Guillet et al., 2022) and debris cover (Scherler et al., 2018) distribution in the Tien Shan and Pamir~~

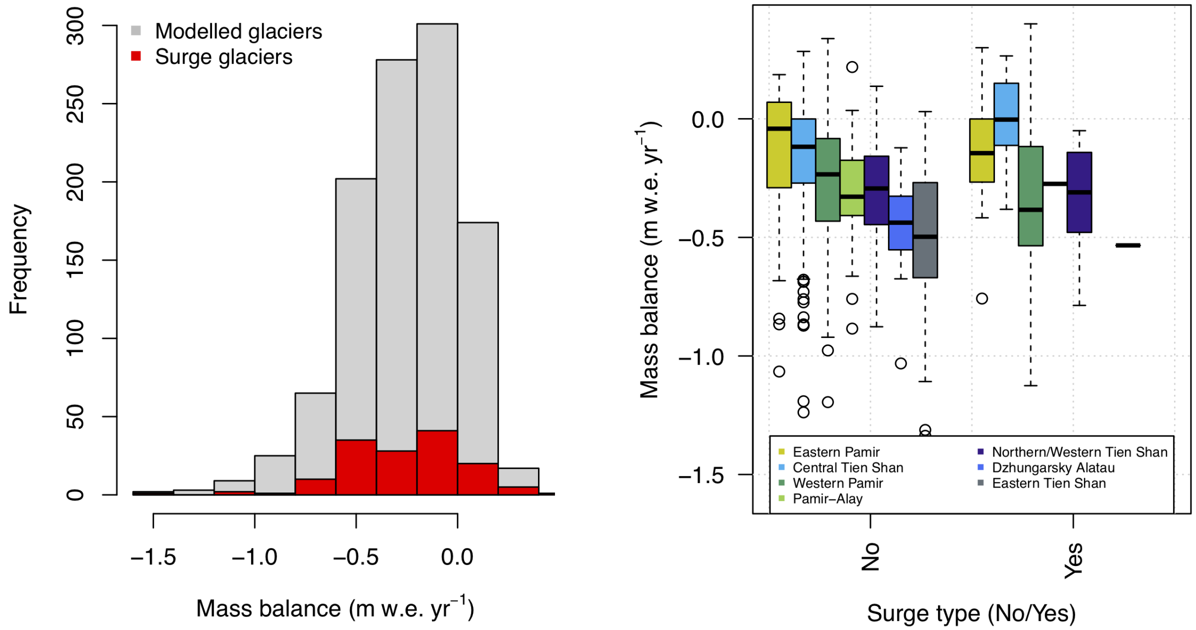

Figure A5. Distribution of ~~surge type~~ surge-type glaciers and mass balance range of all glaciers (left) and for the HiMAP regions (right). The regional comparison shows that no systematic difference was found between the relationship of surge- and nonsurge-type glaciers with mass balance.

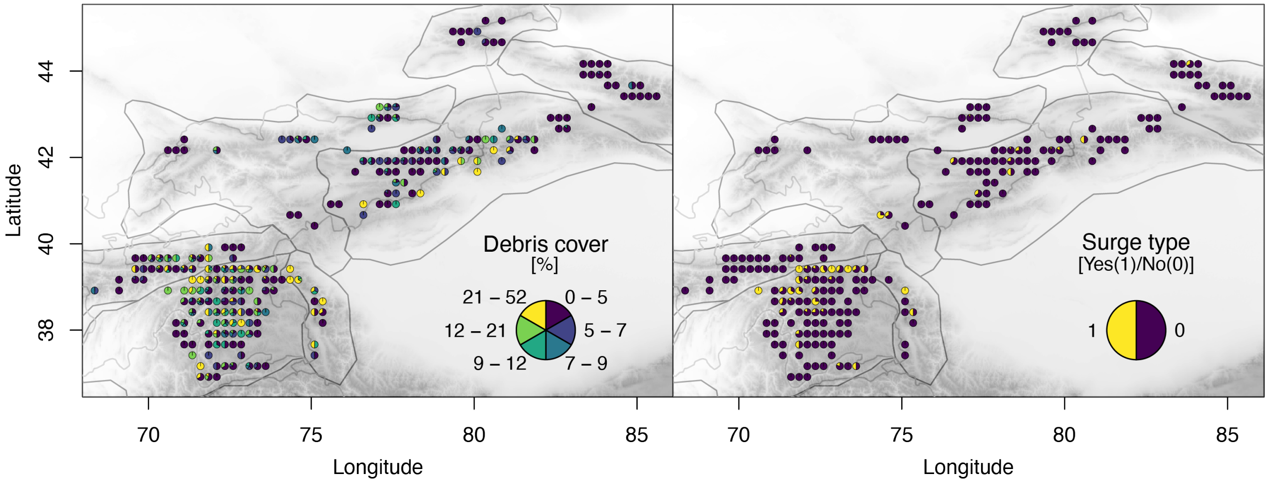

Figure A6. Surge-type glacier (Guillet et al., 2022) and debris cover (Scherler et al., 2018) distribution in Tien Shan and Pamir

