Quantifying rates of glacier recession in the Peruvian Andes since the Little Ice Age

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This study makes use of Minitab® 18.1 (2017) statistical software and ArcGIS® ArcMap™ version 10.6 (Esri, 2017).

ABSTRACT

Peru hosts 92% of the total glacierised area of the tropics, and those glaciers are losing mass at an unprecedented rate with ongoing climate change. This glacier mass loss delivers meltwater that has the potential to have dramatic and dangerous impacts on the local – and larger-scale – surroundings via meltwater release. This study uses extensive geomorphological evidence detected within high resolution digital elevation models and satellite imagery, together with GIS reconstructions, to determine glacier area and volumetric changes since the Little Ice Age (LIA) maximum (1579 to 1728). These data show a reduction in glacierised area of 45% and a reduction in volume of 40% (almost 75 km^3) when aggregated across all Peruvian Cordilleras. Using the median date for the LIA maximum, this volume loss equates to 6.34 x 10^{-5} km^3 yr^{-1} km^{-2}, with a mass balance of -0.3 ± 0.09 m w.e. yr^{-1} and sea level equivalent of 0.17 mm, or 0.0005 mm yr^{-1}, between 1644 and 2003. When six of Peru's Cordilleras are compared, no significant difference between rates of recession is observed, which indicates that the response of these glaciers to long-term climate change is driven by large-scale climatic controls. Overall, this study contributes to the improved understanding of spatial and temporal rates of glacier melt in Peru by providing novel long-term data over a broad area, and provides a literature analysis to contextualise the rapid rates of contemporary glacier recession within a long-term record.

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1. INTRODUCTION

1.1 Why study tropical glaciers?

Tropical glaciers are retreating at an unprecedented rate (Burns and Nolin, 2014; Huh et al., 2017; Mark et al., 2017) due to climate change, with subsequent meltwater release leading to potentially dramatic and dangerous impacts on local and larger-scale surroundings. Low latitude tropical glaciers, as found in Peru, are of particular scientific interest due to their high sensitivity to climate change (Jomelli et al., 2008b). Despite their rapid rates of recession (Georges, 2004) tropical glaciers are thus far under-represented in the literature (Georges, 2004; Jomelli et al., 2008b; Carrivick et al., 2020) which warrants the need for this study.

There is vast debate in the literature regarding the dominant influence on tropical glacier change. Many studies identify air temperature as the predominant control (Thompson et al., 2006; Malone et al., 2015), although other theories include topography (Mark et al., 2002), precipitation (Engel et al., 2014), or ENSO and South American summer monsoon (Bird et al., 2011; Engel et al., 2014). A good understanding of the controls of tropical glaciers to climate change is important for forecasting future glacier change, and can be used in conjunction with the results of this study in order to predict future glacier change in Peru over long-term timescales. While some studies have investigated future glacier change in response to climate change (Motschmann et al., 2020), this study will provide a good understanding of Peruvian glacier changes in response to climate controls over a multi-centennial time scale, and will help to contextualise the magnitude of future changes.

The melting of ice caps and mountain glaciers such as those in Peru is the second highest contributor to sea level rise, after thermal expansion, and are estimated to contribute 0.106 m to sea level rise by 2100 (Church et al., 2001; Raper and Braithwaite, 2006); that's just less than half of the total sea level equivalent held in ice caps at the beginning of the 21st century (Church et al., 2001). Many tropical glaciers are ice caps which means most of their mass is distributed across a small elevation range, as well as having high mass balance gradients and rapid response times, which makes them sensitive to small changes in climate. Changes in equilibrium line altitude (ELA) could transition large areas of these glaciers into an area of ablation, thus increasing the risk of sudden and catastrophic melt events. For example, the Quelccaya Ice Cap (QIC) is arguably the most extensively studied glacier in Peru (Thompson et al., 1985; 1986; 2006; Albert, 2002; Buffen et al., 2009) and is a flat-topped dome shape (Thompson et al., 2006) with the majority of its surface distributed at relatively similar elevations between 5245 and 5545m a.s.l. This means a small increase in the ELA could place the majority of the glacier into the ablation zone.

The ELA of the Cordillera Vilcanota, highlighted in turquoise in **figure 2**, has risen 250 to 300 m since the initial LIA cold phase around 1270 to 1360 A.D. (Jomelli et al., 2008b), although this source provides no value for the ELA at the LIA maximum which will be calculated in this study. Estimates for the current ELA vary, with those cited for the Cordillera Vilcanota largely ranging between 5000 and 5436 m (Malone et al., 2018; Yarleque et al., 2018). Yarleque et al. (2018) combined a CMIP5 model and Landsat imagery and found that, under RCP 8.5 (i.e. the most extreme climate scenario), the QIC would be entirely beneath the ELA by mid-2050 and subject to rapid ablation as a result.

1.2 Glaciers in Peru

The Peruvian Andes contain 92% of the total area covered by tropical glaciers (Seehaus, 2019; **figure 1**), and consequentially the country is of paramount importance when considering the future of tropical glaciers. Peru's glaciers are vitally important for drinking water, irrigation, and sanitation in the country, as well as sustaining a range of ecosystems and ecosystem services. Above all, Peruvian glaciers are essential for sustaining the 39 hydroelectric power stations in Peru, which generate approximately 50% of the country's electricity (IHA, 2018).

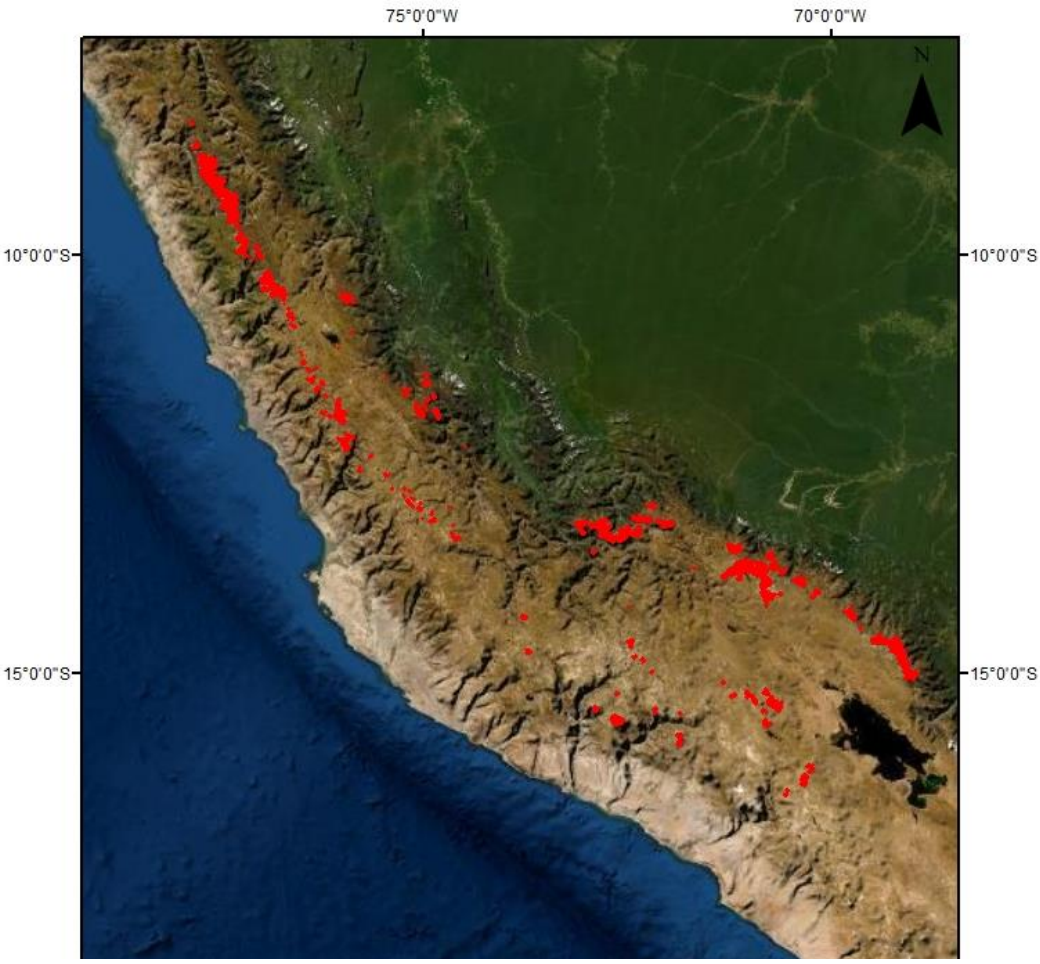

***Figure 1**: Glacier distribution across Peru. Red sections indicate presence of modern day glaciers. Basemap is Esri World Imagery (2009).*

An example of this is the Cañon del Pato hydroelectric plant, which captures water from the Rio Santa river, and in turn this is fed by the majority of glaciers in the Cordillera Blanca (Baraer et al., 2017). This sub-region is highlighted in orange in **figure 2**. The Cañon del Pato is one of the most important hydroelectricity plants in Peru and is essential for providing energy to the country, especially during the dry season. Climate change could result in a surplus of water supply in the short-term future (Leavell and Portocarrero, 2003), however total glacier melt in the long-term will seriously threaten water availability.

Links have been drawn between glacier recession in Peru and frequency of natural disasters, for example glacier mass loss from the Cordillera Blanca has been associated with an increased risk of avalanche, which poses a threat to local communities (Bury et al., 2011) and can dramatically impede the local tourism industry via destruction of infrastructure. The tourism and fishing industries are among the most valuable to Peru's economy (Omondi, 2019) and have already been heavily impacted by glacier recession (Bury et al., 2011). However, most of these studies only assess changes over short time periods and small spatial scales, for example the oldest data used by Mark et al. (2010) is from the 1950s and only covers the Cordillera Blanca. In contrast, this study will offer an insight into long-term past glacier change across the whole of Peru which can be used to compare with modern rates to help forecast future glacier changes in the country.

The long-term study of glacier change in Peru is of paramount importance in order to forecast changes in meltwater availability and to allow for planning to accommodate these changes. As a lesser developed economy, third party research such as this could be incredibly valuable to mitigate this and provide insight into the changing nature of glaciers in Peru where resource availability may be limited. However, in-depth understanding of hydrological processes and subsequent impacts of glacier melt in the country is somewhat limited due to the remote nature of many settlements (Baraer et al., 2009) and, therefore, many studies on Peru's hydrology have focussed on specific catchments (Baraer et al., 2009). This results in the generalisations of hydrological effects of glacier recession, although most sources agree that glacier recession will result in accentuated discharge variability (Mark and Seltzer, 2003; Barnett et al., 2015) and resultant threat to settlements, industry, and populations (Bury et al., 2011).

1.3 Using satellites to observe glacier changes

The study of glaciers has become much more prevalent since the first Landsat satellite was launched in July 1972. The availability of repeat satellite imagery has produced more in-depth analyses of glaciers in South America since the 1970s, with more robust observations of glacier variation within the last 50 years (Bamber and Rivera, 2007; Barcaza et al., 2009; Heid and Kääb, 2012; Falaschi et al., 2013; Melkonian et al., 2013; Braun et al., 2019). Whilst field observations are beneficial for providing a snapshot of the glacier, inaccessible glacierised environments can hinder the ability to carry out comprehensive analyses (Stumm et al., 2017).

Glaciers have been used as climate change indicators since the foundation of the Commission Internationale des Glaciers in 1894, although successful studies were not undertaken until the mid-1900s (Clarke, 1987). Their importance as climate indicators has since been recognised by the Global Climate Observing System who class glaciers as essential climate variables thanks to their high sensitivity to climatic change. The results from this study could therefore be used to help develop understanding of the relationship between climate and glacier mass balance in Peru by being analysed alongside climate models.

1.4 The Little Ice Age in the Southern Hemisphere

The LIA was an unusually cold period characterised by substantially lower temperatures than present; with temperatures dropping by 0.7ºC to 1.1ºC compared to present day temperatures in South America (Jomelli et al., 2008b; Engel et al., 2014; Malone et al., 2015), and with systematic switches between dry and humid phases (Jomelli et al., 2008b). The LIA is associated with the Northern Hemisphere due to a much higher proportion of research conducted there (Rowan, 2016) – perhaps due to the insufficient availability of climate proxy data around the inter-tropical zone (Jones et al., 2001; Chambers et al., 2014) or lower land to ocean ratio (Meyer and Wagner, 2008) in the Southern Hemisphere. While there is some alignment in the timing of cold phases between the hemispheres, the extent of temperature changes and therefore glacier advance, as well as timing and extent of warm periods, differ (Neukom et al., 2014).

The LIA succeeded the Medieval Warm Period which ended around 1250, although some studies report this warm period may have been followed by an extended warm phase, exclusively in the Southern Hemisphere, which ended ~1350 (Neukom et al., 2014). According to Jomelli et al. (2008b), the main glacier expansion period in the Southern Hemisphere occurred between ~1580 (although this date is debated which will be discussed below) and 1730. The most likely cause of the LIA was from climatic responses to natural reduction solar activity and radiative forcing (Jomelli et al., 2008b; Mann et al., 2009). Although the temperature reduction during the LIA was relatively low, it caused large environmental consequences such as floods and droughts and had substantial effects on human communities (Jomelli et al., 2008b).

The timing of the LIA in the Southern Hemisphere is highly debated, even just within the country of Peru. The majority of the literature covering the LIA in Peru suggests an initiation date as early as the 1300s (Grove, 2004; Jomelli et al., 2008a; Bird et al., 2011; Malone et al., 2015; Sagredo et al., 2017), but others claim that the LIA didn't commence until the 1500s (Denton and Karlen, 1973; Thompson et al., 1986; Fagan, 2001; Liu et al., 2005; Jomelli et al., 2008b; Thompson et al., 2013). These dates correspond with the two main glacier expansion periods in Peru outlined by Jomelli et al. (2008b) when conditions were humid and cold and therefore promoted accumulation. The majority of the cited sources do, however, agree that the LIA lasted until around the late 1800s in Peru.

While the consensus is that the LIA lasted over hundreds of years, the majority of glacier advance in Peru occurred between the early 1600s and 1730s during an exceptionally cold and humid phase (Clapperton, 1983; Rabatel et al., 2005; Thompson et al., 2006; Solomina et al., 2007; Jomelli et al., 2008b; Jomelli et al., 2009; Neukom et al., 2014; Stroup et al., 2014; Huh et al., 2018), although some studies claim this phase began in the 1500s (Thompson et al., 1985; 1986; 2013; Liu et al., 2005). There were two main glacier expansions during the LIA period (Jomelli et al., 2008b), with the second being the larger of the two and was followed by relatively continuous glacier recession (Jomelli et al., 2008b). This study therefore assumes that the innermost moraines represent the second, and maximum, LIA glacier expansion; so results represent the difference between the LIA maximum and modern-day glacier extent.

The majority of sources claiming glacier expansion began in the 1500s are, however, older investigations from the same author and are therefore less likely to contradict each other. Is would therefore be feasible to draw from this that the main LIA cold phase began in the 1600s. This study will use moraine dating to pinpoint a more precise date for the LIA maximum, and will use the literature to validate this study's results.

The few investigations in the Southern Hemisphere of the LIA extent of glaciers largely focus on Bolivia and Patagonia (Villalba, 1994; Koch and Kilian, 2005; Rabatel et al., 2005; 2006; 2008; Meyer and Wagner, 2008; Glasser et al., 2011; Rivera et al., 2012; Davies and Glasser, 2012; Meier et al., 2018) and, while there have been some LIA studies in Peru, these are either short-term or small-scale. Similar studies to the one presented here have been conducted in New Zealand (Carrivick et al., 2020), Patagonia (Glasser et al., 2011), the Himalaya (Rowan, 2016), and briefly in Antarctica (Carrivick et al., 2012) which can be used to infer how Peru's glaciers may have changed since the LIA. Despite this, the study of the LIA in Peru is important in order to gain an understanding of long-term glacier change local to the country, rather than using implications from other countries in South America.

1.5 Study aims

This investigation aims to quantify changes in area, volume, and mass balance of glaciers across Peru since the LIA, with the overall goal of providing an in-depth analysis of how glaciers in the country have changed since the LIA, primarily to provide the long-term context within which contemporary rates of change can sit. This will be done by reconstructing glacier outlines of the LIA maximum extent based on observations of post-glacial features. Previous studies that have dated post-glacial features will help to identify a date bracket for the LIA maximum extent specific to Peru. Relationships between spatial factors and the rate of glacier change will also be investigated in order to assess whether mass balance in Peru is influenced by other factors irrespective of climate changes. Finally, the study will make informed estimates to predict how Peruvian glaciers could change in the future.

1.6 Importance of this study

The study of Peruvian glaciology is thus far limited and, until now, there has not been a nationwide study into Peruvian glacier changes across a large time frame. Seehaus et al. (2019) pioneered the study of Peruvian glacier mass balance across the entire Peruvian Andes, although this was concentrated between 2000 and 2016. There is vast evidence to prove that tropical glaciers across the world are losing mass at a rapid rate (Poveda and Pineda, 2009; Thompson et al., 2011; Willis et al., 2012; Gardner et al., 2013; Carrivick et al., 2016; Barcaza et al., 2017; Braun et al., 2018), in fact, South American glaciers are the highest contributors to sea level rise per glacier unit area (Carrivick et al., 2016). However, very little is known about the long-term context since the majority of glacier research has utilised Landsat satellite imagery since 1972.

