Journal of South American Earth Sciences 122 (2023) 104173

Contents lists available at ScienceDirect

Journal of South American Earth Sciences

journal homepage: www.elsevier.com/locate/jsames

(Paleo)glacier studies in Patagonia over the past decades (1976–2020): A bibliometric perspective based on the Web of Science

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ARTICLE INFO

Keywords:
Last glacial maximum
Last glacial termination
Holocene
20th century
Patagonia
Glaciers

ABSTRACT

Patagonia features the most extensive glaciers of the Southern Hemisphere, excluding Antarctica, and a vast inventory of glacial landforms, so it is thought to have played a key role in (paleo)glacier studies since the late 19th century. However, no systematic attempts to characterize the specific research trends and the scientific community focused on Patagonian cryosphere have been conducted so far. To fill this gap, we analyzed the metadata associated to 305 articles compiled from the Web of Science database following a bibliometric approach covering the period between 1976 and 2020. Our results point to an irregular but net increase on the number of contributions on Patagonian (paleo)glaciers. Mass balance analyses based on satellite data of present-day glaciers and the reconstruction of past glacier activity by dating glacial landforms formed during the Last Glacial Termination, were the most addressed topics during the analyzed period. Patagonian (paleo)glacier studies are mostly published in generic Earth Sciences publications, followed by Quaternary and glaciological journals. Most of the studies were led by scientists from the United Kingdom, followed by Chile, Argentina and United States. In terms of collaborations, these studies can be divided into two main clusters, one composed by researchers from United States, Chile and Argentina institutions, and another mostly composed by British researchers. So far, the most prolific authors are nearly equally distributed in nationality, yet gender inclusion and international collaborations are still caveats that must be solved. Even though our query on the Web of Science missed highly influential (so-called) grey literature, such as local scientific journals and technical reports, the reviewed scientific literature unambiguously indicates that Patagonia is a privileged location for (paleo)glaciers studies worldwide and that it will continue offering vast opportunities to tackle critical questions related to global cryosphere and past-to-present climate changes.

1. Introduction

Mountain glaciers are shrinking rapidly in response to the ongoing climate change (Hock et al., 2019). The demise of the planetary cryosphere will lead to profound socioeconomic, environmental and scientific impacts including the decrease of global freshwater for human consumption, food and energy production (Carey et al., 2017; Taillant, 2015), the disappearance of coastal ecosystems and heavily-populated urban areas caused by sea-level rise (Frederikse et al., 2020; Hauer et al., 2020), the increase of the social exposure to glacial-derived hazards (e.g., glacial lake outburst floods; Clague et al., 2012; Ding et al., 2021) and, finally, the loss of the valuable scientific data potentially provided by ice cores and other geological records that can be used as test beds for predictive models (Tierney et al., 2020).

Patagonia and Tierra del Fuego, is the region that extends to the southernmost tip of South America, encompassing Chile and Argentina from ∼40° to ∼56° S (Coronato et al., 2008) (Fig. 1). Patagonia includes the Southern Andes, which defines a narrow western flank featuring numerous islands and fjords opened to the Pacific Ocean and an eastern slope characterized by extensive steppes, locally known as pampas, towards the Atlantic Ocean. The regional climate is directly influenced by the Southern Westerly Winds which in its interaction with the Andes generate a strong moisture gradient resulting in hydroclimate conditions that ranges from hyper-humid to the west of the divide and semi-arid to

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https://doi.org/10.1016/j.jsames.2022.104173
Received 6 September 2022; Received in revised form 19 December 2022; Accepted 20 December 2022
Available online 27 December 2022

the east (Garreaud et al., 2013).

Since the pioneering works of 19th century European naturalists (e. g., Darwin, 1846; Nordenskjöld, 1899), Patagonia has received much attention in terms of glacier-related research because it contains around 20,000 mountain glaciers, nearly accounting for the ~80% of the South American ice bodies (Pfeffer et al., 2014; Barcaza et al., 2017). Among them, the Northern and Southern Patagonian icefields constitute the most extensive ice masses of the Southern Hemisphere outside Antarctica, covering approximately 15,000 km^2 (Millan et al., 2019; Mouginot and Rignot, 2015). In addition to the present-day glaciers, the Patagonian landscape also exhibits some of the oldest and best-preserved glacial geomorphological features of the Southern Hemisphere, spanning the Quaternary glaciations and beyond (Rabassa and Coronato, 2009).

The current knowledge about the Patagonian cryosphere, including glacial geologic records, has been summarized within traditional synthesis of up-to-date (at the time) papers, which mostly compiled available data regarding ice dynamics, mass balance estimations, landform inventories and chronological data (e.g., Davies et al., 2020; Masiokas et al., 2020). However, despite decades of scientific efforts in Patagonia,

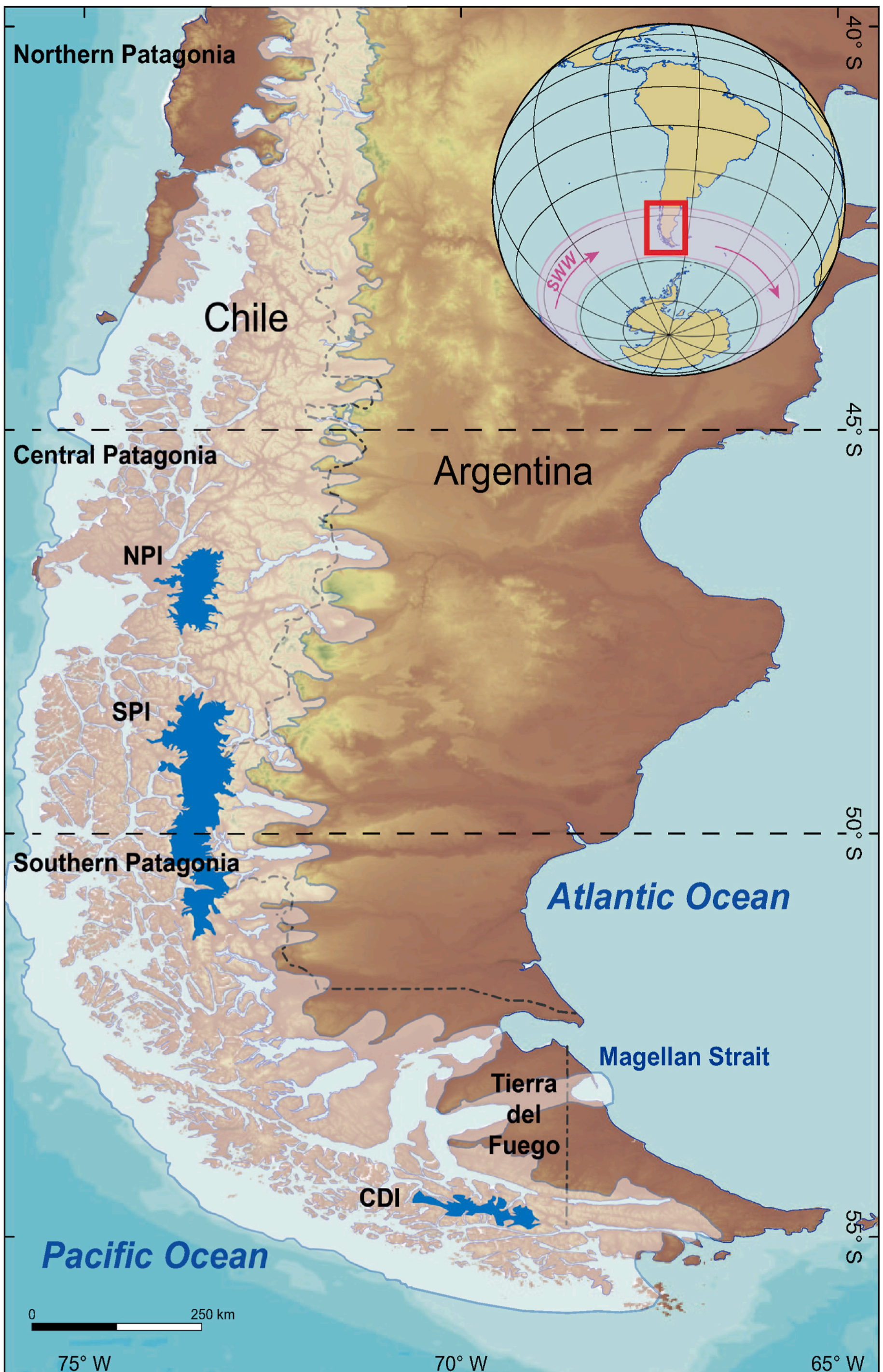

Fig. 1. Regional map of Patagonia showing the informal division of the region. NPI: Northern Patagonia Icefield. SPI: Southern Patagonian Icefield. CDI: Cordillera Darwin Icefield. White polygon: geomorphic-based reconstruction of the Patagonian Ice Sheet 35,000 years ago (Davies et al., 2020).

the understanding of the evolution of the (paleo)glaciological research, including how disciplines have changed or developed in time, and the characteristics of the scholar community involved have remained elusive. This circumstance obscures potential insights regarding past evolution of the scientific topic that might shed light into future research trends.