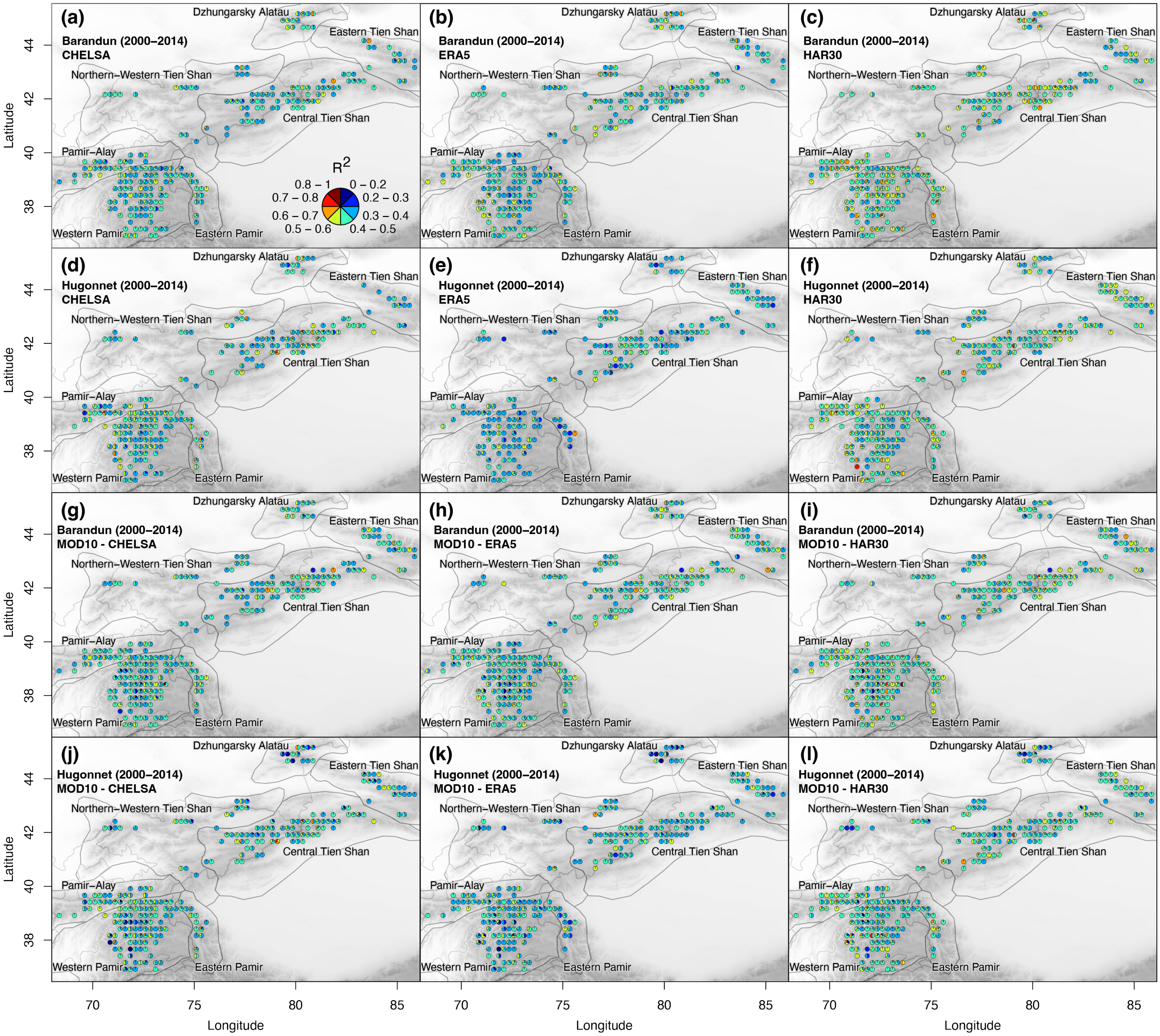

Figure A7. Coefficient of determination (R^2) of temporal analysis between annual mass balance estimates from ~~Barandun et al. (2021)~~ Barandun et al. (2021) and ~~Hugonnet et al. (2021)~~ Hugonnet et al. (2021) and two meteorological variables from the different reanalysis datasets as indicated in the figure legends. Upper two panels without ~~,~~ and lower two panels including snow cover.