Many glaciology studies in Peru also focus on small-scale areas such as just one Cordillera; for example, the majority of glaciology studies in Peru are exclusive to the Cordillera Blanca (Kaser et al., 2003; Georges, 2004 Solomina et al., 2007; Recoviteanu et al., 2008; Huh et al., 2018) or the Cordillera Vilcanota (Mercer and Palacios, 1977; Goodman et al., 2001; Mark et al., 2002), with some focussing exclusively on the QIC in the Cordillera Vilcanota (Stroup et al., 2014; 2015; Malone et al., 2015; Sagredo et al., 2017). Spatial influences may be causing glaciers in different regions of the country to behave differently; something this study will address.

This investigation will offer a unique perspective by addressing all glaciers across the Peruvian Andes and how they have changed long-term since the LIA; two factors which are so far under-represented in the literature. This research will be crucial for making predictions about the future of these glaciers. Results can also be extended to the remaining tropical glaciers located in western South America, Africa, and Australasia in order to suggest how they may have changed in the past and make future predictions.

2. METHODOLOGY

2.1 Initial data acquisition

Modern-day glacier outlines were acquired from the Randolph Glacier Inventory (RGI) via Global Land Ice Measurements from Space (GLIMS) (Raup et al., 2007). These outlines represent the glaciers in

2000 and 2009 with a median of 2003; so henceforth 'modern-day' glacier extent refers to ~2003. Peru is generally divided into three glacierised regions; Cordilleras Central, Oriental, and Occidental based on climate differences (Sagredo and Lowell, 2012), or can be split into multiple smaller regions within these Cordilleras (Seehaus et al., 2019; Clark and Barrand, 2020). This study discriminates six glacierised regions: Cordilleras Apolobamba, Blanca, Vilcanota, Vilcabamba, Chila, and Chonta (**figure 2)** for spatial analysis as these are the most commonly referenced region names in the literature.

Modern-day 30m resolution digital elevation models (DEMs) were obtained from TanDEM-X (Krieger et al., 2007) for the Cordillera Vilcanota region and ALOS AW3D30 which uses imagery from between 2006 and 2011 (Tadono et al., 2014) for all other regions. These DEMs which were hillshaded for visualisation to assist in identification and interpolation of LIA glacier extent. NW azimuth was predominantly used although aided by a SE azimuth and satellite basemap imagery where moraines were more difficult to identify.

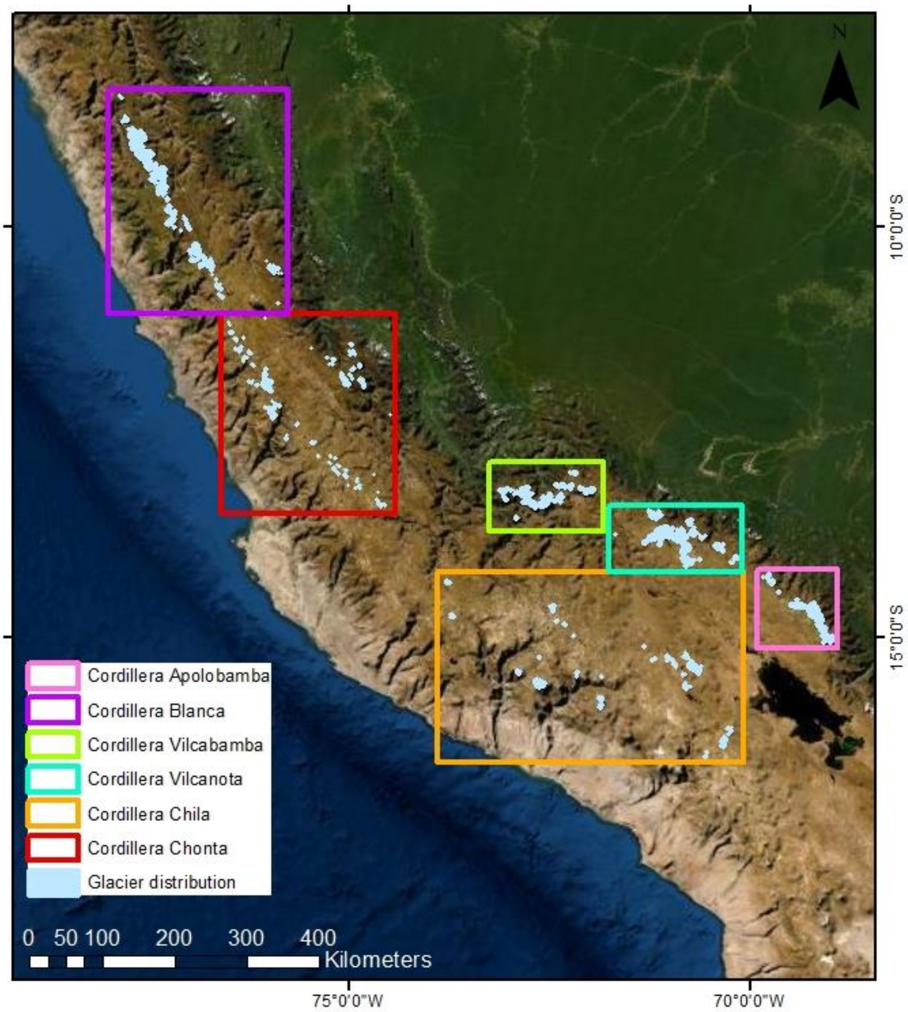

Figure 2*: Location of each glacierised area in Peru for the purposes of this study, featuring GLIMS modern-day glacier distribution. Basemap is Esri World Imagery (2009).*

2.2 Mapping LIA extent

A selection of LIA landforms and surface features have been formerly identified and dated in the literature. 74 of these moraines were found from 13 literature studies which are compiled in **table 1**, the majority of which were published after 1990 with the exception of Mercer and Palacios (1977). The different methods used by sources in **table 1** to date moraines are detailed in **table 1** and shown in **figure 3**; with the majority across all dates using lichonometry as this is generally the easiest method and subsequently most widely used so easy to compare. The relatively uniform spread of techniques, however, implies that no one technique is less reliable than another and as a result this study treats all moraines reported in **table 1** as equally reliable. The studies generally focus on valleys that are easy to access such as Qori Kalis on the Cordillera Vilcanota, which leaves those valleys that are more difficult to access without any dated moraines.

The majority of the moraines from **table 1** are located in Cordilleras Blanca (**figure 4**) and Vilcanota (**figure 5**), with only three in the Cordillera Vilcabamba (**figure 6**) and none in the other regions.In total these moraines aided with the mapping of approximately 50 of a total 2276 glaciers that were visually mapped across Peru.

Moraines dated in the literature were mapped in GIS and divided into groups by date, based on phases of glacier advance and recession between 1270 and 1880 A.D. set out by Jomelli et al. (2008b); see **figures 4** to **6**. Formerly identified and dated moraines were instructive for recognising LIA moraines from the hillshaded DEM. Mapping of the LIA extent by this study relies on these formerly identified moraines in order to calibrate the distance from the modern-day glacier of the past LIA extent. For glaciers where dated moraines were available, the modern-day glacier outline was extended to the moraine peak in order to create a shapefile of LIA glacier extents. Where moraine dating was unavailable, hillshade and basemap imagery was used in order to identify the innermost moraine as this was most likely to represent the second, and final, LIA glacier advance. In areas such as Quori Kalis, where multiple moraine dates were provided, those that corresponded to the maximum advance (1600 to 1700) were used.

LIA glaciers recognised here are based on those present in GLIMS files. It is highly likely that some smaller glaciers that were present during the LIA have disappeared entirely since, however no obvious topographical evidence remains in order to confidently map these.

***Table 1**: Dated moraines in Cordilleras Blanca, Vilcanota, and Vilcabamba compiled from 13 former literature studies*

Region	Paper	Area	Lat (oN)	Long (oE)	Years BP	Date	Date +/-	Altitude (m)	Technique
C. Blanca	Emmer 2017	Lake Artesa	-9.113	-77.517	620	1400	1370-1430	4537	Lichenometry
C. Blanca	Emmer 2017	Lake Milluacocha	-9.365	-77.410	555	1465	1440-1490	4729	Lichenometry
C. Blanca	Emmer 2017	Lake Cancaraca	-9.142	-77.504	535	1485	1460-1510	4657	Lichenometry
C. Blanca	Emmer 2017	Lake Jancarurish	-8.857	-77.676	430	1590	1570-1610	4319	Lichenometry
C. Blanca	Emmer 2017	Lake Rajururi	-9.064	-77.683	430	1590	1570-1610	4033	Lichenometry
C. Blanca	Emmer 2017	Lake Palcachocha	-9.393	-77.381	410	1610	1590-1630	4677	Lichenometry
C. Blanca	Emmer 2017	Lake Yanaraju	-9.136	-77.485	390	1630	1610-1650	4198	Lichenometry
C. Blanca	Emmer 2017	Lake Palcachocha	-9.402	-77.384	350	1670	1650-1690	4545	Lichenometry
C. Blanca	Emmer 2017	Cancaraca grande	-9.168	-77.512	275	1745	1730-1760	4458	Lichenometry
C. Blanca	Huh et al. 2018	Yanamarey	-9.658	-77.274	100	1850		4640	-
C. Blanca	Huh et al. 2018	Queschque	-9.796	-77.263		1850		4815	-
C. Blanca	Jomelli et al. 2008a	Pacharraju	-9.069	-77.558	663	1287	1268-1312	4411	Lichenometry
C. Blanca	Jomelli et al. 2008a	Pacharraju	-9.069	-77.558	389	1561	1539-1572	4411	Lichenometry
C. Blanca	Jomelli et al. 2008a	Llaca	-9.433	-77.442	378	1572	1550-1583	4461	Lichenometry
C. Blanca	Jomelli et al. 2008a	Llaca	-9.433	-77.442	375	1575	1558-1577	4461	Lichenometry
C. Blanca	Jomelli et al. 2008a	Pacharraju	-9.069	-77.558	358	1592	1583-1608	4411	Lichenometry
C. Blanca	Jomelli et al. 2008a	Pacharraju	-9.069	-77.558	326	1624	1608-1640	4411	Lichenometry
C. Blanca	Jomelli et al. 2008a	Llaca	-9.433	-77.442	307	1643	1635-1654	4461	Lichenometry
C. Blanca	Jomelli et al. 2008a	Pacharraju	-9.069	-77.558	252	1698	1660-1728	4411	Lichenometry
C. Blanca	Jomelli et al. 2008a	Llaca	-9.433	-77.442	219	1731	1698-1750	4461	Lichenometry
C. Blanca	Rodbell 1992		-9.618	-77.316	550	1400		4378	Lichenometry
C. Blanca	Rodbell 1992		-9.796	-77.258	<200	1700	1600-1700	4673	Lichenometry
C. Blanca	Seltzer 1990	Ocshapalca Glacier	-9.408	-77.435	440	1510	1325-1695	5765	-
C. Blanca	Solomina et al. 2007	Yanamarey (1996)	-9.658	-77.274	360-410	1615	1590-1640	4640	Lichenometry
C. Blanca	Solomina et al. 2007	Yanamarey (2002)	-9.658	-77.274	340-390	1635	1610-1660	4640	Lichenometry
C. Blanca	Solomina et al. 2007	Yanamarey (2002)	-9.658	-77.274	320-360	1660	1640-1680	4354	Lichenometry
C. Blanca	Solomina et al. 2007	Llaca	-9.433	-77.442	320-360	1660	1640-1680	4461	Lichenometry
C. Blanca	Solomina et al. 2007	Uruachraju	-9.595	-77.322	320-360	1660	1640-1680	4681	Lichenometry

C. Blanca	Solomina et al. 2007	Checouiacraju	-9.164	-77.541	320-360	1660	1640-1680	4640	Lichenometry
C. Blanca	Solomina et al. 2007	Cancahua	-9.067	-77.556	300-340	1680	1660-1700	4657	Lichenometry
C. Blanca	Solomina et al. 2007	Uruachraju	-9.595	-77.322	300-340	1680	1660-1700	5097	Lichenometry
C. Blanca	Solomina et al. 2007	Checouiacraju	-9.164	-77.541	300-340	1680	1660-1700	4457	Lichenometry
C. Blanca	Solomina et al. 2007	Pisco	-8.999	-77.641	340-390	1680	1660-1700	4354	Lichenometry
C. Blanca	Solomina et al. 2007	Huanday	-8.974	-77.708	300-340	1680	1660-1700	4681	Lichenometry
C. Blanca	Solomina et al. 2007	Artesonraju	-8.966	-77.643	280-320	1700	1680-1720	4705	Lichenometry
C. Blanca	Solomina et al. 2007	Yanamarey (2002)	-9.658	-77.274	200-220	1790	1780-1800	4640	Lichenometry
C. Blanca	Solomina et al. 2007	Yanamarey (2002)	-9.658	-77.274	190-200	1805	1800-1810	4640	Lichenometry
C. Blanca	Solomina et al. 2007	Artesonraju	-8.966	-77.643	170-190	1820	1810-1830	4705	Lichenometry
C. Blanca	Solomina et al. 2007	Uruachraju	-9.595	-77.322	150-160	1845	1840-1850	4681	Lichenometry
C. Blanca	Solomina et al. 2007	Broggi	-9.011	-77.600	140-150	1855	1850-1860	4464	Lichenometry
C. Blanca	Solomina et al. 2007	Cancahua	-9.067	-77.556	140-150	1855	1850-1860	4457	Lichenometry
C. Blanca	Solomina et al. 2007	Yanamarey (1996)	-9.658	-77.274	120-130	1875	1870-1880	4640	Lichenometry
C. Vilcabamba	Licciardi et al. 2009	Tucarhuay valley	-13.340	-72.520	270	1740	1710-1770	4252	10Be
C. Vilcabamba	Licciardi et al. 2009	Sisaypampa valley	-13.350	-72.560	240	1770	1690-1850	4282	10Be
C. Vilcabamba	Licciardi et al. 2009	Rio Blanco valley	-13.370	-72.590	200	1810	1790-1830	4370	10Be
C. Vilcanota	Goodman et al. 2001	Upismayo valley, Nevado Auzangate	-13.919	-70.857	394	1556	1451-1661	4477	Radiocarbon
C. Vilcanota	Goodman et al. 2001	Chalpacocha valley, Quelccaya	-13.913	-70.849	300	1650	1450-1850	5147	Radiocarbon
C. Vilcanota	Mark et al. 2002	Upismayo valley, Nevado Auzangate	-13.762	-71.269	394	1556	1451-1661	5106	Cosmogenic isotopic analysis
C. Vilcanota	Mercer and Palacios 1977	Upismayo valley, Nevado Auzangate	-13.750	-71.272	630	1320	1255-1385	4495	Radiocarbon
C. Vilcanota	Mercer and Palacios 1977	Qori Kalis Hu-1.1	-13.903	-70.852	270	1680	1600-1760	4907	Radiocarbon
C. Vilcanota	Mercer and Palacios 1977	Qori Kalis Hu-1.2	-13.926	-70.857	270	1680	1600-1760	5107	Radiocarbon
C. Vilcanota	Mercer and Palacios 1977	Qori Kalis Hu-1.3	-13.948	-70.864	270	1680	1600-1760	4937	Radiocarbon
C. Vilcanota	Mercer and Palacios 1977	Qori Kalis Hu-1.4.1	-13.956	-70.869	270	1680	1600-1760	5176	Radiocarbon
C. Vilcanota	Mercer and Palacios 1977	Qori Kalis Hu-1.4.2	-13.976	-70.875	270	1680	1600-1760	5104	Radiocarbon

C. Vilcanota	Sagredo et al. 2017	Jasscara valley	-13.799	-70.990	575	1375	1360-1390	4970	10Be and 36Cl
C. Vilcanota	Sagredo et al. 2017	Jasscara valley	-13.797	-70.987	240	1710	1690-1730	5007	10Be and 36Cl
C. Vilcanota	Sagredo et al. 2017	Jasscara valley	-13.797	-70.987	160	1790	1780-1800	5007	10Be and 36Cl
C. Vilcanota	Seltzer 1990	Upismayo valley	-13.763	-71.267	455	1495	1365-1625	4492	-
C. Vilcanota	Stroup et al. 2014	Qori Kalis Hu-1a	-13.901	-70.852	520	1430	1370-1490	4899	10Be
C. Vilcanota	Stroup et al. 2014	Qori Kalis Hu-1b	-13.902	-70.851	380	1570	1540-1600	4907	10Be
C. Vilcanota	Stroup et al. 2014	Qori Kalis Hu-1c	-13.901	-70.849	330	1620	1600-1640	4912	10Be
C. Vilcanota	Stroup et al. 2014	Qori Kalis Hu-1d	-13.902	-70.845	300-350	1625	1600-1650	4967	10Be
C. Vilcanota	Stroup et al. 2014	Qori Kalis Hu-1f	-13.903	-70.848	310	1640	1630-1650	4919	10Be
C. Vilcanota	Stroup et al. 2014	Qori Kalis Hu-1g	-13.904	-70.846	230	1720	1710-1730	4916	10Be
C. Vilcanota	Stroup et al. 2014	Qori Kalis Hu-1h	-13.905	-70.846	220	1730	1720-1740	4916	10Be
C. Vilcanota	Stroup et al. 2015	Chalpacocha valley	-13.923	-70.859		1310	1280-1340	5098	10Be
C. Vilcanota	Stroup et al. 2015	Chalpacocha valley	-13.918	-70.855		1470	1450-1490	5155	10Be
C. Vilcanota	Stroup et al. 2015	Qori Kalis Hu-1a	-13.900	-70.850		1534	1370-1660	4905	10Be
C. Vilcanota	Stroup et al. 2015	Qori Kalis Hu-1e	-13.902	-70.848		1620	1600-1640	4916	10Be
C. Vilcanota	Stroup et al. 2015	Qori Kalis Hu-1b	-13.901	-70.850		1627	1580-1680	4912	10Be
C. Vilcanota	Stroup et al. 2015	Qori Kalis Hu-1c	-13.901	-70.848		1680	1660-1700	4917	10Be
C. Vilcanota	Stroup et al. 2015	Qori Kalis Hu-1f	-13.903	-70.847		1750	1700-1790	4921	10Be
C. Vilcanota	Stroup et al. 2015	Qori Kalis Hu-1g	-13.904	-70.846		1780	1760-1800	4917	10Be
C. Vilcanota	Stroup et al. 2015	Qori Kalis Hu-1h	-13.904	-70.845		1787	1770-1810	4919	10Be