Bibliometrics constitute a powerful tool to assess the state of the art of a given scientific topic using publications as proxy (Ellegaard and Wallin, 2015). For example, by analyzing literature metadata, such as authors, journals, countries and institutions it is possible to address quantitatively the evolution of the subject of interest. Furthermore, titles, abstracts and keywords accompanying publications allow to recognize qualitatively past trends and to infer future directions in research. The bibliometric approach has been successfully applied to various disciplines linked to glaciers, including climate change (e.g., Haunschild et al., 2016; Li et al., 2011), Antarctic glaciers (e.g., Liang et al., 2018) and glacial hazards (e.g., Emmer, 2018), as well as other geological topics (e.g., Niu et al., 2014; Silva et al., 2022). Therefore, in order to explore spatially and temporally the nature and evolution of the key topics in the scientific literature focused on (paleo)glaciers in Patagonia in past decades, as well as the characteristics of the related scientific community, we introduce a comprehensive bibliometric analysis based on specialized software in tandem with individually-checked articles retrieved from the Web of Science (WOS) database. We aim to provide a comprehensive overview on Patagonian (paleo)glaciers studies that will help to identify potential gaps on our knowledge and weaknesses of our scientific community to further encourage research projects focused on the cryosphere of the southern tip of South America.

2. Data and methodology

This study does not intend to be a traditional up-to-date review of the Patagonian (paleo)glacier literature. Instead, our analysis builds upon both quantitative and qualitative metadata associated to scientific publications that were obtained from the Science Citation Index Expanded of the WOS. The query was conducted in the advanced search mode of the database by introducing previously selected keywords linked to glacial activity in Patagonia in combination with theme and title operators (i.e., TS and TI, respectively) joined by the boolean arguments "AND" and "OR" (Table 1). We performed several search iterations spanning the period 1900–2020 during 2021 to retrieve the maximum number of publications for bibliometric analysis and to cover all the terminological variability commonly associated with glacier-related studies. Subsequently, all WOS-listed contributions were checked individually to exclude the non-related scientific literature.

We analyze the information related to i) journals; ii) countries; iii) institutions; iv) authors and both iv) author keywords (AK) and v) WOS keyword plus (KP). AK are specific terms provided by the original authors to highlight the main topics of their research, whereas KP are automatically generated by WOS algorithms considering the titles of the cited references of a given article (Zhang et al., 2016). Metadata from WOS-indexed articles were later exported to the SciMAT environment for data repairs (e.g., unify authors affiliations) and basic statistical analysis (Cobo et al., 2012).

Table 1
Keyword used on the WOS query.

Operator	Location	Boolean	Topic
TS =	"South* America"	AND	Glaci*
TI =	Patagonia	OR	Glaci* Chronolog*
			Glaci* Fluctuation*
			Glaci* History
			Glaci* Advance*
			Glaci* Activity
			Glaci* Variation*

To understand better the development of research foci and methodologies on WOS-indexed publications, we first performed a word cluster analysis (WCA) to avoid terminological misperceptions by grouping synonymous terms under a single keyword based on the expertise of the authors (Li et al., 2011; Mao et al., 2010). Subsequently, we mapped the most frequent topics and methods to analyze the geographical footprint of Patagonian (paleo)glaciers studies by informally dividing the region in northern (~40°–45° S), central (~45°–50° S) and southern (~50°–56° S) Patagonia.

Finally, to assess scientific collaborative efforts, we considered as an independent item those papers in which all the authors come from institutions belonging to the same country and, on the contrary, a collaborative item is that in which authors are associated with institutions from different countries. The collaborative network analysis was carried out on the VOSviewer software, which produces distance-based maps in which the size of the items reflect the number of scientific literature contributions and the collaborative strength is represented by the thickness and distances of the lines connecting different items, so large items linked by thick and short lines indicate stronger relation and vice versa. Further information about the statistical procedures performed by the software could be found in van Eck and Waltman (2010).

3. Results and discussion

3.1. Limitations of the WOS database

We used WOS to conduct this bibliometric analysis over other academic databases, such as Scopus or Google Scholar, because it easily provides synthetic metadata collectively from scientific literature published in ~34,000 journals, conference proceedings and academic books (Birkle et al., 2020). Moreover, given that metadata differs from each database, for instance, Scopus does not present additional keywords such as the KP, intercomparison might alter the results. This is more noticeable when literature queries are focused on research topics instead of authors (Harzing and Alakangas, 2016). In addition, it has been proposed that Google Academics may lack robust literature quality controls and, therefore, the larger number of scientific items provided are not comparable with other databases (Aguillo, 2012). So far, WOS has proven to be a reliable source for bibliometric analysis focused on Earth sciences (Mikki, 2010).

We noticed some caveats in the WOS database that need to be considered. First, WOS tends to miss early publications in Patagonian glaciers, presenting an extensive gap during the second half of the 20th century, which is consistent with other studies suggesting that the difficulties to find old literature in WOS could be linked to the lack of metadata regarding authors, abstracts and author keywords in papers published prior the 1990s (Liu, 2021). Second, similar analyses has proven that WOS algorithms tend to penalize non-English publications (Mongeon and Paul-Hus, 2016) and, therefore, Patagonian glacier literature written in Spanish or any other languages and published in local journals are less likely to be reached. Third, several publications not-controlled by commercial publishers, the so-called grey literature, such as national scientific journals or technical reports appear to be absent in the WOS repository (Mahood et al., 2014), hampering the access, for instance, to relevant publications produced by local monitoring programs and public institutions from Chile and Argentina. Forth, in early articles, WOS usually only considers the institution of the leading author, which obscure potential collaborative efforts between local and foreign scientists and institutions.

3.2. Evolution and characteristic of the scientific literature focused on Patagonian (paleo)glaciers

We retrieved a total of 305 peer-reviewed publications from the WOS database published between 1976 and 2020 (Supplementary Material).

Between 1976 and 1992, we only found four papers, leaving a significant number of influential studies on Patagonian (paleo)glaciers out of the WOS database. Subsequently, related scientific literature began to growth more profusely, and between 1992 and 2020 every year at least 1 article was published each year. During this period, a total of 301 items were included in WOS (Fig. 2). Most of the items are indexed under one (or both) of the WOS research categories: “Geology” (238) and “Physical Geography” (199) (Supplementary Material).

Because of the foundational relevance of the few early works (including those not indexed in the WOS database; Supplementary Material), we consider the interval spanning between 1976 and 1992 as the pioneering period and the subsequent decades until 2020 as the consolidation stage.

According to the WOS database, the number of articles on Patagonian (paleo)glaciers has increased over time, with five prominent peaks occurring in 1995, 1999–2000, 2005, 2012 and 2020 (Fig. 2). In a broad sense, we observe that this scientific production tended to reach a maximum productivity peak roughly every seven years. It is worth noting that the 1999 and 2005 peaks coincide with the publication of special issues (i.e., Denton et al., 1999; Sugden et al., 2005), so they might be reflecting the work of an specific research groups or projects instead of a general interest pulse of the scientific community, we consider however that these issues strongly contributed to open new research lines on Patagonian (paleo)glacier studies. The net increase of publications since the early 1990s suggests the incorporation of new research groups most likely boosted by new (paleo)glaciological interests, the development of modern analysis techniques and the increase of economical support during the last decades (e.g., national glaciers inventories; Barcaza et al., 2017; Zalazar et al., 2020).

3.3. Journals of reference for Patagonian (paleo)glaciers studies

The presence of certain topics in well-positioned and high-impact journals is a reflection of major interests of the scientific community (Glänzel and Moed, 2002). Our WOS-based analysis reveals that 56 journals have published glacier-related articles in Patagonia between 1976 and 2020, but only 19 of them (33.9%) featured more than five papers (>1.6% of the total contributions), containing 230 articles (75.9% of the total contributions) of the total literature revised (Fig. 3).

Patagonian (paleo)glaciers WOS-indexed literature appears in journals focused on both glaciology and Quaternary studies (Fig. 3), indicating that related research is dedicated to both present and past glacial activity. However, ten out of nineteen of the main journals could be considered as generalist Earth's sciences journals (Fig. 3), which imply that the interest on the topic extends beyond the specialized scientific community. This interpretation is further supported by additional papers published in miscellaneous high-impact journals, such as *Science* and *Nature Geoscience* (Supplementary Material). In terms of number of publications, the most prolific journals focused on Quaternary studies, general Earth sciences and glaciology are *Quaternary Science Reviews* (14.2% of total contributions), *Geografiska Annaler, Seria A* (5.9%) and *Journal of Glaciology* (5%), respectively.