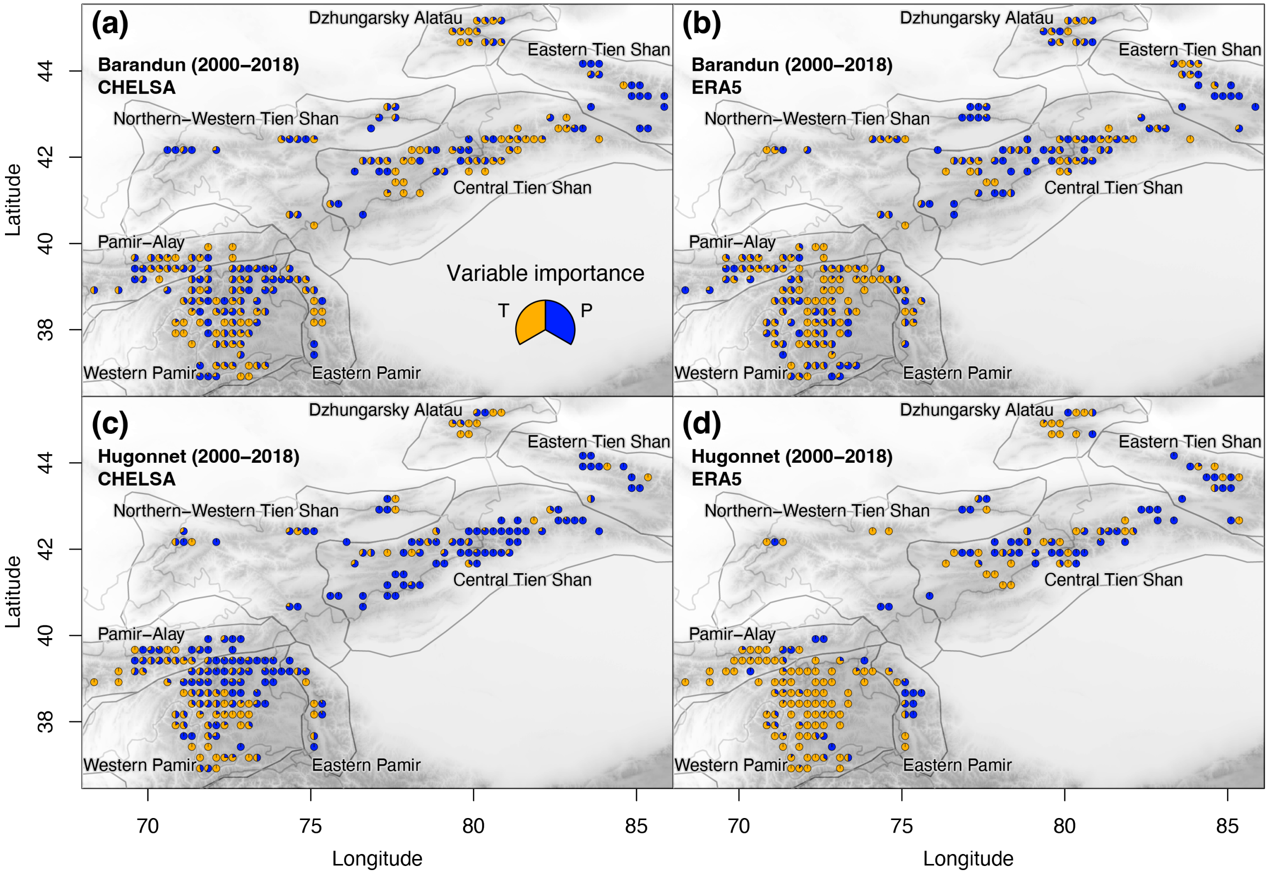

Figure A8. Importance of meteorological variables for temporal analysis between annual mass balance estimates from ~~Barandun et al. (2021)~~ Barandun et al. (2021)(top) and ~~Hugonnet et al. (2021)~~Hugonnet et al. (2021)(bottom) ~~,~~ and two meteorological variables (T and P) from the different reanalysis datasets.

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