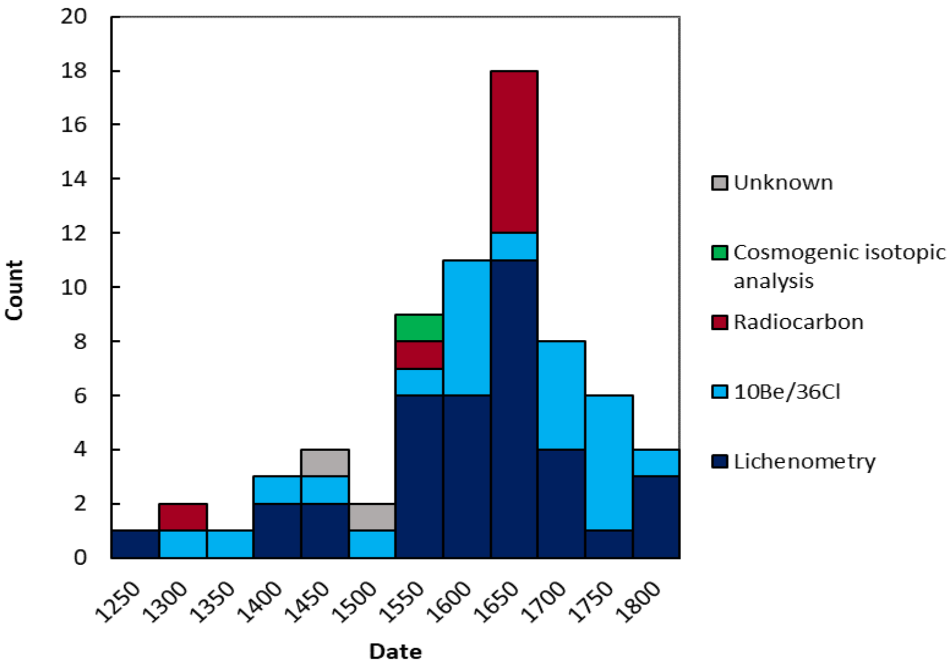

***Figure 3**: Geochronological techniques used to date moraines from **table 1**.*

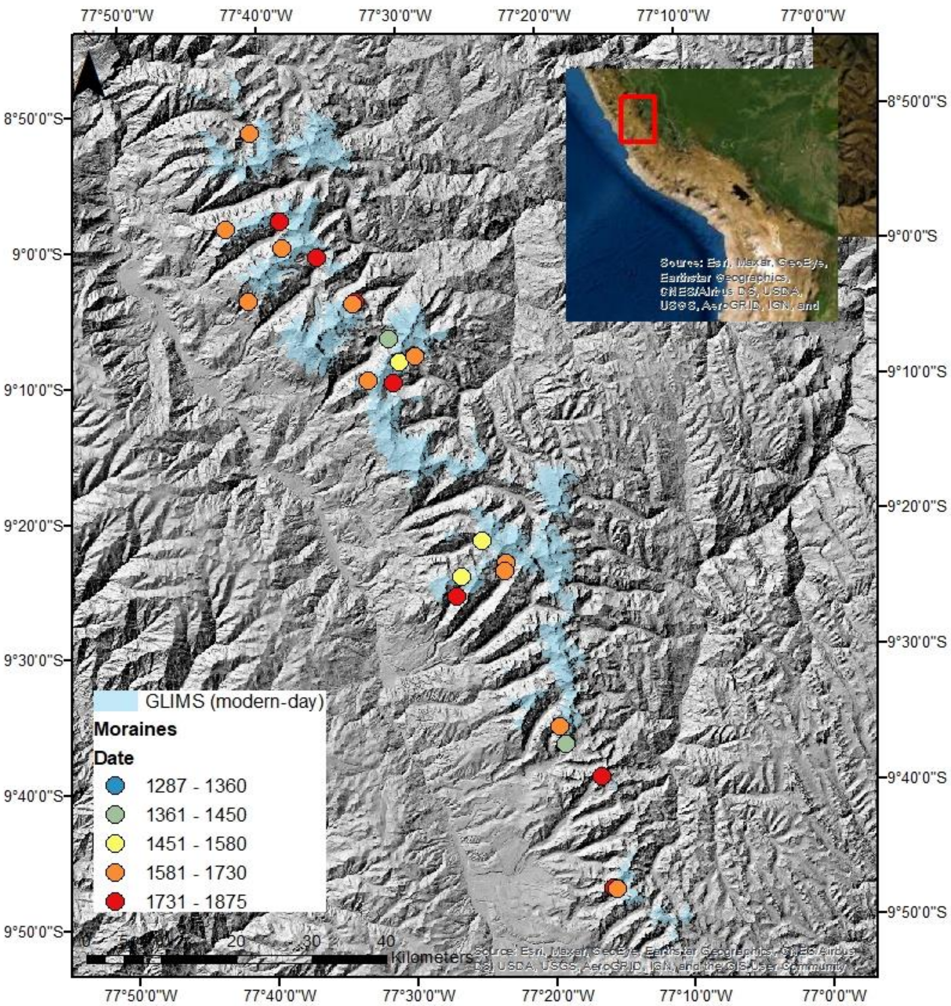

***Figure 4**: Location and date category of LIA moraines in Cordillera Blanca. Insert basemap is Esri World Imagery (2009).*

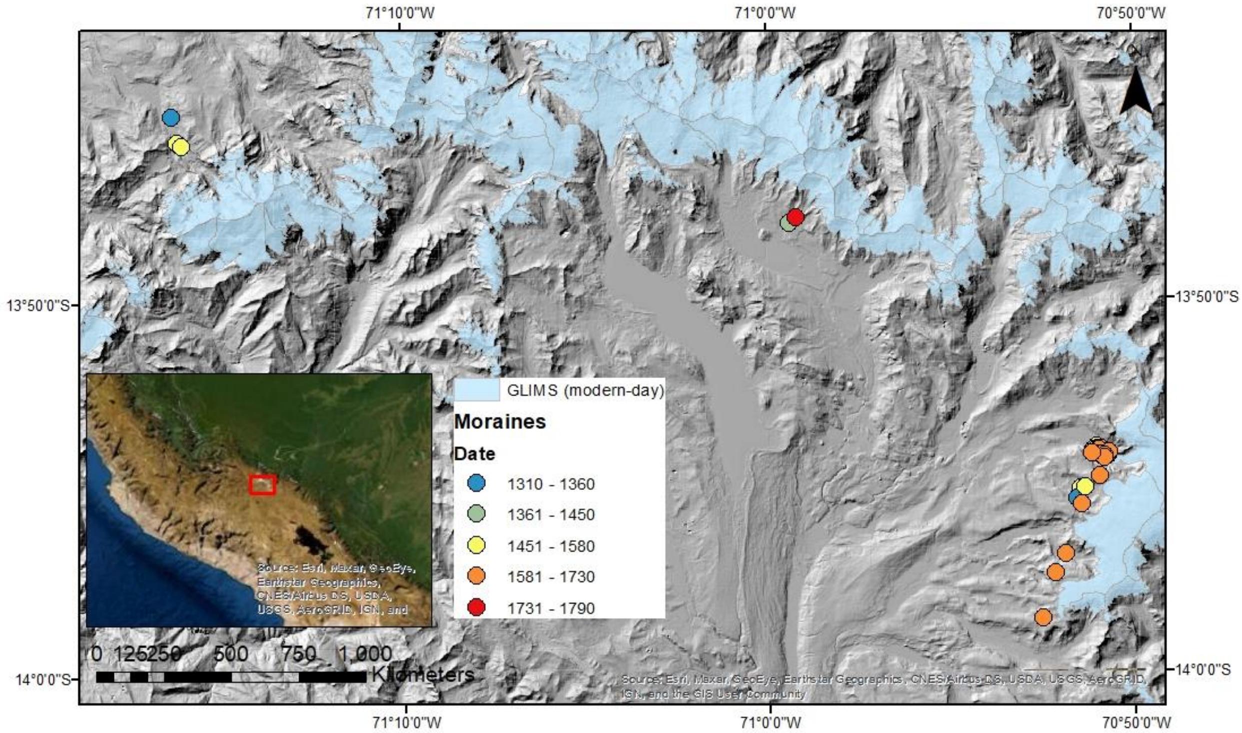

***Figure 5**: Location and date category for LIA moraines in the Cordillera Vilcanota. Insert basemap is Esri World Imagery (2009).*

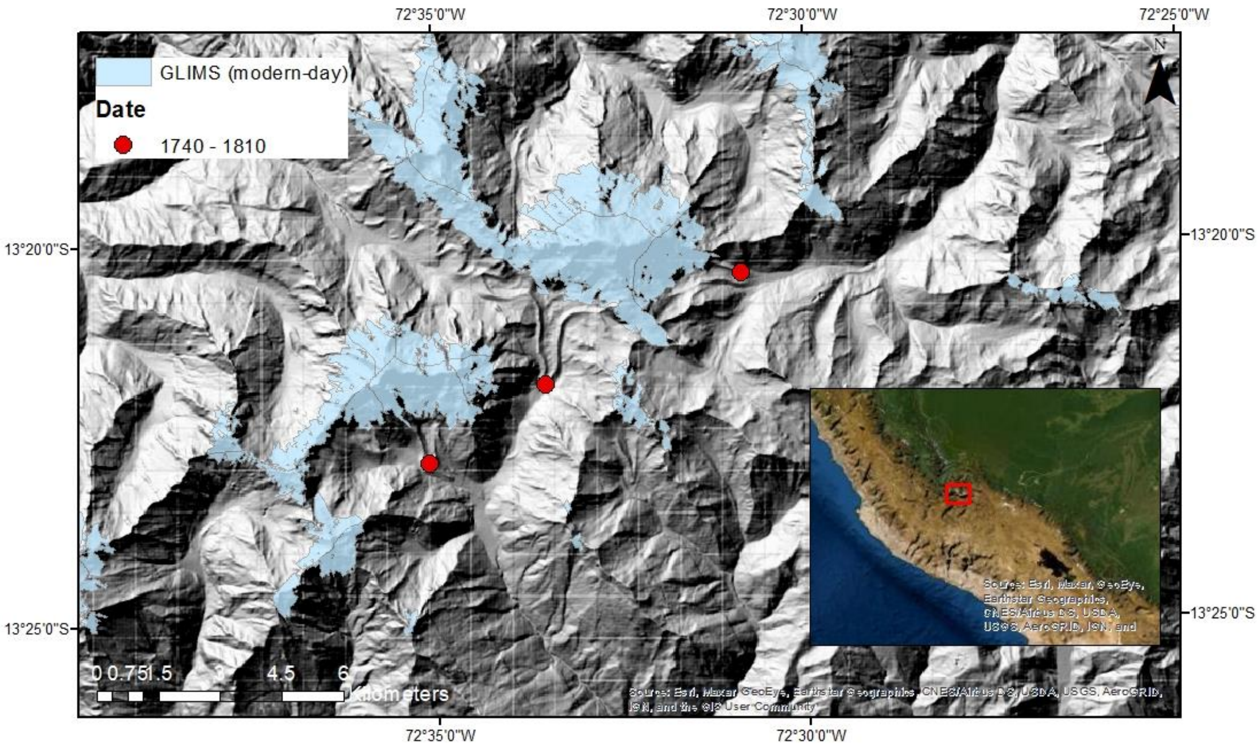

***Figure 6**: Location and date category for LIA moraines in the Cordillera Vilcabamba. Insert basemap is Esri World Imagery (2009).*

Landforms and surface features indicative of the LIA extent; most notably moraines, trimlines, and vegetation changes, were identified using a hillshaded DEMand ArcGIS Basemap World Imagery (2009; updated 2021). Where possible, moraine crests were used as the main indication as these are the most obvious to visually identify and carry the greatest confidence as indicators of the last glacial expansion. When in doubt, or if moraines were more complex with multiple ridges, the innermost ridge was always used and thus the resultant outlines mark a conservative estimate of the LIA glacier extent.

Alternative study methods were considered in the development of this project including using numerical modelling to simulate LIA glacier extent and other glacier characteristics. Numerical models have in the past been used to reconstruct past glacial maximum events (Hubbard et al., 2005) and relationships with parameters such as climate (Rowan, 2011), and could have been used by this study to simulate LIA maximum extent where post-glacial landforms are unavailable (Rowan, 2011). However, this would have required large data input and is more commonly used to study smaller-scale glaciers (Rowan, 2011), so is beyond the scope and time constraints of this study. Field studies were also considered and would have been highly beneficial prior to mapping in order to gain a more advanced understanding of the Peruvian landscape, although the ability to travel overseas was hindered during the study period and therefore a greater portion of time was designated to studying satellite imagery of the study site.

The visual mapping method used here is a robust strategy, and has been successfully used in past investigations of LIA glacier extent (for example Carrivick et al., 2020). Unlike a modelling approach, the method can be applied in exactly the same way to glaciers across a large area and was thus deemed the most appropriate for this particular investigation.

2.3 Dating the LIA maximum extent

Minimum, mean, and maximum rates of volume loss were calculated using moraine date upper (1728) and lower (1579) quartiles, and the average (1644) calculated from the moraine dates provided in **table 1**. The variation in LIA maximum date (1579 to 1728) was used to calculate uncertainty brackets for annual rates of change and mass balance, and reflects the different response times that is likely across the large number of glaciers studied. The variation in modern-day dates was deemed to be too narrow to significantly contribute to any error in results and so the uncertainty in LIA date forms the only basis for data error brackets.

The LIA dates presented here align well with estimates for main LIA Southern Hemisphere glacier expansion in the literature explored in section 1.4, since the majority of studies agree that the maximum extent occurred in the 1600s during an intense cold phase. There is no significant difference between the LIA moraine dates in each sub-region (**figure 7**), which justifies the use of 1644 as a uniform date for the LIA maximum across all sub-regions. However, this is only based on three data entries for the Cordillera Vilcabamba and none for Cordilleras Apolobamba, Chila, and Chonta as no other data was available for these regions, which has resulted in a large uncertainty bracket for the Cordillera Vilcabamba in **figure 7**. While the ANOVA in **figure 7** suggests there is no statistical difference between regions, this is only due to the lack of moraine data for Cordillera Vilcabamba, and in reality the date of the LIA maximum for the Cordillera Vilcabamba should be interpreted as different from Cordilleras Blanca and Vilcanota. Greater availability of moraine data across Peru would have been beneficial here to more confidently conclude if there is any statistical difference between timing of the LIA across Peru, however due to the lack of data for the Cordillera Vilcabamba, it would be futile to conclude from the highly limited data that there is a difference in LIA maximum date between the regions. Ideally, sufficiently more moraine data would be incredibly beneficial to defend the uniform use of 1644 as the date for the maximum LIA across all sub-regions. However, owing to the lack of this data, this study must assume that 1644, the average of all dated moraines across the three reported regions, including Cordillera Vilcabamba, is representative.

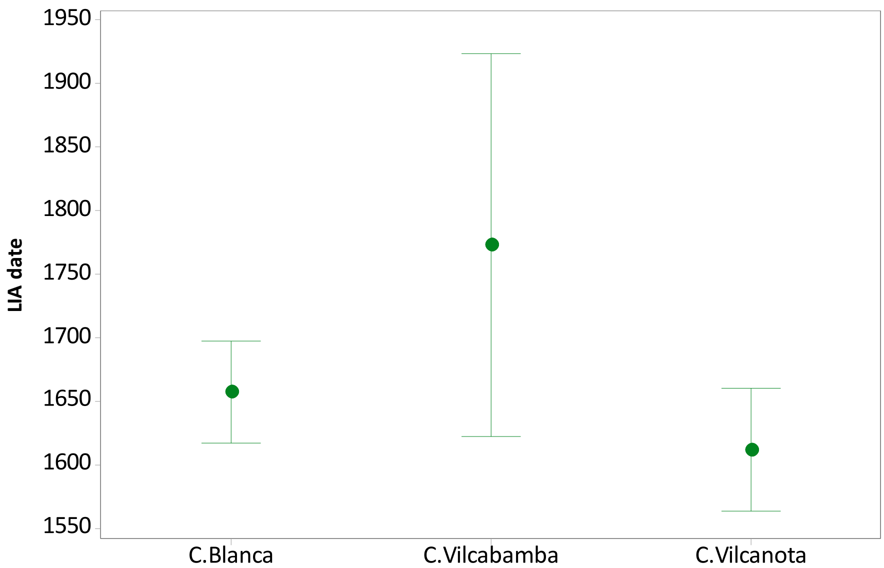

Figure 7*: ANOVA of moraine dates for each sub-region. Uses dates of 74 moraines from 13 studies.*

2.4 Mapping uncertainty

In order to investigate the degree of human error in glacier reconstructions, one glacier from Cordilleras Vilcanota, Vilcabamba, Blanca, and Apolobamba were additionally mapped thrice by myself (MD), then once each blind by experts in the field, Dr Jonathan Carrivick (JC) and

Dr Duncan Quincey (DQ). Glaciers were selected to create a variation in size and extent of visible post-glacial evidence in order to observe the precision of mapping on this study. The variation between LIA glacier area calculated from these digitisations is shown in **figure 8**, where MD values represent an average across all four attempts (original mapping and three additional error samples for the individual glaciers).