3.4. Main topics addressed by Patagonian (paleo)glaciers research

The keywords analysis reflects the specific interest of the scientific community (Zhang et al., 2016). Therefore, they offer an ideal opportunity to assess the evolution of the main topics that have drawn interest of the scientific community regarding Patagonian (paleo)glaciers. We identified a total of 1076 keywords corresponding to 521 AK (i.e., author keywords) and 673 kP (i.e., WOS keywords plus). However, 391 (75.0%) of the AK, and 374 (55.6%) of the KP appear only once, suggesting a wide variety of the research topics and/or a lack of standardization on the scientific terminology. We show in Table 2 the most frequent AK and KP for the period 1976–2020, excluding toponymical and generic terms. Our analysis indicates that, on the one hand, the AK clearly point to the most significant topics addressed in each publication and, thus, they are a suitable proxy for identifying the most relevant research focuses. However, we acknowledge that keywords might encompass several subtopics, so we consider them as a general indicator to outline the evolution of the topic in past decades. On the other hand, the KP tend to be more ambiguous presenting a high number of toponymic terms and, therefore, consist of a less reliable source of information (Supplementary Material). Overall, these facts agree well with other bibliometric analysis focused on Earth's sciences (Niu et al., 2014).

Based on the standardization of terminology provided by the WCA methodology, we recognize four types of keywords that broadly indicate: i) chronozones; ii) methodological approaches; iii) aims/objectives of the research and, finally, iv) disciplines (Table 3). Collectively, these categories denote major trends on Patagonian glaciers research over the

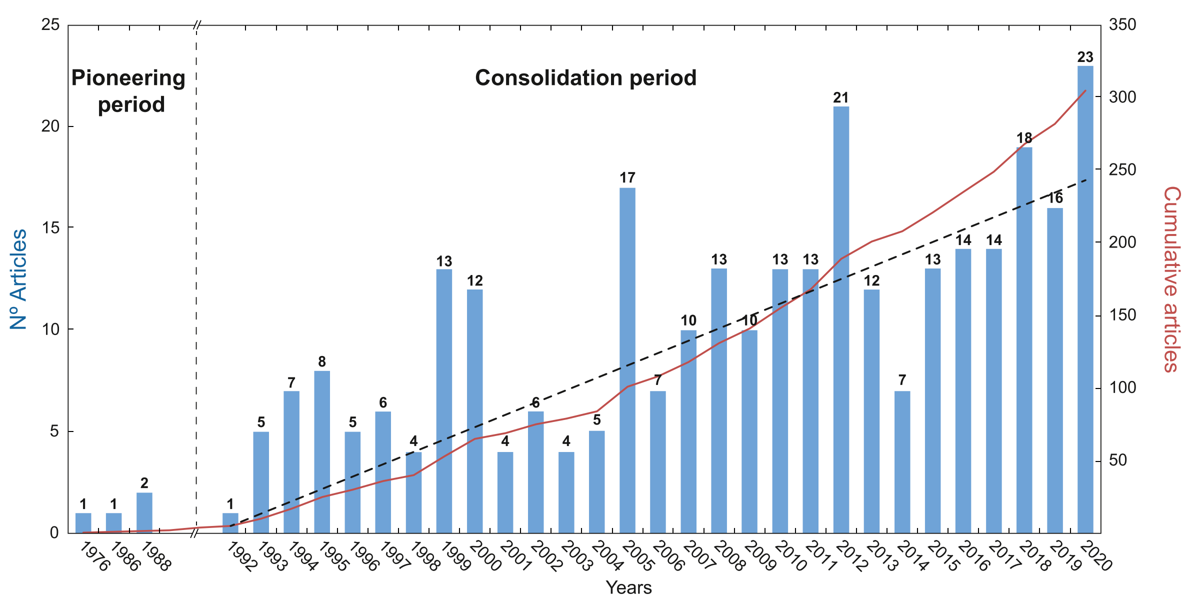

Fig. 2. Number of WOS-listed publications focused on Patagonian (paleo)glaciers published between 1976 and 2020. Blue bars represent the number of articles published each year and the red line is showing the cumulative number of articles in the period spanning 1976–2020. Dashed black line correspond to the linear tendency during the consolidation period (1992–2020).

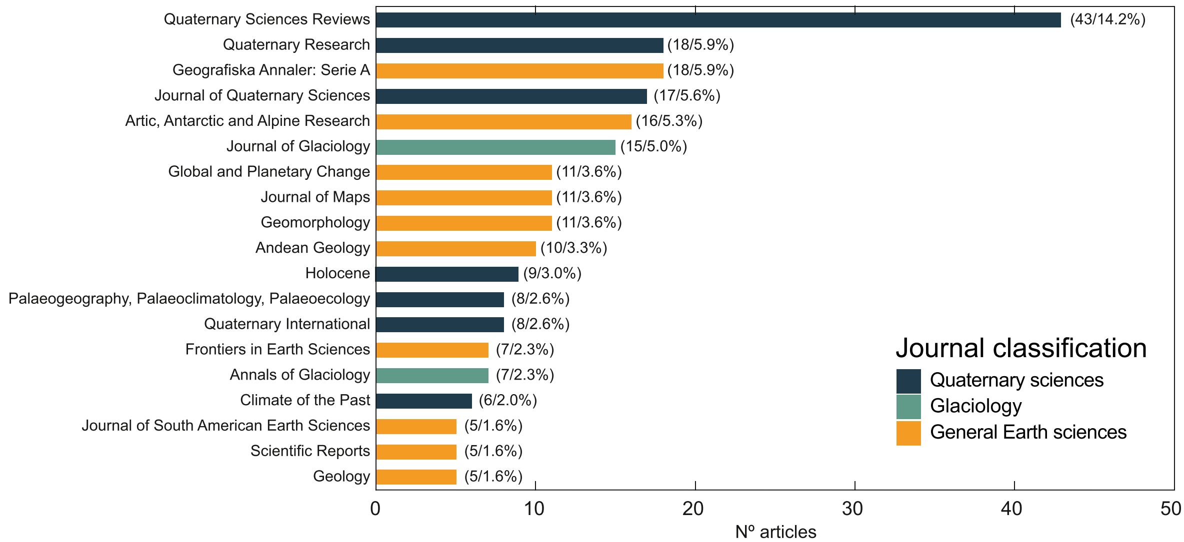

Fig. 3. Top WOS-listed journals with the highest number of publications focused on Patagonian (paleo)glaciers. Bar colors denote focus of the journal. Total articles and percentage of each journal are also shown.

Table 2
Most common keywords from the WOS-listed literature excluding generalist terms and toponyms. AK: Author keywords. KP: Keyword Plus.

	Author Keyword (AK)	n	Keyword Plus (KP)	n
1	Holocene	20	Fluctuations	53
2	Glacier fluctuations	20	Climate	46
3	Glacier geomorphology	20	Chronology	39
4	Cosmogenic dating	15	Cosmogenic dating	36
5	Last Glacial Maximum	13	Climate change	33
6	Remote sensing	12	Last glaciation	32
7	Late Glacial	11	Younger Dryas	30
8	Little Ice Age	11	Mass balance	25
9	Glaciation	10	Satellite	23
10	Glacial chronology	10	Late Pleistocene	22
11	Climate change	9	Holocene	21
12	Deglaciation	9	Be-10 dating	21
13	Neoglaciation	8	Antarctic Cold Reversal	19
14	Dendrochronology	8	Pleistocene	18
15	Paleoclimatology	8	Inventory	17
16	Geomorphology	8	Deglaciation	15
17	Chronology	7	Radiocarbon chronology	14
18	Younger Dryas	7	Paleoclimate	13
19	Antarctic Cold Reversal	7	Elevation changes	13
20	Calving glacier	7	Last Glacial Maximum	12
21	Surface exposure dating	7	Sea level rise	12
22	Last Glacial Termination	7	Glacier fluctuations	10
23	Southern Westerly Winds	7	Calving glaciers	9

past decades. Therefore, we infer that the scholar interest in (paleo) glaciers studies in Patagonia has been primarily focused on both i) present-day glaciers, particularly satellite-derived (26 WCA keywords) mass balance analysis (38), glacier inventories (17) and calving dynamics (16), and ii) paleoglacier studies using geomorphological (32) and geochronological (49) approaches (in order of importance; cosmogenic nuclides (62), radiocarbon (29) and tree-ring dating (16)) (Table 3).

3.5. Evolution of (paleo)glacier research in Patagonia by chronozones

To identify comprehensively past directions on Patagonian glaciers research, we analyzed WOS-retrieved literature individually in tandem with keywords referring to chronozones. From younger to older, we consider studies focused on cryosphere dynamics during the 20th century as i) modern glaciological works. Paleoglaciological research are those focused on reconstructing glacier behavior in the past millennia and earlier relying in proxy evidence. Because paleoglacier studies aimed usually to intervals spanning particular paleoclimatic events, we present our analysis by the following chronozones in ii) Last Glacial Maximum (LGM); iii) Last Glacial Termination (LGT) and iv) Holocene. The LGM spans between ~26.5 and 18.0 ka (ka = 1000 years before present; present = 1950; Clark et al., 2009) coinciding with the period in which the continental cryosphere globally reached its maximum volume during the last glacial cycle. The LGT is characterized by a net warming trend featuring a stepped sequence of millennial-scale climate shifts that led to the end of the last glaciation between ~18.0 and 11.7 ka (Denton et al., 2010). Finally, the last ~11.7 ka correspond to the Holocene, which exhibit a relative stable warm condition, only interrupted by subcentennial-to-centennial-scale cold snaps (Walker et al., 2012).

Considering the number of contributions within each chronozone, present-day glacier studies is the most addressed topic between 1976 and 2020 (87; ~28.6% of the total contributions), followed by LGT (78; ~25.6%), Holocene (66; ~21.6%) and LGM (52; ~17.1%) (Fig. 4a). However, research focused on past glacier activity clearly overcomes current glacier studies when considering prior-to-20th-century chronozones altogether. This data indicates that Patagonia is a fantastic location for both analyzing recent oscillations and dynamics of present-day glaciers and for deciphering past glacial activity through geological records. Overall, our interpretation is further supported by the WCA as well (Table 3).

Based on individual contribution checking, we identified present-day glacier research (87 articles) as the most common foci, which is supported by the WCA on keywords such as mass balance (38 WCA keywords), satellite (26), inventory (17) and calving glaciers (16). In addition to mass balance estimations, geophysical analyses to estimate ice thickness and ice flow velocities are also relatively abundant. Glacier activity during the 20th century was first addressed on WOS-listed papers in the late 1980s experiencing an isolated pulse in 1999, followed by a net increasing trend from 2004, highlighting peaks in 2012, 2014 and 2017 (Fig. 4a). We assume that pioneering modern glaciological research is particularly susceptible to be missed by WOS because several studies were probably published as book volumes or technical reports (e.g., Aniya et al., 1996, Casassa et al., 2002; Naruse, 2006) and/or difficulties before the 1980s in acquiring aerial and/or satellite imagery as well as organizing regular glaciological expeditions in preceding decades. The recent push in contributions is most likely linked to the development of remote sensing techniques, the release of more accurate satellite-derived data and the incorporation of new research teams

Table 3
Word cluster analysis (WCA) showing the most repeated keywords produced by joining together synonym terms from the AK and the KP. We classified the keywords following the typology discussed above; green denote our best-fitted classification proposal, while yellow indicates a secondary category that can be apply to some keywords.

	WCA Keywords	n	Chronozone	Methodology	Aim	Discipline
1	Cosmogenic Dating	62				
2	Holocene	56				
3	Last Glacial Termination	50				
4	Glacial chronology	49				
5	Late Pleistocene	42				
6	Mass balance	38				
7	Last glaciation	37				
8	Younger Dryas	36				
9	Glacier fluctuations	34				
10	Glacial geomorphology	32				
11	Radiocarbon chronology	29				
12	Last Glacial Maximum	29				
13	Paleoclimatology	27				
14	Satellite	26				
15	Antarctic Cold Reversal	25				
16	Glaciation	19				
17	Inventory	17				
18	Production rate calibration	17				
19	Calving glaciers	16				
20	Dendrochronology	16				

probably from national and international institutions, especially that publish in WOS-listed journals.

In chronological order, the reconstruction of the glacial history during the Holocene, also known as Neoglaciations, were the third most studied topic in Patagonia in past decades after individually-checked articles (52) and the WCA (56). Although occasional pioneering works addressing the topic appears in WOS, it is most likely that influential studies were missing. Accordingly, more recent works started to appear regularly in the early nineties featuring three peaks in 1993, 1996 and 2000. Subsequently, studies have continued to increase more irregularly, peaking in 2004 and 2012 before experienced a marked decrease between 2012 and 2020 (Fig. 4a). In addition to the good preservation of Holocene ice-marginal landforms, it is likely that the popularity of the Holocene paleoglacier topic was linked mainly to the wide variety of suitable and affordable geochronological techniques to date glacial features, such as radiocarbon dating, dendrochronology and lichenometry.

Our WOS-listed paper checking (78) and the associated WCA (50) places the LGT as the most popular chronozone in Patagonian glaciers research when including keywords referring to the millennial-scale cold snaps within the chronozone, namely the Antarctic Cold Reversal (25) (~14.5–12.8 ka; Pedro et al., 2016) and the Younger Dryas (36) (~12.8–11.7 ka; Rasmussen et al., 2014) (Table 3). Earliest studies on the LGT may have lacked specific mention of the Antarctic Cold Reversal, and discussed only the Younger Dryas event. Since its recognition, the Antarctic Cold Reversal has become a more common focus of Late Glacial events. Although earliest WOS-listed studies broadly include glacial fluctuations during the LGT, the related literature started to growth annually from 1993, again, leaving out a relevant number of founding works published prior the 1990s. Subsequently, the most noticeable increase on LGT contributions occurred in 2005 followed by additional peaks in 2008, 2012 and 2017 (Fig. 4a). The early incorporation of LGT works was likely boosted by the excellent preservation of the contemporaneous ice-marginal features and that they were created during a time slice well within the operational limits of radiocarbon dating (Hogg et al., 2020) and subsequent modern geochronological techniques such as cosmogenic nuclides likely boosted these studies in the most recent decades (Balco, 2011).

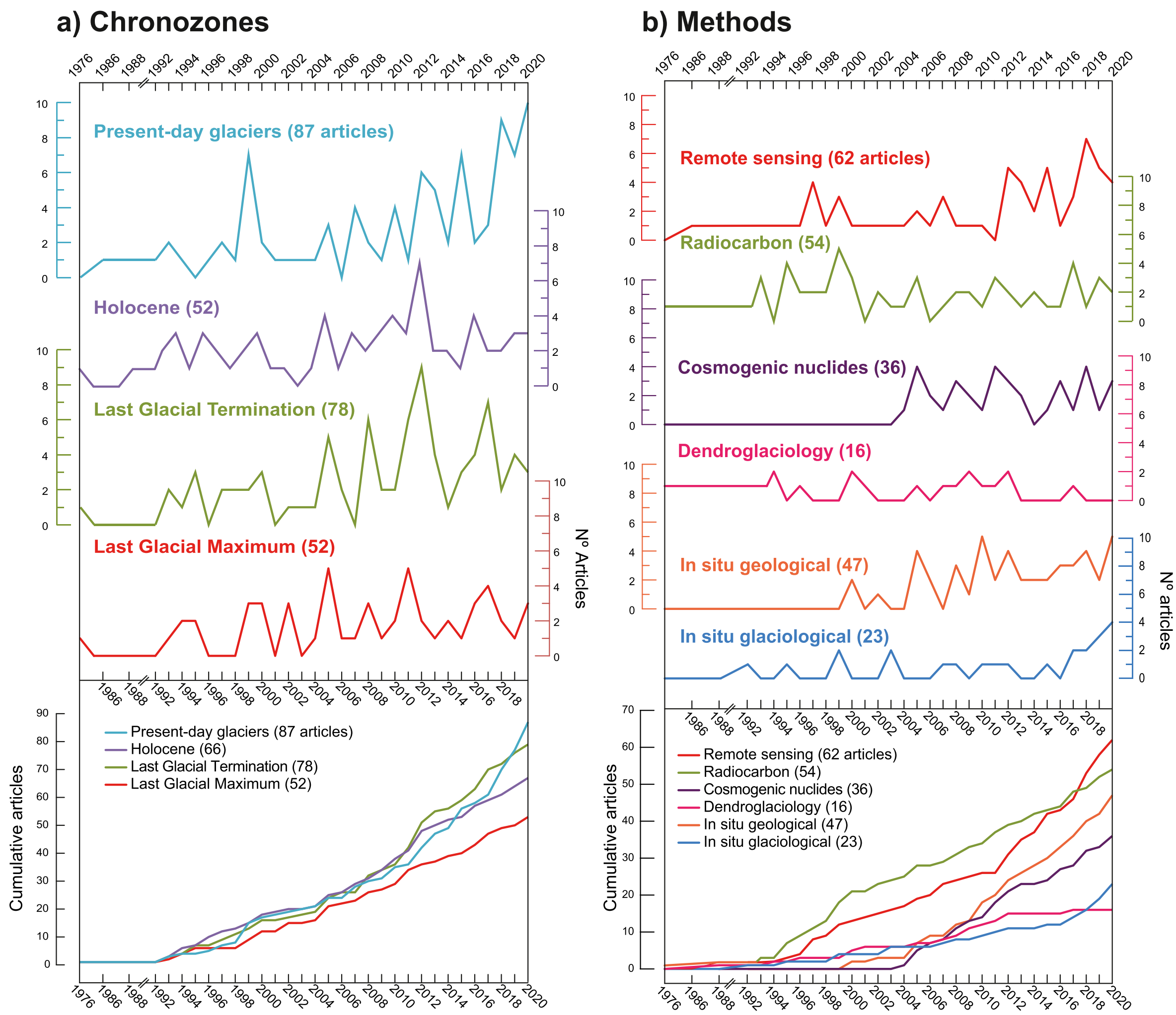

Fig. 4. Evolution of Patagonian (paleo)glaciers publications between 1976 and 2020. a) Published papers according to chronozones. b) Published papers according to methodology. Top box is the number of papers published by year and lower box is the accumulated articles. Note the temporal discontinuity in the x-axis.