Percentage changes in area between the LIA and modern-day, shown in **figure 8b**, are relatively similar for Cordilleras Apolobamba (**figure 9**), Blanca (**figure 10**), and Vilcanota (**figure 11**), whereas there is some variation between percentages from the Cordillera Vilcabamba (**figure 12**); in which calculations of area change vary from 44.6% (DQ) to 53.5% (MD). This glacier was selected for its limited post-glacial evidence to signpost the LIA in order to gain an extreme assessment of human error, and therefore the high variation in values was expected here.

The outcome of this test for uncertainty shows that there is an element of human error present in digitising for all glaciers, and therefore calculations of area and volume change would likely be different if digitised by a different individual. However, **figure 8** does not highlight any significant differences, i.e. no individual consistently produced anomalous LIA area estimates. In order to clarify whether the potential human error in this study is significant enough to considerably reduce confidence in results, a comparison with the other literature is useful, although the lack of literature covering the LIA in Peru means data for comparison is scarce.

Here, the glacierised area of the Cordillera Blanca in 2003 is 598 km^2, which is similar to Racoviteanu et al. (2008) who reported an area across the sub-region of 570 km^2 in the same year. This can be used to infer that this study's modern-day glacier extents are sound.

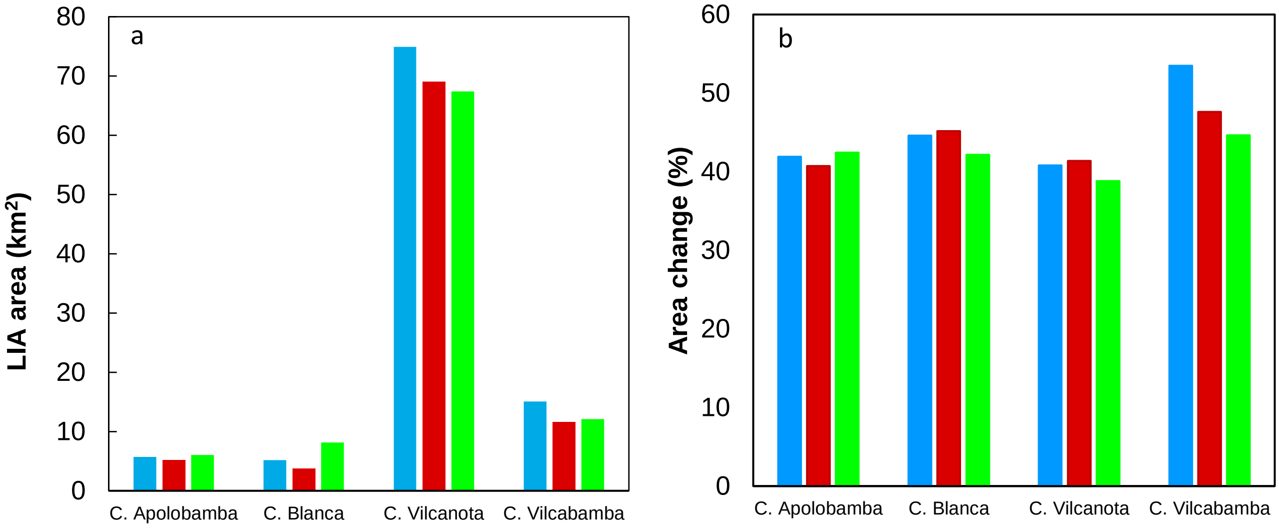

Figure 8*: Comparison of individual blind tests for Cordilleras Apolobamba, Blanca, Vilcanota, and Vilcabamba in Peru by MD (blue), JC (red), and DQ (green). Graphs show (a) comparison of individual LIA glacier areas, and (b) percentage change in area from each digitised LIA and modern-day extents.*

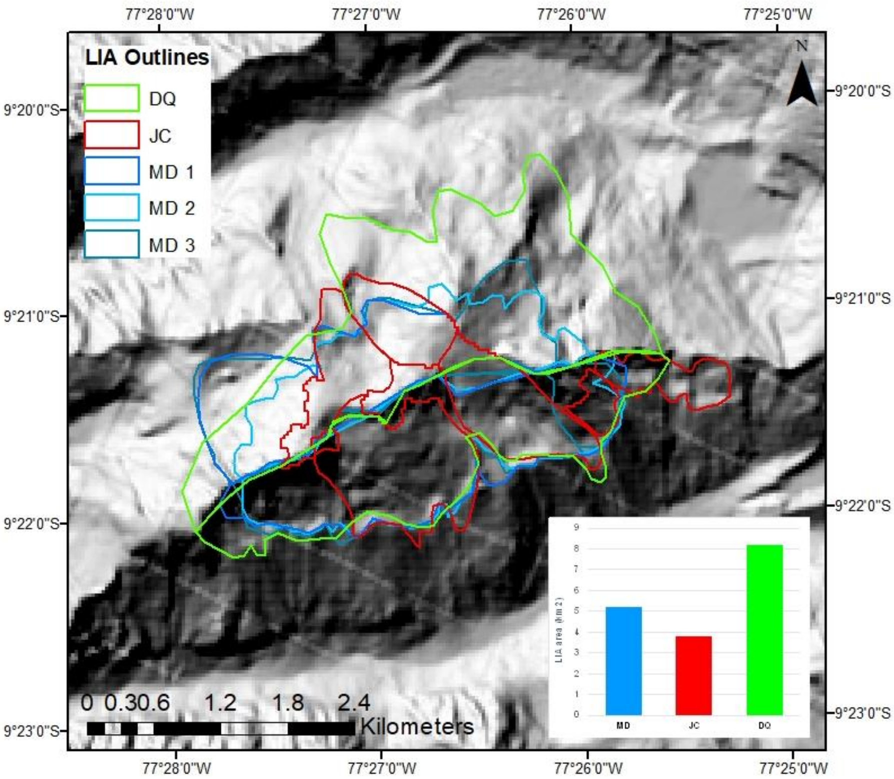

Figure 9*: MD, JC, and DQ LIA digitisations of an ice massin Cordillera Blanca.*

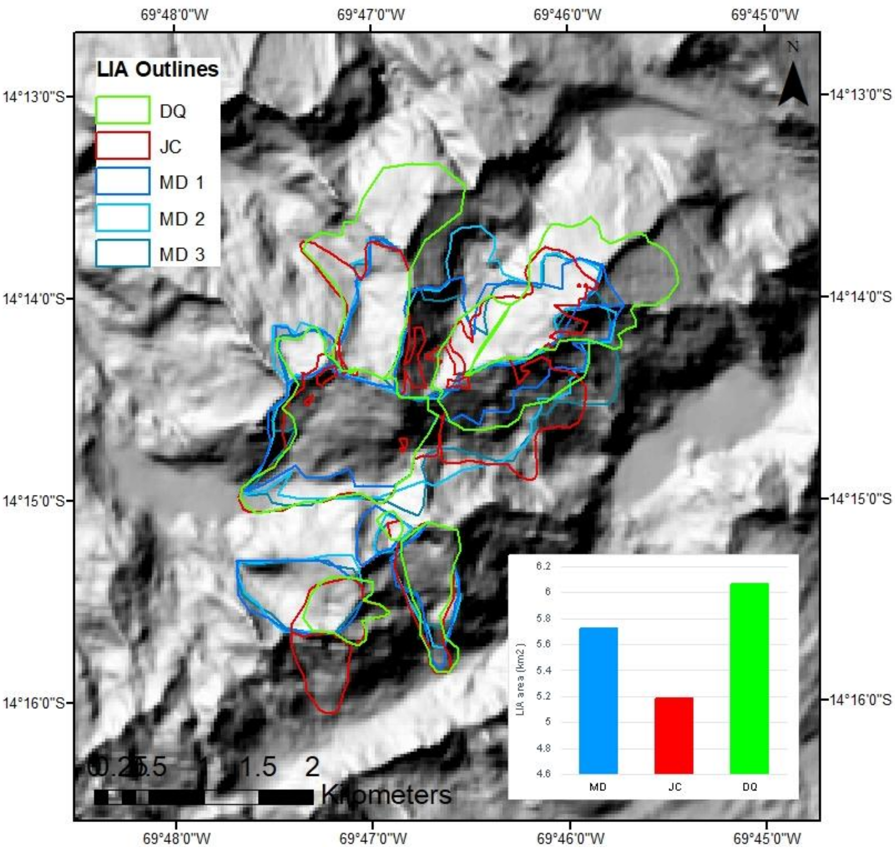

Figure 10*: MD, JC, and DQ LIA digitisations of an ice massin Cordillera Apolobamba.*

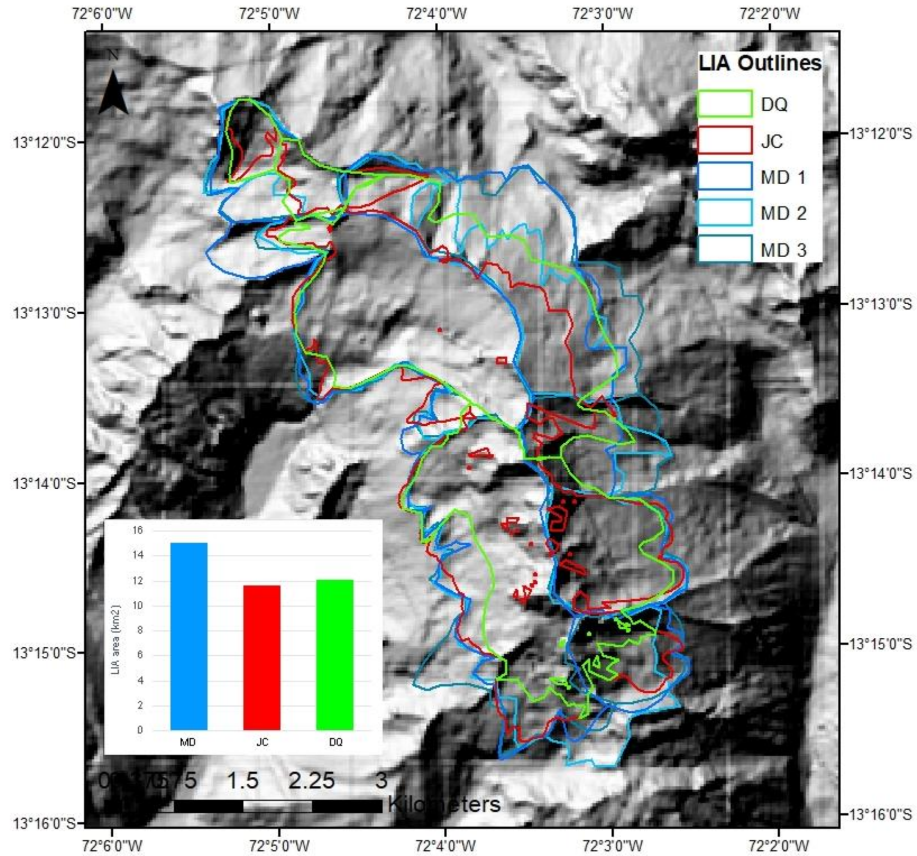

***Figure 11**: MD, JC, and DQ LIA digitisations for an ice massin Cordillera Vilcabamba.*

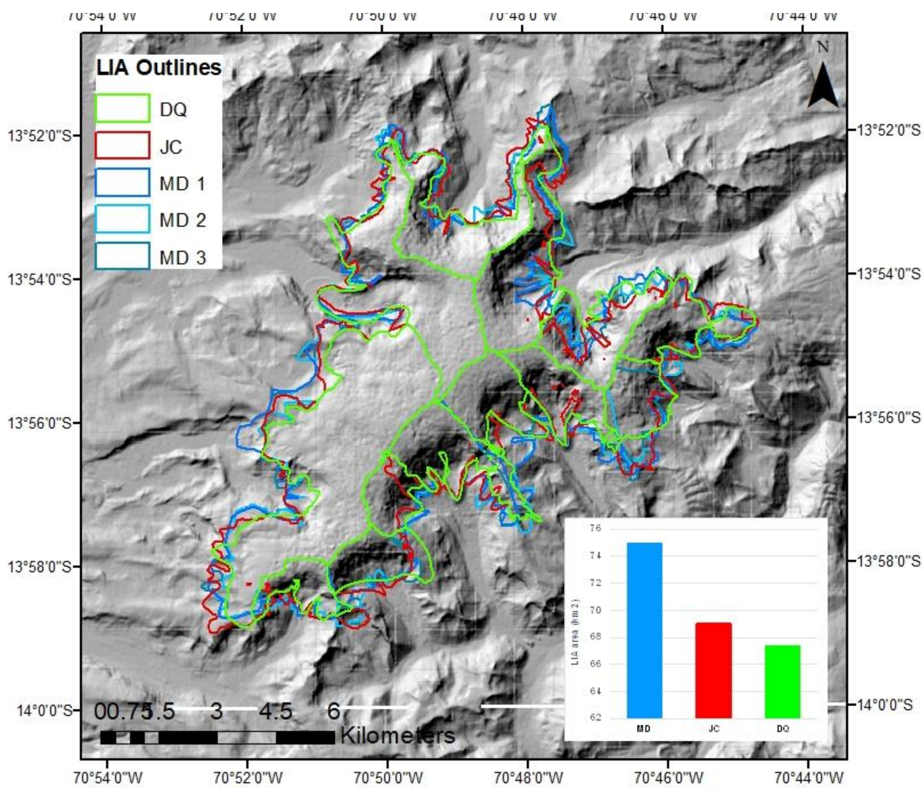

***Figure 12**: MD, JC, and DQ LIA digitisations of the QIC in Cordillera Vilcanota.*

2.5 Cordillera Vilcabamba

Sudden drops in basal elevation were identified in the Cordillera Vilcabamba which resulted in areas of anomalously thick ice over convex base topography seen by this study. A cross section of basal elevation from Farinotti et al. (2019) is plotted in **figure 13** below, where a large portion of the ice cap on the south side was over 500 m thick. In an attempt to mitigate this, all ice thicknesses over 500 m were ruled as anomalous and removed, which only occurred in the Cordillera Vilcabamba. Therefore, for example, much of the region highlighted in **figure 13** was removed. The sub-region still has a very high modern-day ice thickness in comparison with Farinotti et al. (2019), which is used here as an accuracy reference, and therefore confidence in the percentage change in volume for the Cordillera Vilcabamba is limited.

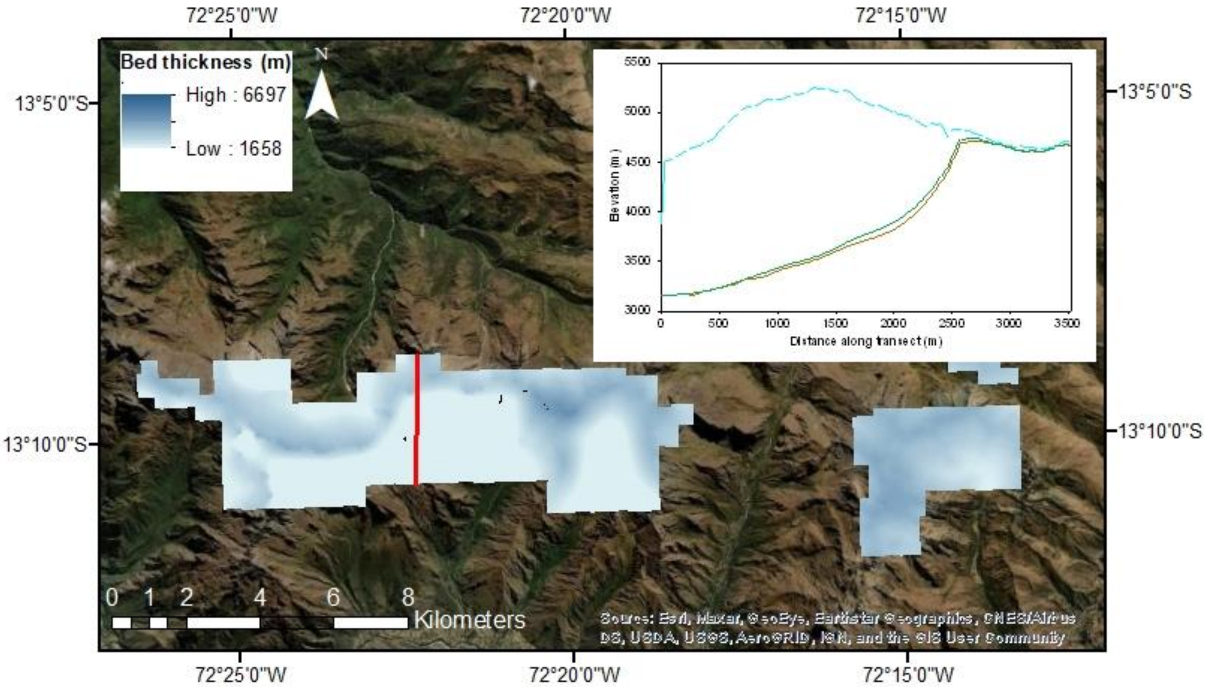

***Figure 13**: Cross section of a glacier in central Cordillera Vilcabamba, showing cross section data for bed topography (brown), modern day ice thickness from Farinotti et al. (2019) (green), and LIA ice thickness (blue).*

2.6 Isolating ablation areas

The analysis of volume change in this study is restricted to areas below the ELA, since it is only within these areas that moraines are deposited, and moraines are the primary evidence of former glacier extent used in this study. This study therefore uses a Python-coded ArcGIS tool originally developed by Pellitero et al. (2015) and modified by W. H. M. James to delineate ablation areas for each glacier. The tool calculates the ELA of each glacier using a userspecific balance ratio, then intersects this ELA contour with the digitised LIA outlines (section 2.2) and isolates parts of the LIA glaciers below this line. The balance ratio approach assumes that the accumulation area of a glacier accounts for a certain ratio of the total glacier and takes hypsometry into consideration (Rea, 2009). According to Rea (2009) the global balance ratio is roughly 1.75, which was used herein since no specific value was given for South America. Ablation areas <0.02 km^2 were removed since the majority of areas this size are fragments on the same glacier as larger ablation areas. According to Benn and Lehmkuhl (2000), tropical regions should have highest AABRs due to the glaciers experiencing ablation throughout the year. It would therefore be sensible to anticipate a larger ablation area output when using a higher AABR in the tool by Pellitero et al. (2015), since this assumes that the ablation to accumulation ratio is greater.