Glacier activity during the LGM is the less common research topic in scientific literature within the last decades (Table 3) after our one-to-one checking of WOS-indexed articles (52) and the related WCA (29). Although WOS detects some LGM literature in the early 1990s, it started to growth more profusely by 1999, experiencing additional peaks in 2005, 2010 and 2016, suggesting related publications every five years approximately (Fig. 4a). Unlike LGT and Holocene focused works, which is often conducted in relatively small glacier catchments, we attribute the observed LGM research tendency to the vast extension and complexity of associated geological records that demand long-lasting research projects and strong economical efforts for accomplishing comprehensive studies and, therefore, the knowledge of the LGM glacier activity growths slowly in time.

3.6. *Evolution of (paleo)glacier research in Patagonia by methods*

Based on one-to-one WOS-listed publications checking and related WCA keywords (Table 3), we address the evolution of Patagonian (paleo)glacier research during the past decades from a technical perspective. We discuss the methods from the most to the least used as follows; i) Remote sensing analyses mostly based on satellite imagery; ii) Dating techniques including radiometric and biological methods; iii) In situ geological observations which includes contributions mostly based on fieldwork such as glacial geomorphology, sedimentology and stratigraphy, and, finally, iv) in situ glaciological measurements which group studies conducted with data directly acquire from the glaciers (Fig. 4a).

The combination of checked WOS-listed articles (62) and the related WCA indicate that remote sensing analysis based on satellite data (26) and to a lesser extent airborne sensors are the preferred methodologies to address glacier studies in Patagonia (Table 3). The use of remote sensing techniques in Patagonia have followed a relatively steady rate of publications until a marked pulse occurred in 2011 that continues today (Fig. 4b). This trend is most likely explained by the incorporation of new high-resolution satellite sensors, the release of classified satellite/aerial imagery and the availability of larger temporal datasets.

To us, the wide application of remote sensing techniques is linked to the high number of present-day glacier studies, which permits overcoming complex accessibility and harsh meteorological conditions of the region that prevents difficult in situ glaciological measurements of present-day glaciers (Masiokas et al., 2020). However, given paleoglacier studies are often based on geomorphological maps and stereoscopic aerial photography, in addition multispectral satellite imagery and digital elevations models have become fundamental assets for high-resolution mapping (Chandler et al., 2018).

The number of WOS-indexed articles based on dating techniques, such as radiocarbon (54 articles), cosmogenic nuclides (36) and dendroglaciology (16) in tandem with the high rank of WCA keywords such as cosmogenic dating (62), radiocarbon chronology (29) and dendrochronology (16) clearly indicates that numerous geochronological techniques have been used in Patagonia to determine the timing of the glacial fluctuations recorded by the ice-marginal landforms and other geological evidence (Table 3).

Our WOS-based analysis indicates that the use of radiocarbon ages (54 articles and 29 keywords) was widespread in Patagonia during the 1990s, peaking in 1999 (Fig. 4b). However, we note that our analysis might have missed much of the ^{14}C dating literature, especially that which predates 1992. The popularity of this method is likely related to its early technical development and its dating range which currently spans ~50,000 years (Hogg et al., 2020). Therefore, radiocarbon has been used extensively to provide a chronological control to glacier fluctuations from the LGM to the late Holocene, overcoming any other geochronological method in the past decades.

According to WOS, articles based on cosmogenic ^{10}Be chronologies are the second most abundant (36 articles and 62 keywords), experiencing a marked push since the early 2000s (Fig. 4b). The rapid increase of the application of this geochronological technique is well reflected in the significant growth underwent since 2004. Interestingly, the rate of publications based on cosmogenic chronologies exhibited an irregular pattern presenting peaks every three years between 2004 and 2011 and every two years between 2016 and 2020, which might be related with the development of the technique (Fig. 5b). Considering the WCA, cosmogenic nuclide chronologies are more frequent than those based on radiocarbon (Table 3), however this may be due to the wide variety of keywords linked to the cosmogenic chronologies technique, which are most likely incorporated into WOS more recently (e.g., cosmogenic dating, surface exposure dating, 10-Be dating, etc; Table 2; Supplementary Material). The growing application of this technique in Patagonia is related to the accuracy featured by the chronologies produced with cosmogenic nuclides, given it permits to skip difficulties in finding organic carbon associated with glaciogenic sediments or landforms, especially in eastern Patagonia, by directly dating rocks composing ice-marginal landforms such as moraines. The extensive use of cosmogenic nuclide techniques to decipher past glacial history in Patagonia follows the global tendency on paleoglacier research (Balco, 2011).

Finally, in our WOS-based analysis, dendrochronology (16 articles and 16 keywords) was the third most common techniques to date past glacial advances in Patagonia during past decades. However, it was the most frequent technique to date past glacial fluctuations until 2006, when it was surpassed by radiometric dating methods (Fig. 4b). Nevertheless, a second period of increasing dendrochronological studies culminated in 2012, although most of the last scientific contributions often uses tree ring as a complementary dating technique with some exceptions. At present, dendrochronology is still a popular method to date late Holocene glacier fluctuations because the annual resolution provided by the tree-ring counting and the reduced economical costs of this technique.

Although not reflected on keywords analysis, additional dating techniques were also used across Patagonia, including optically stimulated luminescence (OSL). We found some contributions solely based on this dating method but most of the WOS-listed studies used it as a secondary or complementary technique to constraint glacier fluctuations during the last glaciation. Additionally, K/Ar and ^{40}Ar/^{39}Ar ages were also obtained from lava flows stratigraphically associated with till units to determine the timing of pre-LGM glacial activity (Supplementary Material).

According to our WOS review (47 articles) and related WCA, glacial geomorphology (32) is among the most used method in Patagonia (Table 3, Supplementary Material). These studies have grown profusely in Patagonia during the last decades particularly since the early 2000s. Publications with strong glacial geological foundations started to increase in 2005 and then experienced a plateau with minor peaks until today (Fig. 4b), but we acknowledge that our WOS-based analyses may leave a large number of influential literature published between 1976 and 1999. At present, geomorphological maps cover extensive areas of the Patagonian territory (see references, for examples, in Davies et al., 2020) and are used to infer the structure of past glacier fluctuations providing a spatial framework for interpreting radiometric glacial chronologies, especially based on cosmogenic nuclides. Sedimentological and stratigraphical analyses often appear spatially constrained to a single location and mostly describing former morphosedimentary environments and as a geological setting for interpreting radiocarbon ages. So, the high number of papers presenting in situ geological observations is most likely linked to the widespread use of radiocarbon and cosmogenic nuclides techniques.

One-to-one WOS-indexed papers (23 articles) and WCA keywords such as mass balance (38) and calving glaciers (16) dynamics denote the influence of studies based on in situ glaciological measurements (Table 3). In WOS-listed journals these studies are surprisingly limited during the last decades, presenting an irregular rate of publications that started to markedly increase in 2016 (Fig. 4b). As also discussed above, the small number of articles based on in situ glaciological measurements is most likely determined by logistical and economical constrains that limited widespread and continuous glacial monitoring programs during the early 1990s, when most of the present-say glacier were probably conducted by using remote sensing techniques. It worth noting that

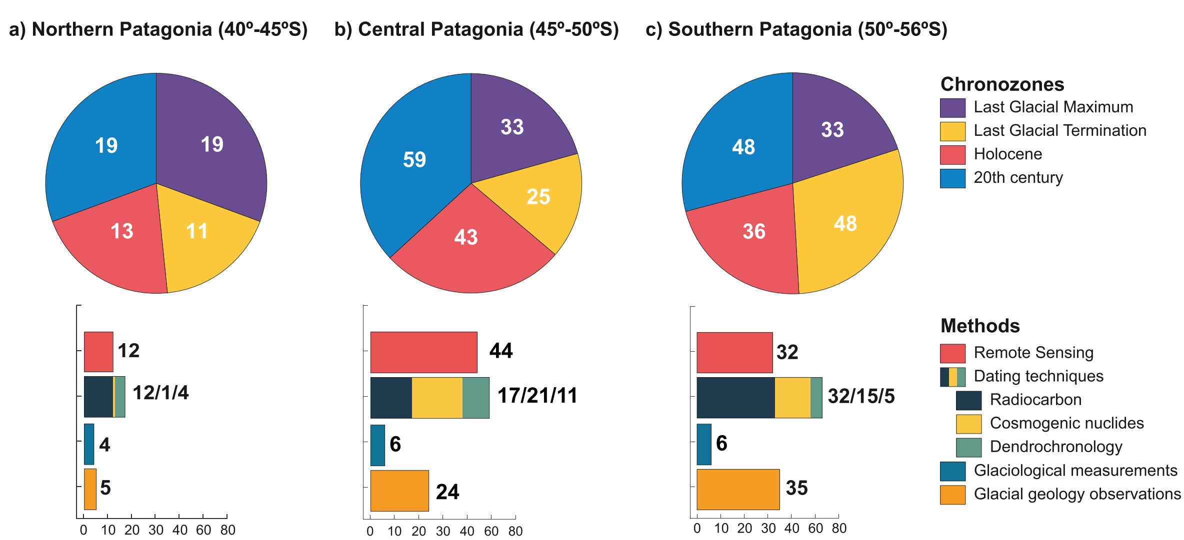

Fig. 5. Spatial distributions of (paleo)glacier research across Patagonia. a) Northern Patagonia; b) Central Patagonia and c) southern Patagonia. Pie charts denote studies divided by chronozones and bar plots show methodologies.

some data were incorporated on technical reports or other types of grey literature produced by local institutions and monitoring programs. To us, the growth in articles based on in situ glaciological measurements in the last years is probably reflecting the recent incorporation of local research groups supported by national administrations that have been conducting more ambitious monitoring programs (Barcaza et al., 2017; Zalazar et al., 2020).

3.7. Spatial distribution of (paleo)glacier research in Patagonia by chronozone and methodology

Given present-day glaciers and geological records associated with past glacial activity are heterogeneously disperse across Patagonia, the number of scientific contributions including methods applied are geographically clustered in different sectors of the region. Here, we explore and compare the topics distribution and methods of related articles in northern (40° – 45° S), central (45° – 50° S) and southern Patagonia (50° – 56° S) to further detect potential spatial gaps of research that might be worth addressing to expand our knowledge on the southern South American cryosphere. The number of scientific contributions produced in each Patagonian sector organized by chronozones and methodologies are shown in Fig. 5.

At a regional scale, central and southern Patagonia (paleo)glaciers were addressed by a higher number of contributions than northern Patagonia (Fig. 5). In relative terms, present-day glaciers mostly based on remote sensing techniques are the most frequent studies in northern (19) central (59) and southern Patagonia (48) (Fig. 5). We link the high number of current glaciers works in central and southern Patagonia to the presence of the Patagonian icefields, which are rapidly retreating and are thought to contribute significantly to the global sea-level rise (Dussaillant et al., 2019). Northern Patagonia, despite this is the less glaciated portion of the region, also features a high number of present-day glacier studies. We attribute this circumstance to the presence of several ice-capped volcanos close to populated areas, which provides logistical advantages that facilitate field campaigns. In relative terms, these studies in northern Patagonia appear to present a strong foundation on in situ glaciological measurements (4 out 19) contrasting with similar works in central (6 out of 59) and southern (6 out of 48) Patagonia. This spatial pattern is further supported by the methods applied, so remote sensing techniques are the most common in central (44) and southern (32) Patagonia, whereas in situ glaciological measurements (18) closely followed by remote sensing (12) are the most frequent techniques in northern Patagonia (Fig. 5).

Collectively, studies focused on past glacier behavior are the most common in Patagonia during the last decades. There are however regional differences on its distributions that are most likely linked to the preservation of the glacial geological records, their suitability for applying different dating techniques, logistics and accessibility. Related to the total number of articles in each region, studies focused on the LGT, and the Holocene are the most abundant in central (33, 43, respectively) and southern (48, 36, respectively) Patagonia, whereas in northern Patagonia they are less frequent (11, 13, respectively) (Fig. 5). This might be due to the relatively easy access to a widespread and well-preserved inventory of ice-marginal landforms contained inside the LGM glacial limits and the variety of suitable techniques to date past glacial fluctuations (Davies et al., 2020). On the contrary, relative contributions centered on the LGM are more frequent in northern Patagonia (19) than in central (33) and southern (33) Patagonia (Fig. 5). Overall, the spatial distribution of articles focused on specific chronozones agrees well with methods, so dating techniques are the most frequently used methods in southern and central Patagonia, whereas in northern Patagonia it is closely behind of methodologies aiming at present-day glaciers (Fig. 5). Radiocarbon dating has been extensively used in northern (12) and southern Patagonia (32), whereas cosmogenic-based chronologies dominated in central Patagonia (21). This could be explained by the preservation and accessibility to glacial landforms assigned to each chronozone and the different climatic conditions between the Patagonian Andean flanks. From west to east, local hydroclimate ranges from hyper-humid to semi-arid, so western Patagonia features dense vegetation formations and lacustrine basins associated with glacial landforms, which permitted the elaboration of early radiocarbon-based glacial chronologies, whereas organic carbon associated to glacial geological evidence is virtually absent in eastern Patagonia and, therefore, cosmogenic nuclide chronologies are more suitable (Moreno et al., 2015; Alloway et al., 2018; Supplementary Material). Finally, glacial geology studies are more abundant in southern Patagonia (35), followed by central (24) and northern Patagonia (5), which is in line with the number of contributions dedicated to the reconstruction of past glacial oscillations in each portion of the region.

3.8. Characteristics of the scientific community involved in Patagonian glacier research

According to the nationality of the institutions that host the leading scientists of the WOS-listed articles, the most prolific countries in glacier-related research in Patagonia are United Kingdom (79 articles, considering England, Scotland and Wales altogether), followed by United States (49), Chile (48) and Argentina (39; Fig. 6). In addition to solid scientific programs and strong economical support, the prominent representation of United Kingdom and also United States could be also enhanced by the biases toward English literature in the WOS (Mongeon and Paul-Hus, 2016). Furthermore, we note that the WOS database tends to ignore grey literature and, thus, diminish the relevance of smaller institutions and non-English speakers (Fig. 7a), whose scientists might have strongly contributed to Patagonian (paleo)glaciers research with a handful of comprehensive studies and reports locally published in past decades. Therefore, it is most likely that Chile and Argentina as well as other countries such as Germany, Japan and France (Fig. 7a) would rise significantly in their relative productivity if using additional databases besides just WOS (Supplementary Material).

The number of international scientific collaborations is often considered as an indicator of the relevance of a certain research topic (Wagner and Leydesdorff, 2005). We found 155 collaborative items (54.6%), indicating that more than a half of the studies in Patagonian glaciers are conducted by groups of scientists based at institutions from different countries. Most of these institutions come from every continent, excluding Africa (Fig. 7a), suggesting that Patagonia offers vast opportunities for tackling crucial (paleo)glaciological questions at hemispheric and global scale.

Regarding the international collaborations, our analysis shows that the most collaborative countries are the United States, followed by Chile, Argentina and, finally, United Kingdom, particularly England and Scotland (Fig. 7a). The strongest partnerships are between institutions from United States and Chile, followed by collaborations between United States and United Kingdom, between the United States and Argentina and, finally, between Chile and Argentina. Other significant associations in the light of WOS-listed literature come from Argentina and Japan and between Chile, Canada, Germany and France (Fig. 7a). In terms of institutions, the tightest clusters are between United States, Chile and, to a lesser extent Argentina (purple in Fig. 7b), while United Kingdom universities and research centers are mostly linked to each other and to other European institutions (blue in Fig. 7b). The stronger link between these two nodes is between United Kingdom and United States and, to a lesser extent, between United Kingdom and Chile. In general, our one-to-one article assessment indicates that these major nodes are mostly focused on paleoglacier reconstructions and paleoclimate estimations. We detect additional nodes such as those grouping institutions from Chile-Japan-United Kingdom (green in Fig. 7b), Chile-France-Belgium (red in Fig. 7b) and Argentina-United States-Canada (yellow in Fig. 7b). Overall, these research nodes are mostly dedicated to present-day glacier studies, except for the Argentine-United States-Canada node which varies between modern and ancient glacier