Following the workflow of Carrivick et al. (2020), volume change of each glacier between the LIA and present-day DEM was calculated by first extracting elevation values from the modern DEM at points on the LIA ablation area outlines – these points were specifically on the digitised moraine crests and along the ELA. LIA glacier surface was then reconstructed using natural neighbour interpolation. Finally, the modern-day DEM was subtracted from the reconstructed LIA surface in order to calculate elevation change (per grid cell), and ultimately to calculate the rate of glacier volume loss from LIA ablation areas between LIA maximum (~1644) and modern-day (~2003).

As reported by Carrivick et al. (2020), the rate of change yielded from this workflow are far more affected by the date ascribed to the LIA rather than to uncertainty in digitising, DEM resolution, or choice of LIA surface interpolation method (for example).

2.7 Calculations

All data was tested for normality using Anderson-Darling prior to statistical testing. In all of the statistical testing presented in this study, at least one variable was not normally distributed ($p < 0.05$) so Spearman's rank was used to test for relationships, and Mann-Whitney U to test for difference. In section 3.4, ANOVA test is used to find out whether differences in volume loss between each region are statistically significant, and subsequent post-hoc tests are carried out in order to identify which sub-regions are statistically similar or different within this ANOVA.

In order to calculate ice thickness, bed topography data from Farinotti et al. (2019) was combined with the modern DEM, using minimum values, in order to create a landscape-wide bed topography. Then the LIA surface (of ablation areas) was combined with the modern DEM, using maximum values, to create a landscape-wide LIA glacier surface. These were differenced in order to calculate the LIA glacier ice thickness.

The LIA surface was calculated by extracting elevation values from the DEM to points along the ablation area edges, then interpolating this using ‘natural neighbour’ to reconstruct the LIA glacier surface. Volume was calculated from this by multiplying by cell size (30m x 30m). Modern-day glacier volume was calculated by subtracting the volume of ablation areas from the total LIA glacier volume.

Rate of volume change was calculated in order to gain a value of volume change that could be compared between regions. This was done for each sub-region as well as for each individual ablation area (2277 in total) using the equation:

$$R = \frac{\left(\frac{\Delta V}{359}\right)}{A}$$

Where R is the rate of volume change (km^3 yr^{-1} km^{-2}), ∆V is volume change (km^3), and A is the LIA glacier area (km^2). 359 is the number of years between the LIA maximum and modern-day (1644 to 2003). Next, mass balance was calculated which first required finding the mass of ice lost since the LIA using the equation:

$$M = \frac{(\Delta V \times D)}{359}$$

Where M is mass balance (m w.e yr^1) and D is the density of glacier ice, which this study assumes is 850 km m^{-3} (Huss, 2013; Seehaus et al., 2019). Sea level equivalent was also calculated from the mass loss since the LIA, which is a useful value to know as it allows us to measure and compare the global impact of glacier melt. This used the following equation:

$$SLE\ (mm) = \frac{1}{361.8}$$

An average latitude and longitude was recorded for each sub-region by identifying the middle point of each area. This does not account for the spread of glaciers within each sub-region, although the distribution is generally uniform within each so the midpoint was decided to be sufficient. Aspect was recorded for each ablation area, and was found by taking the average bearing from 10 randomly generated points in each area. Finally, the LIA ELA was taken as the maximum altitude of each ablation area. The mean for each sub-region and overall Peru LIA ELA were calculated by taking the averages of these.

3 RESULTS

All values presented in this section are summarised in **table 2** on the next page.

***Table 2**: Glacier attributes for both LIA and modern-day, and glacier change between the two. *Average ELA across all individual ablation areas.*

	Glac count (LIA)	Glac count (modern)	Area (LIA) km^2	Area (modern) km^2	Area loss km^2	Volume (LIA) km^3	Volume (modern) km^3	Volume loss km^3	LIA ELA (m a.s.l.)
Cordillera Blanca	610	844	1096.08	598.10	497.98	55.89	29.81	26.08	5005.12
Cordillera Chonta	311	429	237.31	97.18	140.13	8.92	4.70	4.22	4967.92
Cordillera Vilcabamba	210	227	456.02	222.09	233.94	29.47	19.70	9.77	4817.71
Cordillera Chila	222	277	307.76	144.44	163.32	8.41	6.37	2.04	5157.10
Cordillera Vilcanota	295	339	692.88	455.61	237.27	35.25	20.94	14.32	5080.40
Cordillera Apolobamba	139	159	454.02	269.96	184.06	31.34	13.93	17.40	5037.32
PERU TOTAL	**1787**	**2275**	**3244.07**	**1787.38**	**1456.68**	**169.28**	**95.46**	**73.83**	**5012.84***

3.1 Number of glaciers

There are 488 more glaciers now than during the LIA maximum (2275 and 1787 respectively). This is because some smaller glaciers present today were once joined together.

3.2 Area change

Between the LIA and modern-day Peru has lost a total of 1456.68 km^2 of glacier ice, which is 44.9% of the area covered at the LIA maximum. The greatest area loss was 497.97 km^2 from the Cordillera Blanca, while the smallest area loss was 140.13 km^2 from the Cordillera Chonta. However, the Cordillera Chonta lost the greatest glacier area relative of LIA size of 59%. Percentage changes in glacier area for each sub-region are shown in **figure 14.**

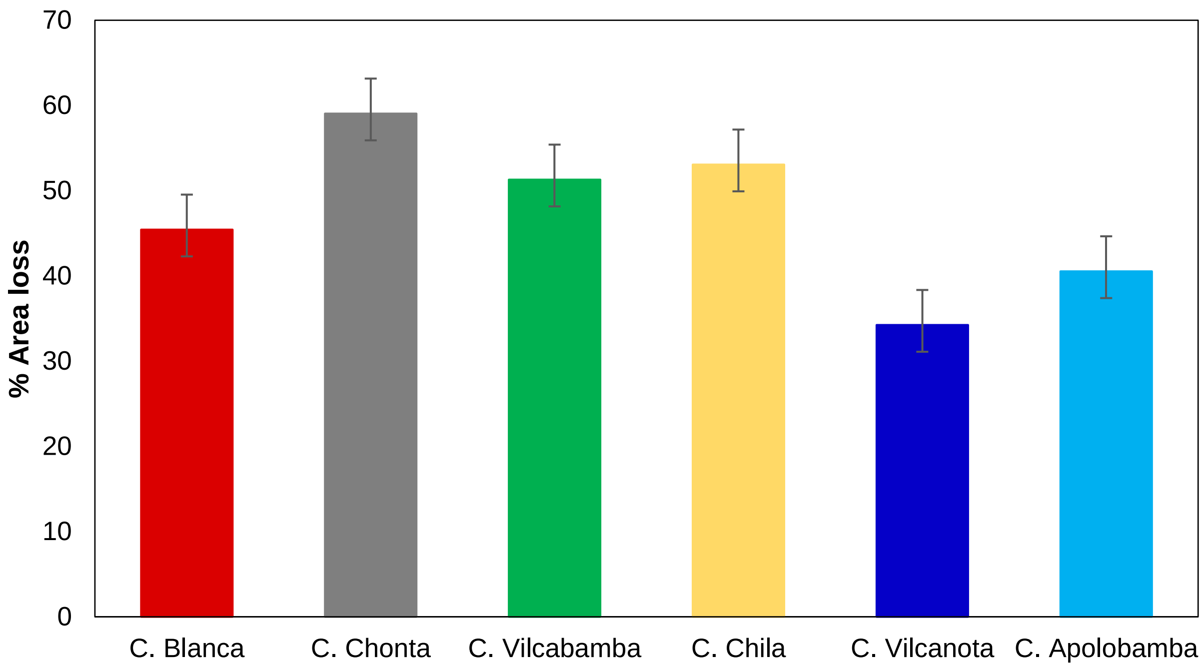

Figure 14: *Percent of LIA glacier area loss in each sub-region.*

3.3 Surface lowering

In general, central sections of ablation areas with a large surface area have had the greatest magnitude of surface lowering between reconstructed LIA extents and modern-day. For example, some ablation areas in central Cordillera Vilcanota (**figure 15**) have a surface area of ~10 km^2 and these tend to have large patches of surface lowering >200 m. As expected, these ~10 km^2 ablation areas tend to belong to large glaciers around 20 km^2 (LIA extent) so it can be deduced that large glaciers are therefore subject to the highest magnitudes of surface lowering >200 m. This trend is very apparent in central Cordillera Vilcanota (**figure 15**).

The greatest surface lowering has taken place in ablation zones of the larger Cordilleras (Apolobamba, Blanca, Vilcabamba, and Vilcanota), whereas Cordilleras Chila and Chonta have much less apparent surface lowering, possibly due to glaciers being much smaller in these sub-regions.

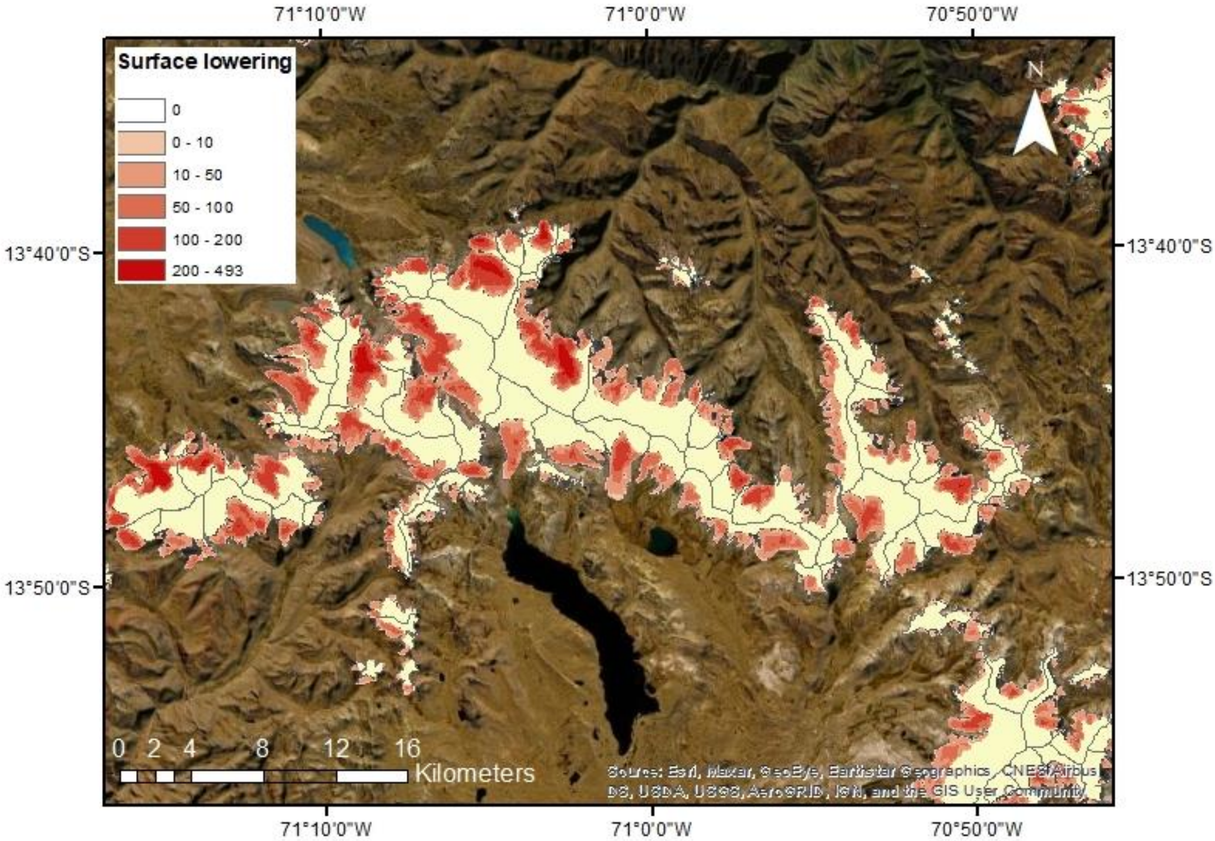

***Figure 15**: Surface lowering of ablation areas against LIA glacier outlines in central Cordillera Vilcanota. Basemap is Esri World Imagery (2009).*

3.4 Volume loss

3.4.1 LIA to modern-day

This study finds a modern glacier volume across Peru of 95.5 km^3 which was calculated from a total 2276 glaciers that were mapped by this study. This can be easily compared with data from Farinotti et al. (2019) in order to check calculations against secondary data. Farinotti et al. (2019) present modern glacier volume data for the entire study region totalling to 107.8 km^3 by using a robust combination of five different glacier models. While this differs from the value calculated in this study, it is argued that this is close enough to be explained by possible minor human and data errors and therefore supports this study's calculation of modern-day glacier volume. This study found a total glacier volume loss of 73.83 km^3 across the whole of Peru between 1644 and 2003 (LIA maximum to modern-day), which is 38.84% of total glacier volume at the LIA maximum. The greatest volume of glacier ice loss was 26.08 km^3 from the Cordillera Blanca, while the least volume loss was 2.04 km^3 from the Cordillera Chila (**figure 16**). However, the greatest percentage of volume loss was from the Cordillera Apolobamba which lost 55.54% of LIA glacier ice, while the lowest percentage of volume loss was still from the Cordillera Chila, which lost 24.23% of LIA glacier ice (**figure 17**).

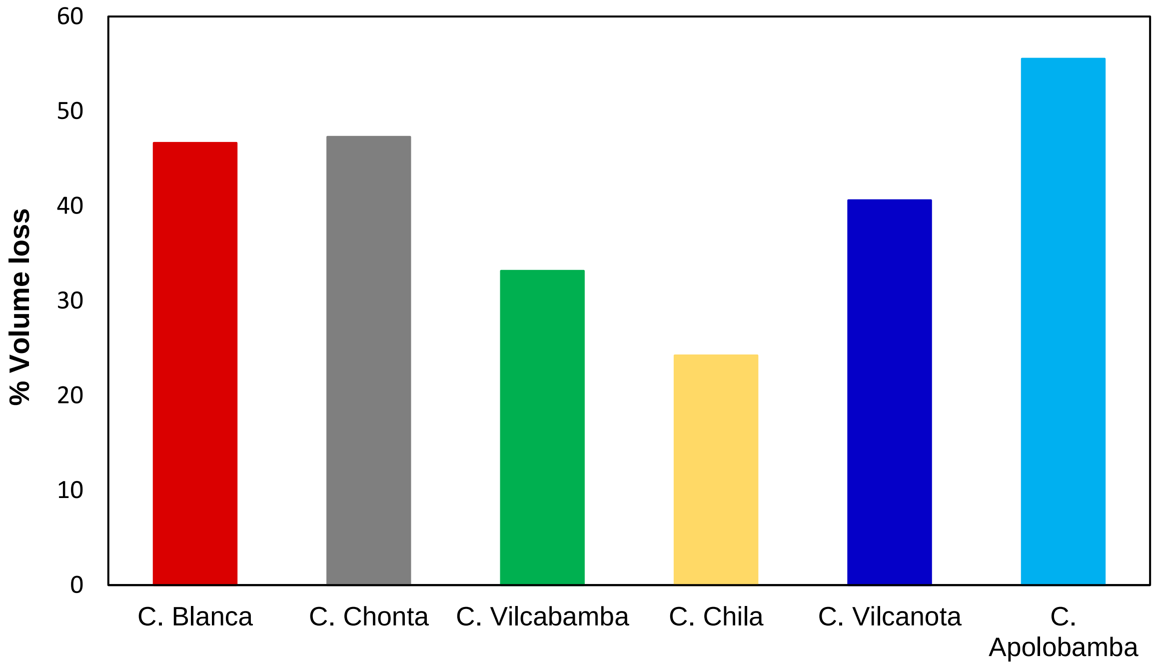

Figure 16: *Percentage glacier volume loss in each area. Calculated from LIA volume minus ablation volume.*