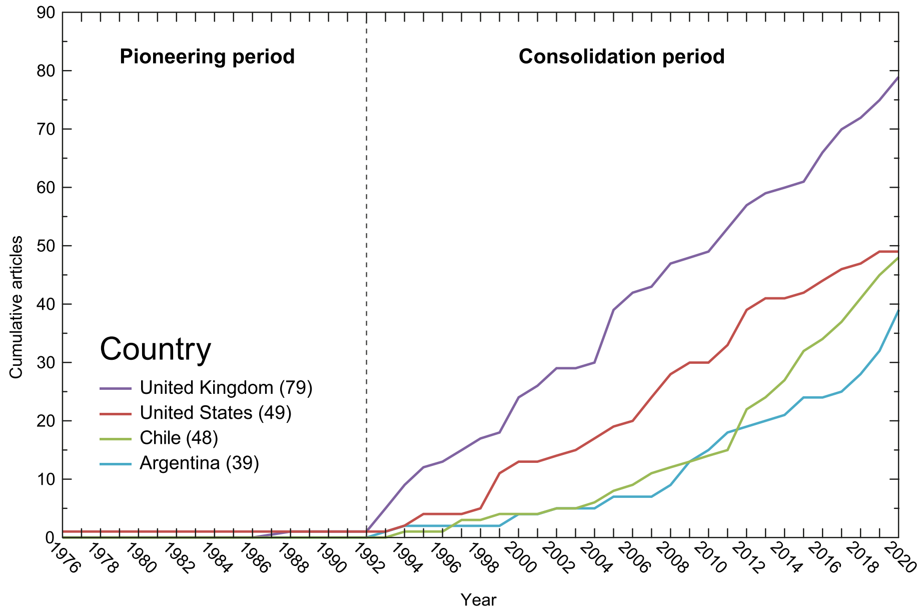

Fig. 6. Cumulative articles from most prolific countries considering institutions of the first author between 1976 and 2020.

dynamics. We also notice that the majority of universities and research centers involved are either pioneering institutions in (paleo)glaciology and/or close to (formerly) glaciated areas (See Fig. 7b and Supplementary Material for clear identification of relevant scientific institutions involved). To us, the geographical distribution of collaborations regarding Patagonian (paleo)glaciers research suggests that tying bonds between foreign and local scientists is still an enterprise to carry out (Dahdouh-Guebas et al., 2003). Fortunately, in the recent years, a connection between these international research nodes is emerging in the form of comprehensive review papers (e.g., Davies et al., 2020; Palacios et al., 2020) and other publication efforts, such as journals special issues edited by scientists from both hemispheres.

In total, 593 authors have participated in, at least, one glacier-related publication specific to Patagonia between 1976 and 2020. However, less than half (210) have produced more than one contribution. Among them, we identify 23 researchers (3.9%) with 10 or more papers and over 200 accumulated citations (Supplementary Material). We named this group of researchers as "core authors". They came from United Kingdom (8 authors), Argentina (5), Chile (5), United States (3), Japan (1) and Sweden (1) (Fig. 8a).

Focusing on the core authors (Supplementary Material), our results imply that Patagonian (paleo)glaciers studies have been developed nearly at equal parts by foreign (United Kingdom (8), United States (3), Japan (1) and Sweden (1)) and local scientists (Chile (5) and Argentina (5)) (Fig. 8a). However, British (33) and Chilean (30) core authors are the most prolific in terms of WOS first-authored contributions, followed by researchers from Argentina (16) and United States (12) (Fig. 8b). The majority of the core authors are focused on past glacial fluctuations (20) (Fig. 8c), further revealing that glacier-based paleoclimate studies have motivated a significant portion of the glaciological research in Patagonia. Present-day glacier specialists (3) are scarcely represented (Fig. 8c) and all of them come from Chile and Argentina, indicating a fruitful scientific production that might be related to an increase of the awareness regarding local cryosphere evolution under the ongoing global warming and/or the application of less time-consuming methodologies (Supplementary Material).

It is noticeable that only two of the core scientists are women (Fig. 8d and Supplementary Material). This circumstance clearly reveals a strong gender bias in WOS-listed literature in the access to glacier-related studies in Patagonia, which is unfortunately replicated in this paper's authors as well, contributing to a negative historical and global trend in glaciology (Carey et al., 2016). Although far from gender equality among the core authors, studies led by female researchers focused on both present-day and paleoglaciology have started to growth profusely in recent years (e.g., Bown et al., 2019; Davies et al., 2020; Hall et al., 2013; Hall et al., 2019; Dussaillant et al., 2019; Mendelová et al., 2020a; Mendelová et al., 2020b; Peltier et al., 2021; Smedley et al., 2016; Zalazar et al., 2020).

Overall, at present, WOS-indexed contributions outline a very dynamic and heterogeneous scientific community focused on Patagonian (paleo)glaciers studies. However, our bibliometric analyses reveals still a need to improve on issues regarding inclusion, and "north-south" scientific cooperation (Bernard and Cooperdock, 2018).

4. Conclusions

Bibliometric analysis based on multiple software environments and one-to-one paper checking is a powerful tool for outlining the state of the art of a particular research topic providing complementary insights to traditional review studies.

In past decades, the scientific literature about (paleo)glaciers in Patagonia have grown diverse in both topics and scopes, reaching from a highly specialized research groups to a wider scholar community, contributing to better understand the cryospheric response to present and former climate changes. The wide variety of research foci addressed in Patagonia during past decades have raised scientific challenges that ultimately helped to promote the development of cutting-edge methodologies. Overall, in our analyses of the last decades, current glacier research has mainly assessed mass balance changes and to a lesser extent ice thickness, motion estimations, and calving dynamics. Whereas paleoglacier studies have mostly followed geomorphological and geochronological approaches to outline the regional glacial history and the past climate conditions, particularly since the LGM.

We identified research foci and methods clearly underrepresented in Patagonia that we considered as scientific gaps and, therefore, aiming to resolve them will strongly contribute to increase our knowledge of past, present and future cryosphere dynamics and climate changes at regional, hemispheric and global scale. For instance, numerical model-based analyses were surprisingly scarce during the past decades even though they started to grow more profusely in recent years, particularly in present-day glacier studies (Fernández and Mark, 2016; Supplementary Material). Similarly, pre-LGM glacial activity has been addressed in