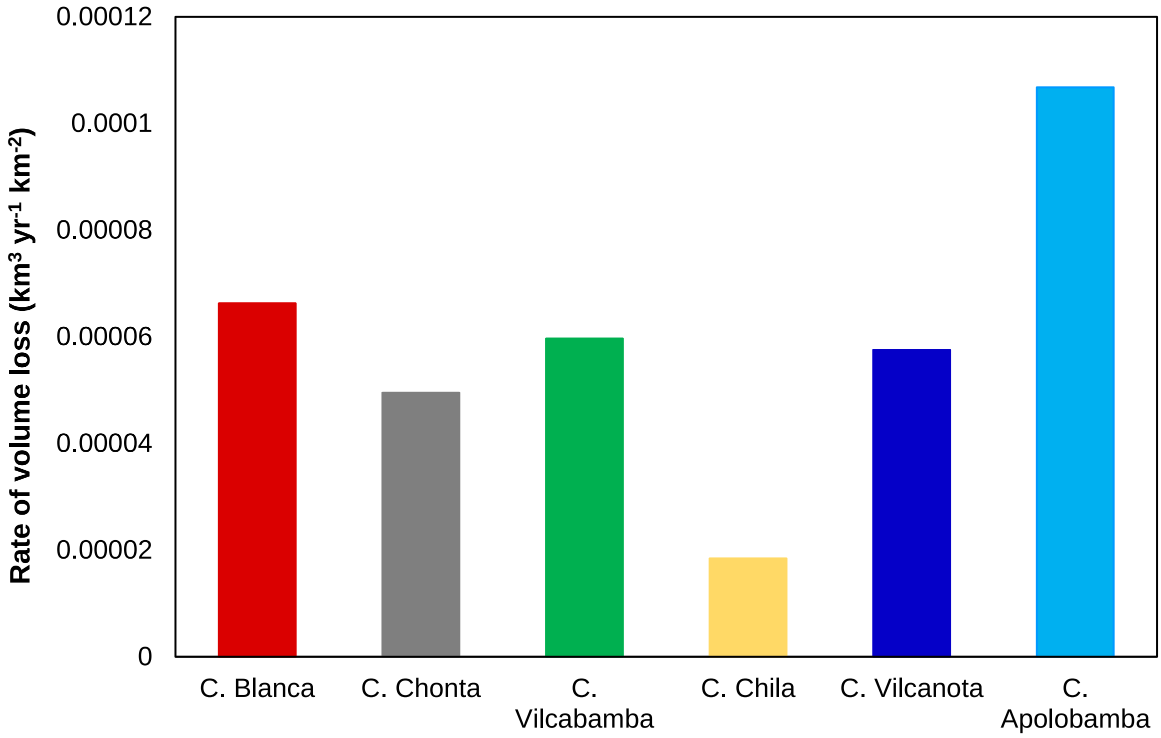

Figure 17: *Annual rate of volume loss in each area per km2.*

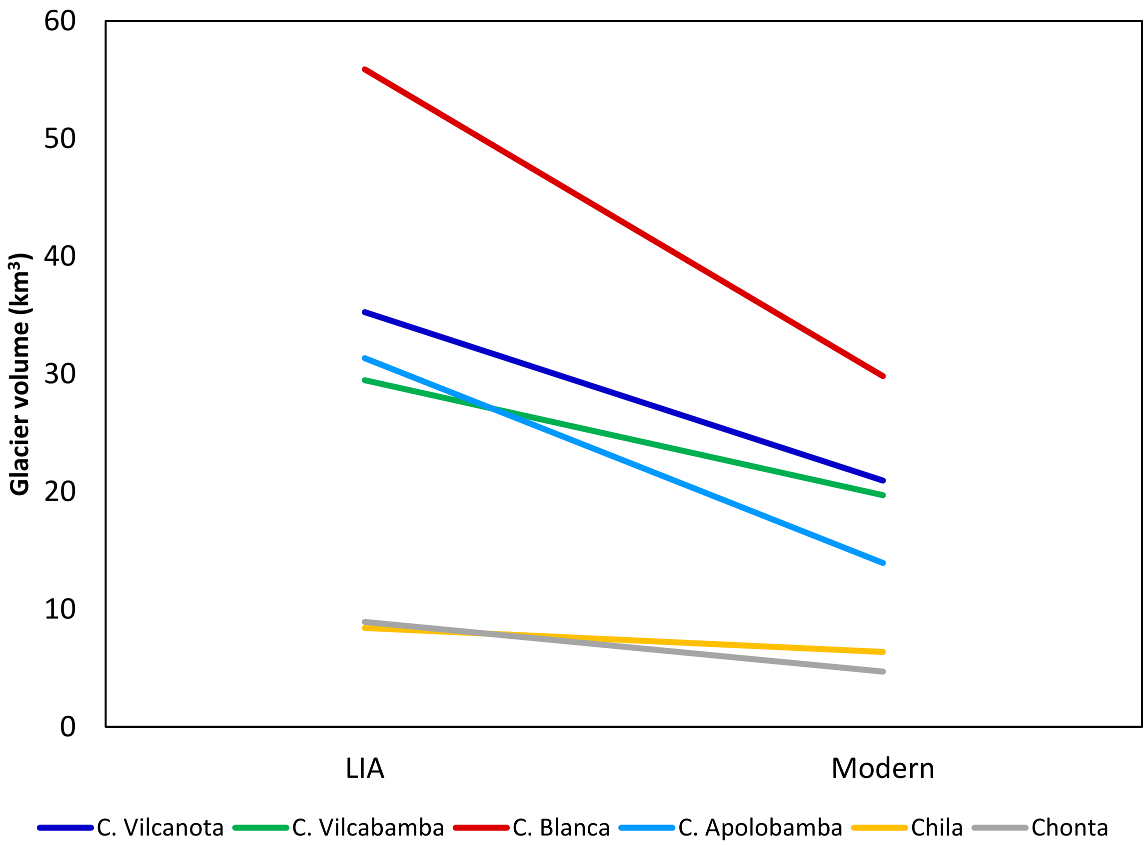

Figure 18: *Total glacier volume in each sub-region at LIA maximum (1644) and modern-day (2003).*

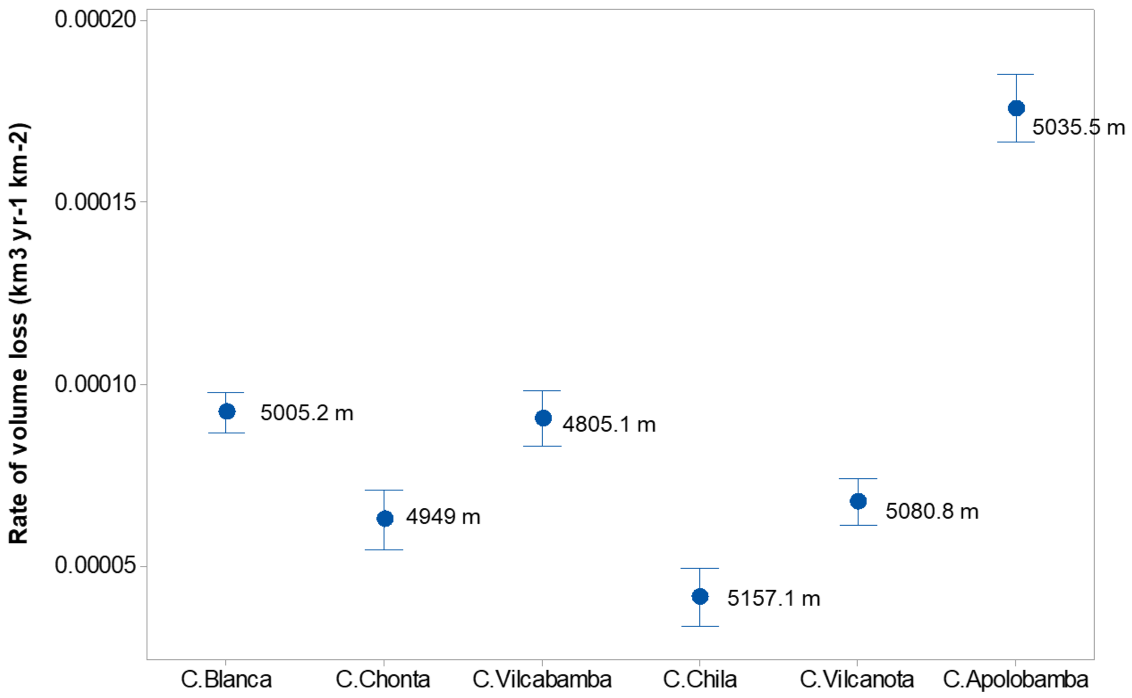

Figure 19*: ANOVA distribution of mean rate of volume loss (km3 yr-1 km-2) in each sub-region featuring ELA values on each point.*

There is some variation between modern-day glacier volumes calculated by this study and Farinotti et al. (2019) in each sub-region (**figure 20**). Smaller regions (Cordilleras Chonta and Chila) appear to have less variation between the two values, while the greatest variation is seen in Cordilleras Vilcabamba and Vilcanota.

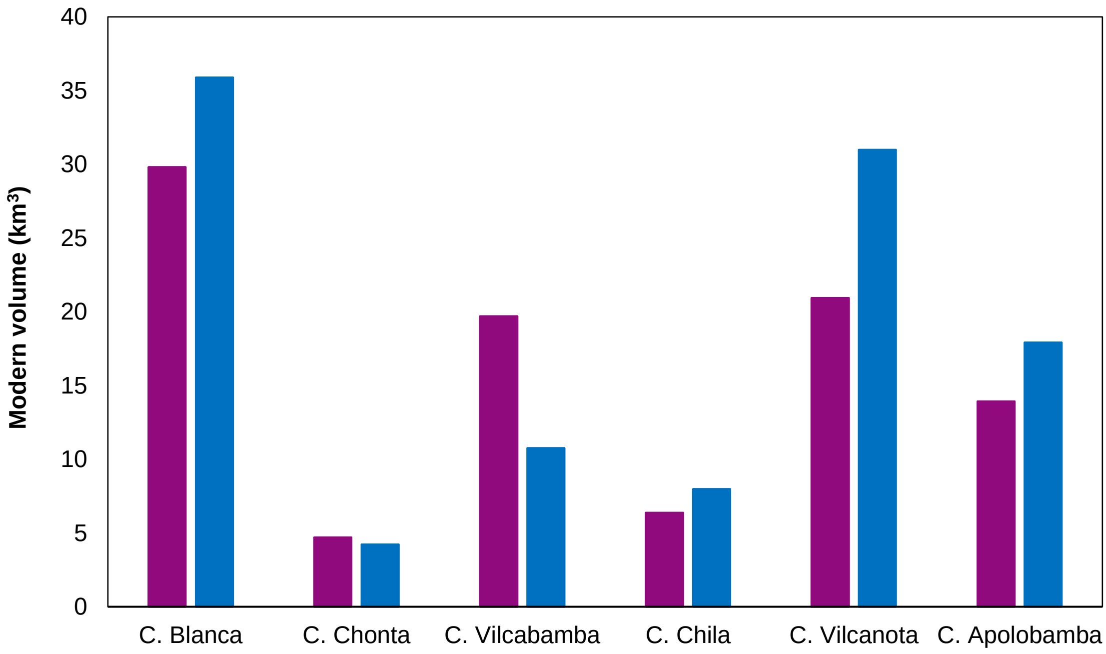

***Figure 20**: Comparison of modern volume between this study's reconstructions in purple (LIA volume minus ablation volume) and Farinotti et al. (2019) in blue.*

3.4.2 Rate of volume loss and mass balance

Due to the uncertainty in LIA dating (see section 2.4), three rates of volume loss were calculated in order to recognise a degree of error in the results, to give an average of 6.34 x 10^{-5} km^3 yr^{-1} km^{-2}, with an upper estimate of 8.28 x 10^{-5} km^3 yr^{-1} km^{-2} and a lower estimate of 5.37 x 10^{-5} km^3 yr^{-1} km^{-2}. Individual estimates for each sub-region are recorded in **table 3**. A significant difference was found between the rates of volume loss between the LIA and modern-day for each sub-region (ANOVA one-way $p < 0.05$, r^2 (adj.) = 19.18%; **figure 19**), although post-hoc testing found that there is no significant difference between Cordilleras Chonta and Vilcanota, and Cordilleras Vilcabamba and Blanca (Mann-Whitney C+V p = 0.290; V+B p = 0.349); see **table 4**. Mann-Whitney was used since all of the data was not normally distributed (Anderson-Darling $p < 0.05$).

This study found a mass balance of -0.3 ± 0.09 m w.e yr^{-1} across the whole of Peru between 1644 and 2003, using upper and lower quartiles (1579 and 1728) to estimate error (**figure 21**). This has a sea level equivalent of 0.17 mm, or 0.0005 mm yr^{-1}.

Table 3: Rate of glacier volume loss between LIA and modern-day.

	Max ($km^3\ yr^{-1}\ km^{-2}$) 1978 to 2003	**Mid ($km^3\ yr^{-1}\ km^{-2}$) 1644 to 2003**	**Min ($km^3\ yr^{-1}\ km^2$) 1579 to 2003**
Cordillera Blanca	8.65×10^{-5}	6.63×10^{-5}	5.61×10^{-5}
Cordillera Chonta	6.47×10^{-5}	4.95×10^{-5}	4.19×10^{-5}
Cordillera Vilcabamba	7.79×10^{-5}	5.97×10^{-5}	5.05×10^{-5}
Cordillera Chila	2.41×10^{-5}	1.84×10^{-5}	1.56×10^{-5}
Cordillera Vilcanota	7.51×10^{-5}	5.76×10^{-5}	4.87×10^{-5}
Cordillera Apolobamba	1.39×10^{-4}	1.07×10^{-4}	9.04×10^{-5}
PERU TOTAL	**8.28×10^{-5}**	**6.34×10^{-5}**	**5.37×10^{-5}**

Table 4: *Post-hoc Mann-Whitney U test results for difference between each sub-region.*

	C. Vilcanota	**C. Vilcabamba**	**C. Blanca**	**C. Apolobamba**	**C. Chila**	**C. Chonta**
C. Vilcanota		$P < 0.05$ significant	$P < 0.05$ significant	$P < 0.05$ significant	$P < 0.05$ significant	$P = 0.290$ not significant
C. Vilcabamba			$P = 0.349$ not significant	$P < 0.05$ significant	$P < 0.05$ significant	$P < 0.05$ significant
C. Blanca				$P < 0.05$ significant	$P < 0.05$ significant	$P < 0.05$ significant
C. Apolobamba					$P < 0.05$ significant	$P < 0.05$ significant
C. Chila						$P < 0.05$ significant
C. Chonta						

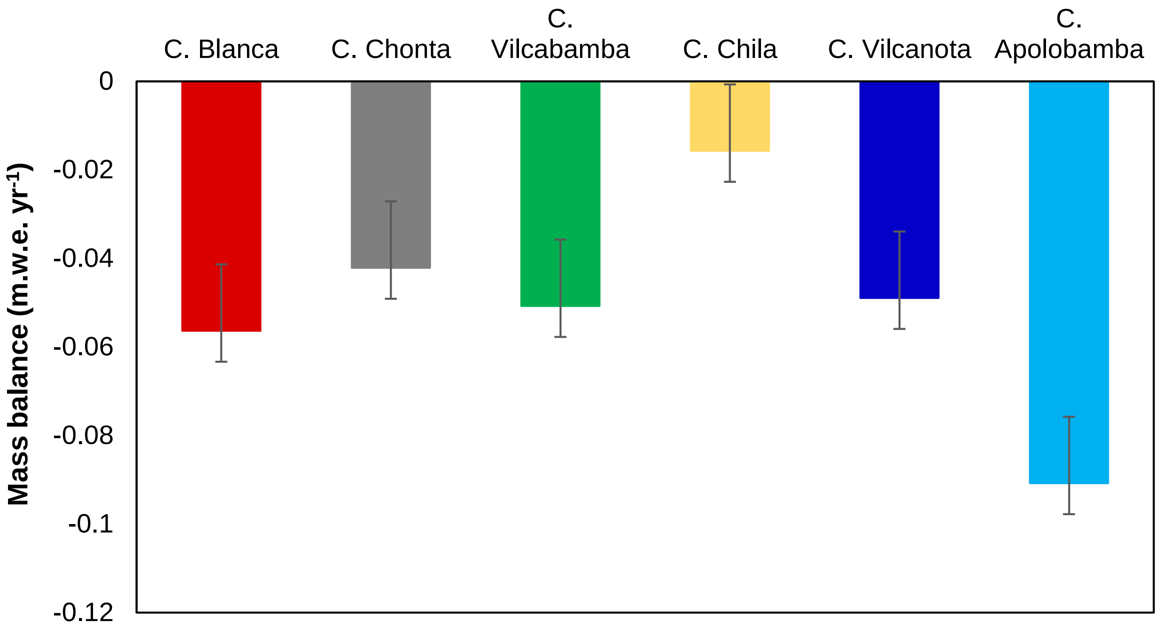

Figure 21: *Mass balance per year in each sub-region between LIA and modern-day.*

3.5 Spatial trend

This study investigated the influence of latitude, longitude, altitude, and aspect on glacier characteristics, and notes minimal relationship between them. There was no significant correlation between spatial variables and the moraine dates presented in **table 1** (Spearman's latitude p = 0.923, r^2 = 0.011; longitude p = 0.932, r^2 = 0.010; altitude p = 0.0946, r^2 = -0.008); which indicates that the timing of the LIA in Peru was not associated with spatial factors.

3.5.1 Spatial influence on rate of volume loss

There was also no significant correlation between average (mid) rate of volume loss and spatial variables (Spearman's latitude p = 0.623, r^2 = 0.257; longitude p = 0.787, r^2 = 0.143; LIA ELA p = 0.544, r^2 = -0.314) for each sub-region (**figures 22** to **24**), indicating that any difference in the rate of volume loss between sub-regions is not associated with their spatial distribution.

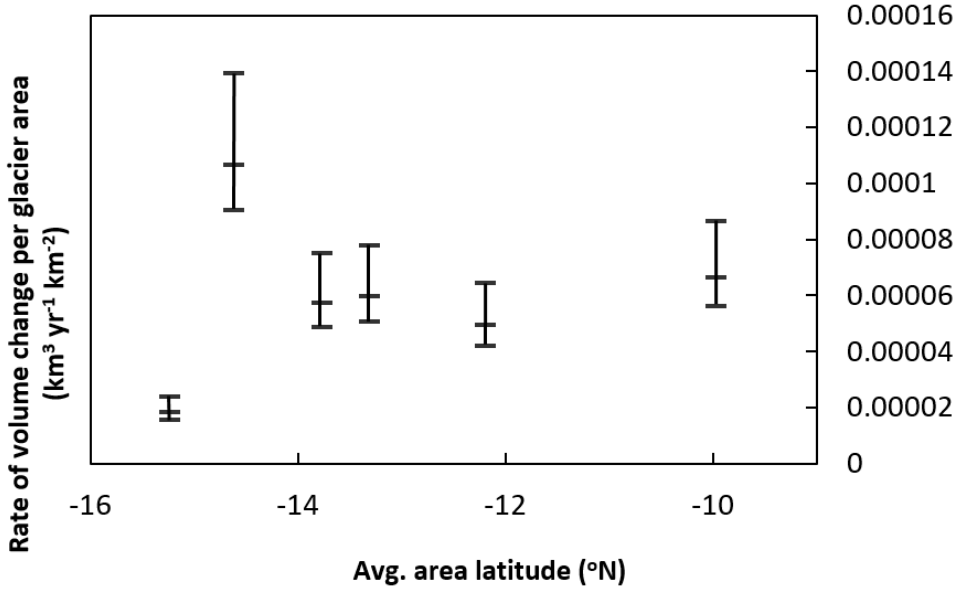

Figure 22: *Line and whisker plot of max, mid, and min rates of volume change for each sub-region plotted against latitude.*

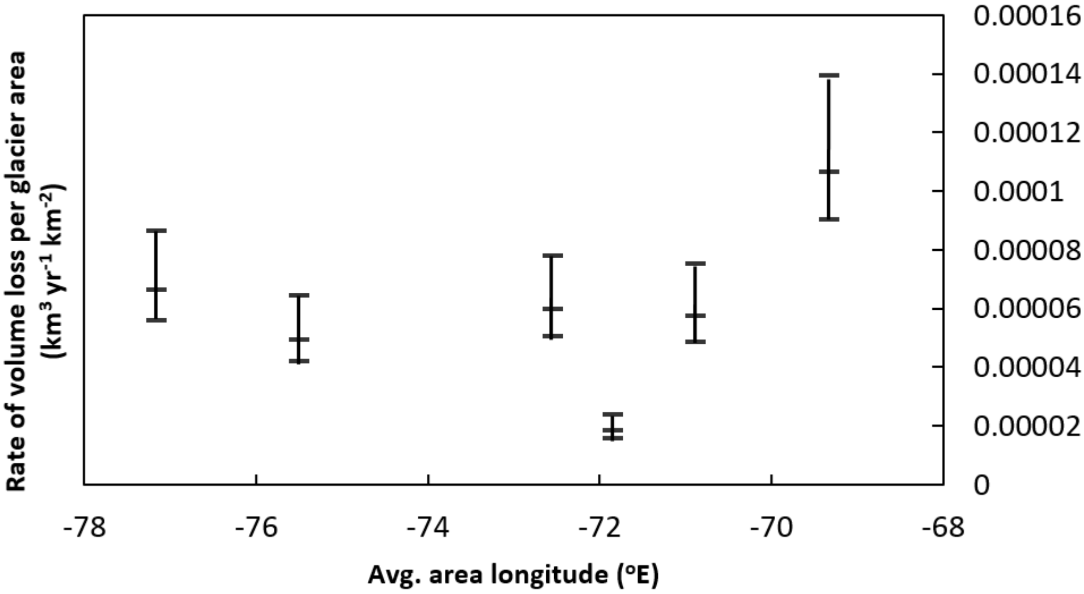

***Figure 23**: Line and whisker plot of max, mid, and min rates of volume change for each sub-region plotted against longitude.*

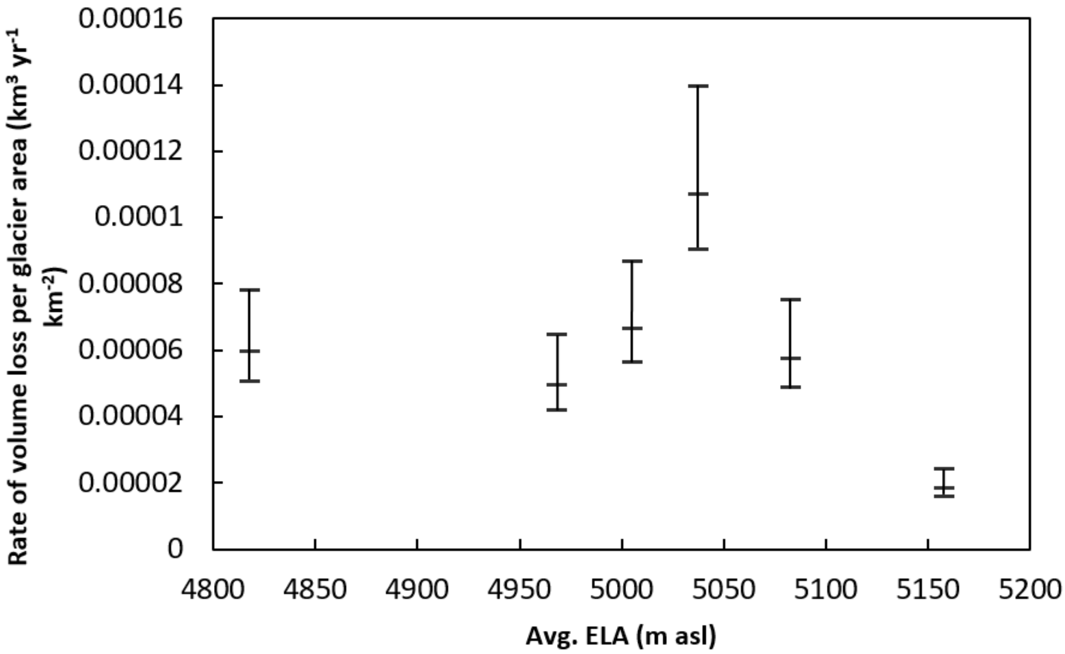

***Figure 24:** Line and whisker plot of max, mid, and min rates of volume change for each sub-region plotted against altitude (ELA).*

3.5.2 Altitude and rate of volume loss

There was, on the other hand, a significant correlation between rate of volume loss (km^3 yr^{-1} km^{-2}) and LIA ELA (Spearman's p < 0.050, r^2 -0.092) for each individual ablation area across the whole of Peru (**figure 25**), when not grouped by sub-region, where higher altitude ablation areas have a lower rate of volume change. However, on a sub-region scale, only Cordilleras Vilcanota and Chonta have a significant correlation between rate of volume loss and LIA ELA (Spearman's: Cordillera Vilcanota p < 0.050, r^2 = -0.128; Cordillera Chonta p < 0.050, r^2 = 0.143). There is no significant correlation in other sub-regions (Spearman's: Cordillera Apolobamba p = 0.437, r^2 = -0.052; Cordillera Blanca p = 0.755, r^2 = 0.012; Cordillera Chila p = 0.401, r^2 = 0.048; Cordillera Vilcabamba p = 0.572, r^2 -0.031). **Figure 25** shows the general trend across all ablation areas.

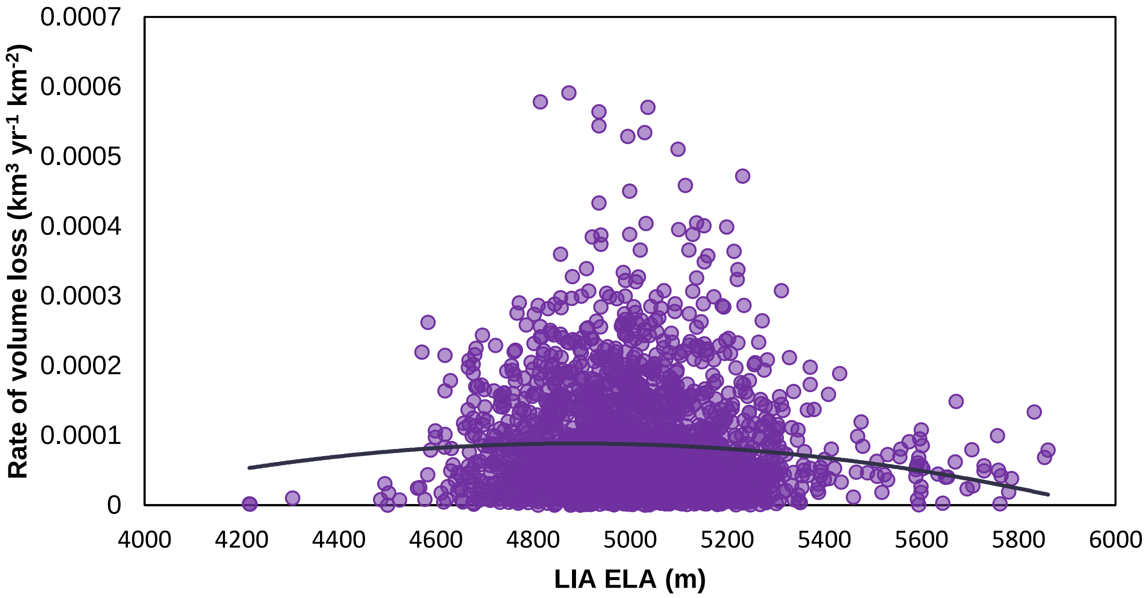

Figure 25: *Rate of volume loss per year per km2 for each ablation area across all sub-regions, against LIA ELA.*

Average sub-region ELA (mean value taken from each ablation area in each sub-region) was not significantly linked to latitude or longitude (Spearman's latitude p = 0.111, r^2 = -0.714; longitude p = 0.266, r^2 = 0.543), which indicates no spatial influence on ELA (**figure 26**). The average LIA ELA across the whole of Peru is 5012.8 m a.s.l, indicated by an orange line in **figure 26.**

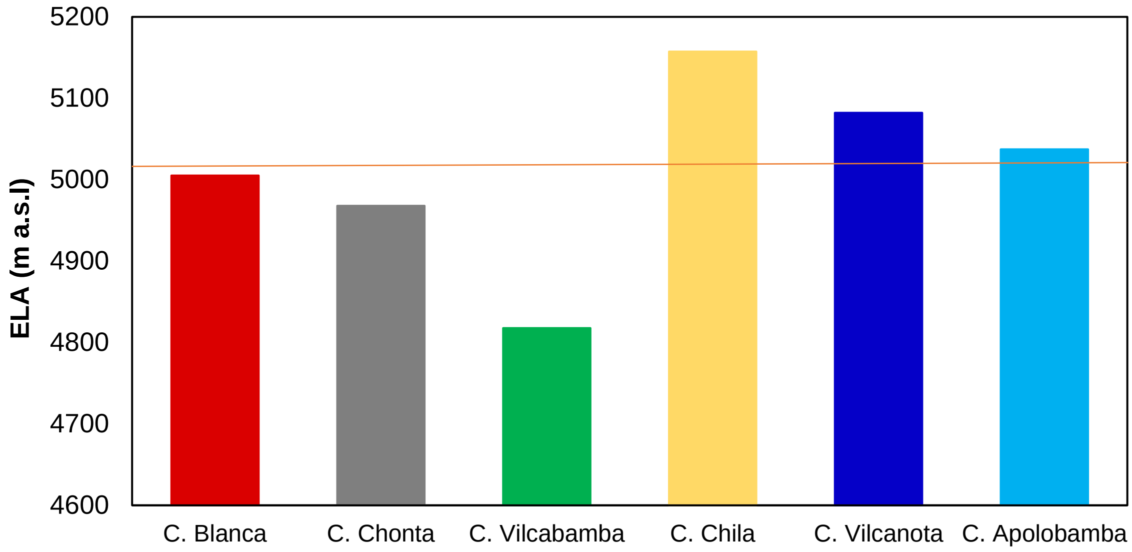

Figure 26: *LIA ELA in each sub-region (regions ordered west to east). Mean calculated from the ELAs of each ablation area. Mean LIA ELA across Peru is shown by orange line at 5012.8 m.*

3.5.3 Aspect and rate of volume loss

The majority of glacier melt in Peru between the LIA and modern-day took place on south-facing slopes, although was fairly even up to northeast and northwest-facing slopes. In contrast, north-facing slopes with bearings between 22.5 and 337.5 degrees had much lower glacier recession rates (**figure 27**).

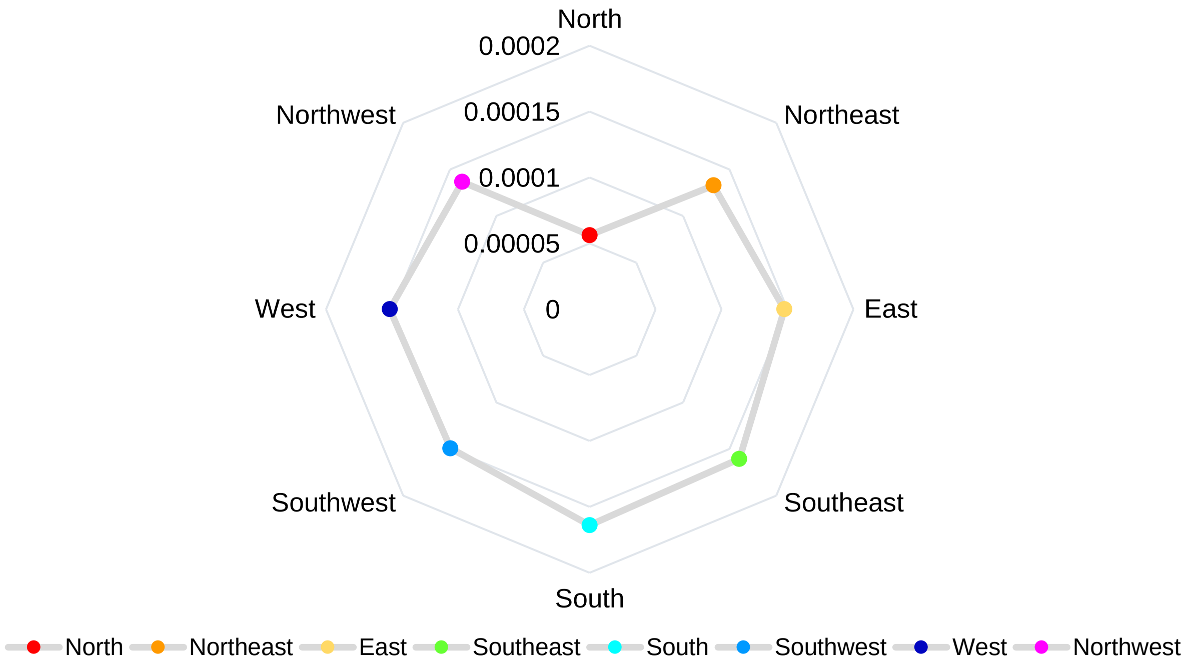

Figure 27: *Aspect distribution of rate of volume loss (km3 yr-1 km2) across all glaciers. Aspect for each ablation area found based on 10 random points in each area (see section 2.6).*

4. DISCUSSION

The main purpose of this study was to investigate changes to Peruvian glaciers since the LIA using physical evidence to reconstruct former glacier extent at the LIA maximum. The study finds a total ice loss of 73.83 km^3 from glaciers across Peru between the LIA maximum and modern-day, which equates to -0.3 ± 0.09 m w.e yr^{-1} (factoring in a LIA dating uncertainty of 1579 to 1728). While spatial influence is minimal, this study finds a weak significant correlation between rate of volume loss and ELA in each individual ablation area.

4.1 Assumptions

This study assumes that accumulation rate remains moderately stable and does not annually fluctuate, which is also assumed to be the case for future projections. In reality, accumulation rate is likely to vary in the future although the true impact of climate on glacier mass balance is difficult to model and predict (Watanabe et al., 2019) so the future changes presented here are only rough estimates. This study also assumes that the rate of glacier change is stable, which is due to the complex calculations that would be required in order to forecast an exponential increase in rate of glacier loss; analysis of which is beyond the scope of this study.

This study does, however, note the exponential trend when forecasting future glacier change (section 4.2) and recognises that future forecasts made here are only estimates.

The limited research on Peruvian glaciers makes validating results difficult, although there are some studies which cover part of the study region – such as a single Cordillera or glacier – that can be a good comparison. This study is therefore forced to make the assumption that other studies used similar delineating of Cordilleras and that original GLIMS outlines used here are accurate.

The timing of the LIA maximum is estimated based on 74 moraines from 13 past studies in Peru, a large portion of which are concentrated on a single glacier, most notably the QIC. This means the assumption has to be made that the timing of the LIA is uniform throughout Peru, since there is limited literature for the timing of the LIA in Cordilleras Vilcabamba, Apolobamba, Chila, and Chonta. It is assumed that, for all sub-regions, the LIA maximum occurred around 1644 and glaciers receded from that point onwards. In reality, the timing may have differed between sub-regions as aforementioned due to the later moraine dates in Cordillera Vilcabamba, however not enough evidence is available to confidently confirm that this was the case. The overall affect that this could have had on this study's results is deemed to be minimal, although may introduce some inaccuracies in rate of change calculations.