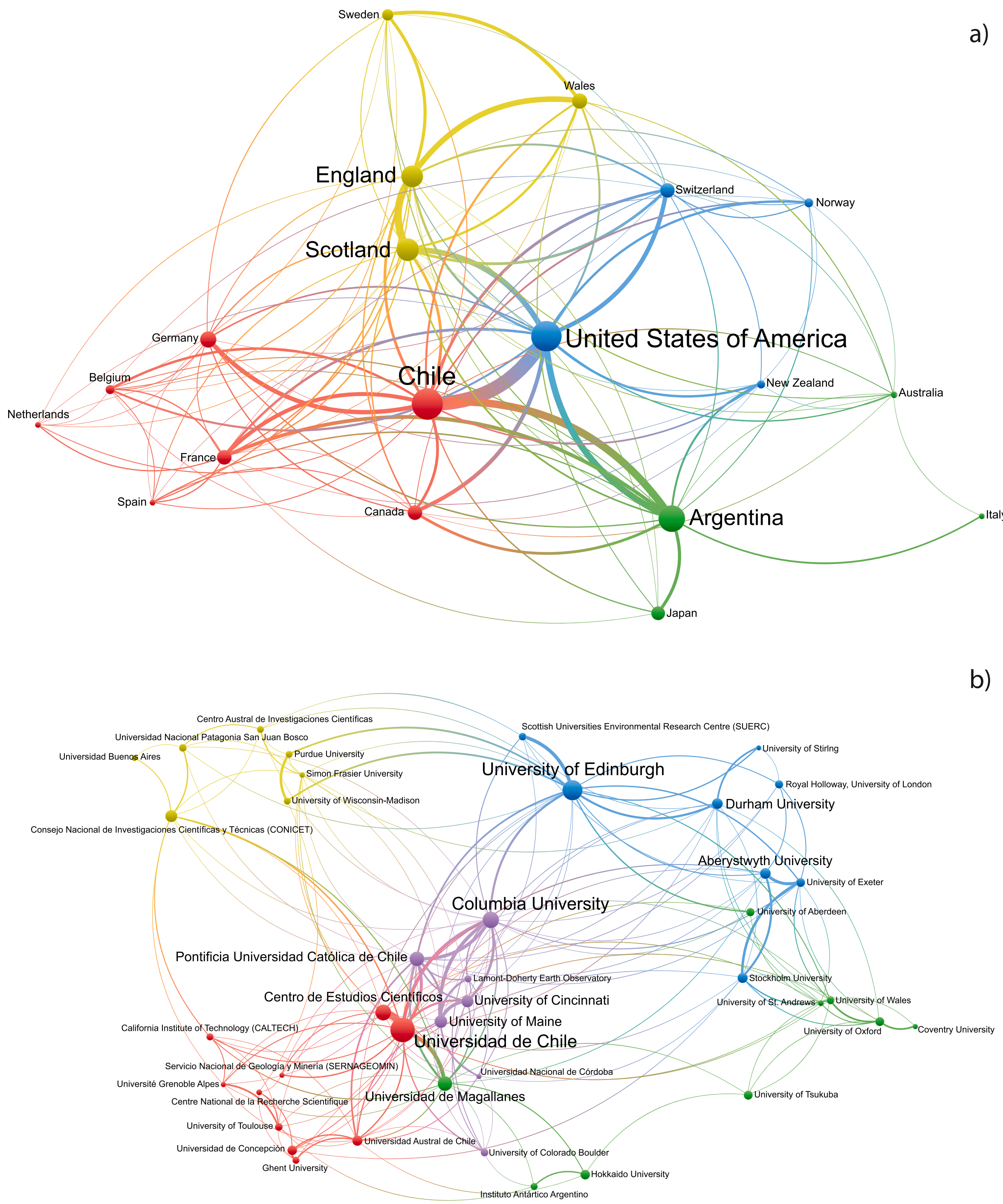

Fig. 7. Collaboration research network in Patagonian (paleo)glaciers based on VosViewer software. a) Countries forming collaborative research network b) Institutional collaborative research network. We note that WOS database separates England, Scotland and Wales, although they commonly share funding agencies (e.g., National Environment Research Council - NERC) and laboratory facilities (e.g., Scottish Universities Environmental Research Centre - SUERC).

particular locations by a few articles, although some key insights have been added to the discussion in recent years (Supplementary Material). Critically, we did not find any WOS-indexed paper assessing glacier-human relations from an historical or social perspective.

Overall, northern Patagonia has received less attention in both present-day and paleo-glaciers research that central and southern Patagonia. We infer that this circumstance could be linked to the limited glacierized areas in the region and the difficulties to access to the Andean headwalls where glaciers and well-preserved, potentially datable geological records are found today.

At present, the growth experienced by Patagonian (paleo)glacier research has been led by a very vibrant scientific community from several countries in both the Southern and Northern hemispheres. However, there are still some bottlenecks to improve imperatively, such as gender inclusion issues and collaborative nodes extension between hemispheres. Fortunately, during the last years these gaps are starting to close rapidly (e.g., Davies et al., 2020; Palacios et al., 2020).

Considering WOS limitations, we posit that the database features enough literature metadata to outline a comprehensive overview of (paleo)glacier research in Patagonia during the past decades. However, it is crucial to acknowledge that tends to miss early works and research not published in high impact journals (Liu, 2021), such as local scientific

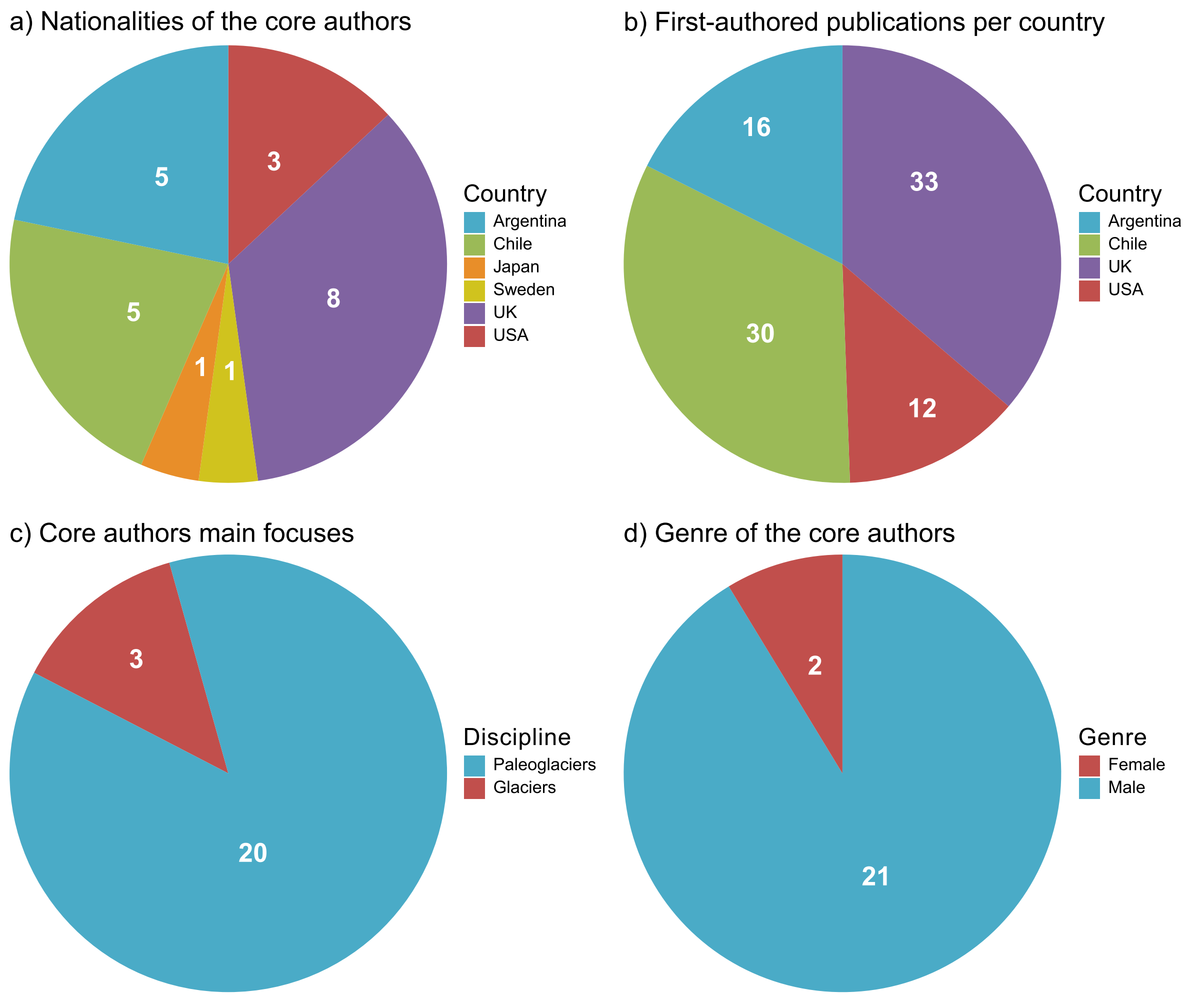

Fig. 8. Characteristics of the scientists with more than 10 publications between 1976 and 2020. a) Nationalities of the core authors. b) First-authored publications per country c) Main topics addressed by the core authors. d) Genre of the core authors. We note these are absolute numbers based on WOS-listed papers on Patagonian (paleo)glaciers and does not take into account the number of scientists in total in each country (i.e., not standardized by population).

literature and technical reports. This WOS-missed grey literature, sometimes highly cited (e.g., Aniya et al., 1996, Casassa et al., 2002; Naruse, 2006), includes pioneering works and papers thereafter that have still been key to understand Patagonian (paleo)glaciers. To avoid this bottleneck, we recommend future studies combine traditional literature reviews and bibliometric analysis considering several databases, such as Scopus and Google Scholar which often include more grey literature than WOS (Harzing and Alakangas, 2016; Martín-Martín et al., 2018).

Our findings invite others to perform similar analyses covering larger geographical scales. In the light of our bibliometric analyses and considering that Patagonia hosts the largest number of mid-latitude temperate glaciers in the Southern Hemisphere, we conclude that the Patagonian Andes have played a crucial role in cryospheric studies worldwide, including paleo- and present-glaciers. Despite the number of scientific contributions already, the region still offers vast opportunities to develop further major Earth sciences disciplines such as glaciology, glacial geology and paleoclimate.

CRediT authorship contribution statement

Rodrigo L. Soteres: Writing – review & editing, Writing – original draft, Investigation, Formal analysis, Data curation, Conceptualization. **Fabián M. Riquelme:** Writing – review & editing, Investigation, Formal analysis, Data curation. **Esteban A. Sagredo:** Writing – review & editing, Investigation. **Michael R. Kaplan:** Writing – review & editing, Investigation.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Scientific contributions and associated metadata used in this study is freely available as Supplementary Material

Acknowledgements

This research was funded by the ANID FONDECYT postdoctoral grant #3220537, the ANID BASAL CHIC #FB210018, the ANID national Ph.D. grant #21211234, the ANID FONDECYT Regular #1220550. Authors are grateful to R. Hidalgo and P. I. Moreno for their useful insights during the first stages of this research and to C. Peltier for her guidance on the disscusion.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jsames.2022.104173.

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