The QIC is arguably the most analysed glacier in Peru and there is therefore a vast amount of comparable data available for it, which allows validation of this study's results as well as an analysis of the reliability of the literature. Jezek and Thompson (1982) reported a maximum thickness of 165 ± 20 m in 1979/80 for the QIC, which corresponds well with Farinotti et al. (2019)'s maximum modern ice thickness of 170 m and this study's thickness of 163 m at the same point on the QIC. This study also finds that the area of QIC decreases from 74.9 km^2 in ~1644 to 51.9 km^2 in 2003. Multiple other studies provide a modern value of between 42.8 and 58.9 km^2 (Albert, 2002; Salzmann et al., 2013; Hanshaw and Bookhagen, 2014; Yarleque et al., 2018), which gives us a high degree of confidence in the secondary data used in this study from Farinotti et al. (2019). A comparison of the LIA QIC area would be incredibly beneficial, however no exact value could be found in the literature due to such limited research on this topic. The uncertainty digitisations by other experts in the field (section 2.4) are therefore valuable data to use for comparison, who calculated LIA QIC area as 69 and 67.4 km^2 respectively. While these values are lower than this study's 74.9 km^2, they are close enough to be confident that this study's area calculations are accurate, if not moderately overestimated.

4.2 Glacier change

4.2.1 Area change

Most studies focus on reporting glacier area rather than volume, so a broad comparison of the area change results of this study is possible with the literature. Studies of area change in the literature use differing time periods so, in order to make a more reliable comparison, area loss per year was calculated from this study's results and the literature. The literature features different sized glaciers across different areas of Peru but will be analysed together here as percentage glacier loss.

As expected, this study's long-term value for area change worked out at a very low 0.13% area loss per year. Other studies which used time periods between the 1960s and 80s to the 2000s obtained low, although comparatively higher, values of 0.68% between 1970 and 2003 (Racoviteanu et al., 2008); 0.75% between 1962 and 2006 (Salzmann et al., 2012); 1.11% between 1962 and 2008 (Huh et al., 2017), and 1.09% between 1987 and 2010 (Burns and Nolin, 2014). Finally, Seehaus et al. (2019) calculated a larger 1.81% area loss in eastern Peru between 2000 and 2016 by using a similar mapping technique to the one used in this study. This shows a clear increase in the rate of glacier area loss across Peru since the LIA, supporting the widely accepted trend that glacier melt rate in Peru is increasing over time.

The studies referred to above are difficult to compare due to studying regions of differing size and location in Peru. For example, Huh et al. (2017) only measured the glacier change of six glaciers in the Cordillera Blanca and reported individual glacier area losses between 30.6% and 72.6%. However, this study uses the average area loss of all glaciers (50.9%) and assumes that there is no spatial difference between glacier melt rates, since this study finds no significant spatial differences in glacier change across Peru (section 3.5). This limits confidence in any comparisons drawn between the studies, although the sparse availability of research on Peruvian glaciers means this comparison is necessary.

4.2.2 Volume loss in Peru

The aspect distribution of volume loss between the LIA and modern-day is unexpected as the majority of glacier melt in the Southern Hemisphere would be expected on north-facing slopes, however the findings of this study show that north-facing slopes have seen the lowest rates of glacier recession. This study proposes that the majority of glacier ice is likely situated on colder south-facing slopes where accumulation is greatest which explains the higher rate of volume loss on south-facing slopes.

This study calculated a 0.04 $km^3\ yr^{-1} \pm 0.01$ glacier loss from the Cordillera Vilcanota spread over 359 years, while Salzmann et al. (2012) calculated a much greater volume loss across the same sub-region of 0.18 $km^3\ yr^{-1}$ over the most recent 44 years. This is a sound study to compare with since Salzmann et al. (2012) acknowledged the scarcity of data in the Cordillera Vilcanota by using a multitude of sources and methods, making their conclusions highly reliable. The results of this study show a total glacier volume loss of 40.6% in the Cordillera Vilcanota between the LIA and modern-day, which corresponds well with Salzmann et al. (2012) who found a volume loss of 41.6% from the same region between 1962 and 2006.

While it would be sensible to expect a higher percentage change in volume over the longer period of time investigated in this study, substantial research suggests the majority of warming has occurred since approximately 1950 due to anthropogenic factors (Ribes et al., 2016; IPCC, 2021) which justifies the similarities between values. An increase in Peruvian glacier melt rate has been widely noted in the literature (for example Burns and Nolin, 2014; Huh et al., 2017; Mark et al., 2017) and is backed up by an abundance of high confidence international data (for example Vaughan et al., 2013; Lutz et al., 2014; Carrivick et al., 2020). Glasser et al. (2011) studied glacier change in southern Patagonia since the LIA and found that sea level contribution is increasing; from ~0.0034 mm yr^{-1} since 1650 to ~0.0050 mm yr^{-1} since 1750. This is higher than this study's value of 0.0005 mm yr^{-1}, likely due to climatic differences between Peru and south Patagonia, although can help to deepen understanding of glacier changes in Peru. For example, based on the rate of change in south Patagonia it could be expected that sea level contribution from Peruvian glaciers increased to ~0.0007 mm yr^{-1} between 1750 and modern-day.

4.2.3 Spatial variation between glaciers

Some studies have noted a spatial influence in glacier change, such as Burns and Nolin (2014) who found that more southerly glaciers in the Cordillera Blanca are losing area at a higher rate than glaciers in the north. Here, this study only analysed spatial influence across sub-regions as a whole, rather than within each sub-region, which presents scope for future analysis in this field. This study did, however, identify a significant correlation between ELA and glacier volume loss for each glacier across the whole of Peru, which is also noted by Burns and Nolin (2014) although they focussed only on the Cordillera Blanca.

Figures 17 and **19** show that Cordillera Apolobamba lost a much greater volume of glacier ice per year per km^2 than the other sub-regions. Post-hoc Mann Whitney U testing (**table 4**) confirms that there is a significant difference in the rate of volume change between Cordillera Apolobamba and all other sub-regions (Mann Whitney $p < 0.05$). However, this does not seem to be linked to any spatial trends, as the high rate of change is distinctively anomalous from the other values, and the LIA ELA of the area sits around the middle compared to the other sub-regions.

However, at the LIA peak, glaciers in the Cordillera Apolobamba were the largest on average of all the Cordilleras in this study, with an average glacier size of 3.3 km^2 compared to the others averaging between 0.8 and 2.3 km^2. It would be sensible to assume that larger glaciers, such as those in the Cordillera Apolobamba, have a larger proportion of mass situated below the ELA and subsequently more susceptible to greater melt. Those sub-regions with the smallest LIA glaciers are Cordilleras Chila and Chonta (average LIA glacier areas of 1.4 and 0.8 km^2 respectively), which also have the lowest rates of volume loss (**figures 17 and 19**) and lost the smallest percentage of LIA glacier extents (**figure 16**) compared to other sub-regions. This supports the argument that the size of glaciers affect the rate of volume loss between sub-regions, although there is still no spatial gradient identified by this study to explain this.

Continentality has often been cited as an important control on glacier dynamics, with maritime glaciers having steeper mass balance gradients and therefore much greater sensitivity to small climatic changes. In contrast, more continental (inland) glaciers have much lower mass balance gradients and consequently greater stability (Munro, 1991). This study, however, finds no significant relationship between spatial variables (latitude and longitude), and conducted a separate test for difference between rate of volume loss in maritime sub-regions (Cordilleras Blanca, Chila, and Chonta) and continental sub-regions (Cordilleras Vilcanota, Vilcabamba, and Apolobamba) which found no significant difference (Mann Whitney $p = 0.383$; 91.91%).

A potential explanation for this is that all of the glaciers studied here could be considered maritime, since they are all located along the same Andean mountain range which spans the western coast of South America. There is very little distinction between continental and maritime glaciers in Peru (**figure 1** for glacier distribution) and therefore any differences may not be very pronounced. Future work may look at this potential control in some detail, by aggregating the data within each region according to their distance to the coast. Previous studies have found that in some cases maritime glaciers are less sensitive to climatic changes than their continental counterparts; for example, Anderson and Mackintosh (2012) found that certain glaciers in central New Zealand are significantly more sensitive to changes in temperature than those located on the west coast. Florentine et al. (2018) also concluded that local topographic controls are becoming a more dominant influence on glacier mass balance over regional climate changes.

This study finds a significant negative correlation between the rate of volume loss and the maximum altitude of each ablation area, which is also the ELA, although this trend does not appear very pronounced in **figure 25**. This relationship, in which ablation areas at higher altitudes closer to the ELA have a less negative mass balance, is expected based on the literature (Rabatel et al., 2013; Burns and Nolin, 2014; Veettil, 2018; Seehaus et al., 2019; Clark and Barrand, 2020). A useful factor to analyse here which could improve these results would be to investigate the gradient of each ablation area to note any volume change differences with altitudinal distance from the ELA.

In **figure 25** the negative correlation between LIA ELA and rate of volume loss (Spearman's $p < 0.050$, r^2 -0.092) appears incredibly faint, which is reflected in the low r^2 value of -0.092. The data presented in **figure 25** shows a clustering of high rates of volume loss around the average LIA ELA around the 5000 m point, where those glaciers with the highest rates of volume loss are also clustered around the middle. **Figure 19** suggests that one sub-region in particular, Cordillera Apolobamba, has the highest rate of volume loss of the other sub-regions despite an average LIA ELA of 2035 m, which sits around the middle of the other averages. This questions the reliability of the statistical analysis here, and suggests that there is in fact limited evidence to suggest altitude has an influence on rate of glacier volume loss.

4.2.4 Glacier mass balance

Mass balance is universally used to measure the difference between glacier accumulation and ablation, and can be used to compare different glaciers. This study finds a mass balance across the whole of Peru of -0.3 ± 0.09 m w.e yr^{-1} between the LIA maximum and modern-day, however no studies have thus far published data that would allow direct comparison with this value. Some studies have addressed individual sub-regions over more recent time periods which can be used as a rough comparison to the results of this study on a sub-region scale, although the large differences in time period make drawing reliable comparisons challenging. A few studies also investigate just one glacier in a sub-region, commonly the Cordillera Blanca, making them non-comparable with the results of this study (Gurgiser et al., 2013; Maussion et al., 2015; Gacha and Koch, 2021).

Numerous studies have investigated mass balance in the Cordillera Blanca since the 1970s, including Clark and Barrand (2020) who reported mass balance of -0.45 ± 0.08 m w.e yr^{-1} (1972 to 2018), Kaser et al. (2003) with -0.5 m w.e yr^{-1} (1972 to 1986), and Seehaus et al. (2019) with -0.21 ± 0.11 m w.e yr^{-1} (2000 to 2016). These values are substantially greater than this study's value for the same sub-region of -0.06 ± 0.01 m w.e yr^{-1}, although considers the recent increase in glacier ablation since this study's value is an average over a considerably greater time period. This same trend is observed in New Zealand by Carrivick et al. (2020) although to a lesser extent. Studies also note high inter-annual variability in tropical glacier mass balance which is more profound at lower elevations (Gurgiser et al., 2013; Clark and Barrand, 2020) which may affect reliability of comparisons with studies over shorter time periods such as Seehaus et al. (2019; see above).

4.3 Future glacier change in Peru

Assuming that the rate of glacier change has remained stable since 1644, and continues to remain the same, this study's data projects that no glacier ice in Peru would be expected by 2826 (based on volume) or 2444 (based on area). However, in order to estimate glacier change in the future, the recent significant increase in melt rate of approximately 9 times (using the average percentage from Racoviteanu et al., 2008; Salzmann et al., 2012; Burns and Nolin, 2014; Huh et al., 2017; and Seehaus et al., 2019) must be considered. Assuming ablation is henceforth 9 times that of this study period (1644 to 2003) and that accumulation rate is stable, an expiration of glacier ice in Peru would be expected by 2094 (91 years from 2003; based on volume) or 2052 (49 years from 2003; based on area).

It is important to note that this is a coarse estimate based on changes that have been recorded in the past, and the reality is likely to be much shorter assuming anthropogenic surface warming continues to increase. The estimate presented here best reflects the IPCC RCP 2.6 (low emissions) scenario where warming is "weak and of little significance" (Collins et al., 2013). However, global surface warming is more likely to fit RCPs 4.5 and 6.0, in the range of 1.5 to 2^{o}C higher than 1986 to 2005 levels (IPCC, 2021), and therefore no ice could be expected in Peru much sooner than this study projects.

A shorter-term study was carried out elsewhere on tropical glaciers on Mount Kilimanjaro which found that this ice mass should be non-existent by 2060 (Cullen et al., 2013), which sits on the lower end of this study's estimate but therefore strongly supports the continuous exponential increase in melt rate.

The estimates also do not consider the hypsometry of glaciers, for example the aforementioned plateau in gradient of many Peruvian glaciers such as the QIC. This means that once the ELA reaches the ice cap plateau of a glacier, the entire glacier will be subject to much more rapid ablation than previously, and so the final stages of glacier melt could be much more accelerated. While it would be beyond the scope of this study to accurately include this trend in future estimates, it would be valuable to note for studies that wish to model the future of Peruvian glaciers in more detail.

A more in-depth analysis of past and future Peruvian climate in line with IPCC projections would be beneficial to verify the estimate offered here and to make more reliable projections for the future of glaciers in Peru. Existing research suggests that, under RCP 8.5 (worst-case scenario), the ELA will be above the QIC summit by 2055 and the entire glacier will therefore be subject to ablation (Yarleque et al., 2018). This is supported by Zemp et al. (2019) who project that mountain glaciers in sparsely glacierised regions of the world, such as Peru, will have completely melted by 2100. This suggests that this study's estimate of complete ice loss occurring between 2052 and 2094 could be valid.

4.4 Wider application

A comprehensive study by Hugonnet et al. (2021) investigated the recent mass balance of glaciers across the world in which the authors project that few of the world's glaciers will remain after 2050. In contrast, multiple studies suggest some larger glaciers will persist into the next century (Kraaijenbrink et al., 2018; Bosson et al., 2019; Rowan et al., 2020). The data published by Hugonnet et al. (2021) suggests that Peru's glaciers are losing mass at a much slower rate than elsewhere around the world, with glaciers in Alaska and Canada among the fastest receding glaciers. So, while comparing Peruvian glaciers with research elsewhere is a useful large-scale comparison to see how global glaciers compare, it is difficult to use this to validate this study's results due to differences in climate, topography, and feedback, among other factors. Hugonnet et al. (2021) also applied the same method across all glacierised regions of the world which may have involved generalisations as a result of such large-scale mapping, for example the inaccuracies identified by this study in the Cordillera Vilcabamba (section 4.2.2) may have been missed by the researchers.

A comparison of the findings presented in this study with other studies is, however, incredibly valuable for predicting a future increase in downstream meltwater input, which could become more inconsistent as glacier recession progresses (Mark and Seltzer, 2003). This carries the potential to overwhelm downstream water systems in high-melt seasons (Mark and Seltzer, 2003) and have reduced discharge in the dry season (Barnett et al., 2015), and provide a less stable input to hydropower stations resulting in possible power outages.

Glacier recession is already having dramatic impacts on the lives of locals in Peru (Bury et al., 2011), particularly those who rely on agriculture, and communities already fear for the livelihoods of themselves and their families (Bury et al., 2011). By comparing the rates of glacier change from this study with more recent studies, there is clear trend of enhanced glacier recession which is highly likely to persevere in future, causing an escalation in the threat to local communities. It is therefore recommended that protective measures are implemented for these Peruvian communities whose livelihoods are threatened due to glacier recession. This study offers insight into the location of glaciers that have been receding the most in the past, which could perhaps be combined with climate data in order to identify those glaciers at greatest threat of short-term expiration.

5. CONCLUSIONS

This study determines and analyses glacier changes across Peru between the LIA and modern-day (~1644 to 2003). This includes a total surface area loss of 1456.7 km^2 (44.9%) and ice volume loss of 73.8 km^3 (38.8%). This study also finds a volume loss rate of 6.34 x 10^{-5} km^3 yr^{-1} km^{-2} and mass balance of -0.3 ± 0.09 m w.e. yr^{-1}. To put this into context this equates to a sea level rise of 0.17 mm, or 0.0005 mm yr^{-1}. While there is limited spatial trend associated with these results, this study does find a significant difference between the rates of volume loss between each sub-region, although this cannot be linked to latitude or longitude. There is also significant correlation between the rate of volume loss per km^2 and ELA for each ablation area across Peru in which higher altitude ablation areas have a lower rate of volume loss, as expected.

The results from this study fit well with modern, shorter-term studies to reflect the expected anthropogenic climate warming and subsequent increased glacier recession. For example, this study finds a total glacier volume loss from the Cordillera Vilcanota of 40.6% in the 359 years between the LIA and modern-day, while Salzmann et al. (2012) reported a loss of 41.6% over 44 years between 1962 and 2006. The same increase in glacier recession since the LIA has been identified across the globe, for example Glasser et al. (2011) in south Patagonia and Carrivick et al. (2020) in New Zealand, which supports comparisons of this study's results with more recent literature. This study is, however, decidedly limited by a lack of Peru-based LIA literature to further validate results.

This study has presented estimates for how Peru could be entirely ice-free in the next 49 to 91 years in response to the observed trend of increased glacier melt. This demonstrates the impact that anthropogenic climate change could have on glaciers in Peru, and yields potential for future studies to build on these results and predict more precise future changes. This study has provided a record of past glacier change over a multi-centennial time period which gives a base understanding of controls on glacier change to use for future projections.

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