Neoglaciation in the American Cordilleras☆

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Concept of Neoglaciation

By the middle of the past century, glacial geologists working in the high mountains of western North America had recognized that moraines near the termini of glaciers, far upvalley from those of the last (i.e., Wisconsin, marine-isotope-stage 2) glaciation, represented small-scale fluctuations of postglacial climate. In the 1930s and 1940s, Francois Matthes of the US Geological Survey published reports concerning his studies in the Sierra Nevada of California and proposed that Sierran glaciers had disappeared at the end of the last glaciation during a time of mild climate, but then were reborn and reached their greatest size after the end of the Pleistocene (**Matthes, 1942**). Previously, it had been widely assumed that modern glaciers were merely shrunken remnants of former large valley glaciers and ice caps and that fresh-looking moraines beyond modern glacier termini were recessional drift bodies left behind as the remaining ice wasted away. Matthes recognized that the large coastal glaciers of Alaska and Canada, as well as large valley glaciers on high Cascade volcanoes, likely persisted throughout the mild postglacial interval, but he inferred that smaller cirque and valley glaciers in the Cascades, Rocky Mountains, and Sierra Nevada disappeared as the climate warmed in postglacial time. He supported his inference by calling attention to a study of Owens Lake, at the eastern foot of the Sierra. **Gale (1914)** estimated that 4000 years were required for the salt content of the lake to reach its modern concentration following the lake's desiccation during a mild mid-postglacial interval and its subsequent regeneration as the climate became cooler and wetter. Matthes postulated that the rebirth of Owens Lake and the nearby Sierran glaciers were responses to the same pattern of postglacial climate change and that the modern Sierran glaciers, therefore, were, in all probability, somewhat < 4000 years old.

Recognition of a "Little Ice Age"

Matthes recognized two sets of young moraines fronting the Sierran glaciers (**Fig. 1**). Those adjacent to the glaciers were unstable and typically ice cored (now known as Matthes), whereas those beyond were shorter, concentric, and stable (now known as Recess Peak). He

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Fig. 1 Oblique view of the northeastern flank of Mt. Brewer showing the twofold moraine sequence common to many cirques in the Sierra Nevada Mountains, California. Image from Google Earth.

surmised that the former were comparable to moraines in the Alps that formed in the 19th century, whereas the latter were several centuries old. Matthes concluded that glacier oscillations of the past few centuries had been among the greatest during the past 4000 years of renewed glacier activity and marked the culmination of a "Little Ice Age," a name that had been proposed by a "clever journalist."

In the six decades since Matthes published his Sierran studies, many additional glacial–geological investigations have clarified the sequence and chronology of Holocene glacier variations, both in the Sierra and throughout the world. The concept of a Little Ice Age is now widely accepted and the term has been formalized by capitalizing it. Nevertheless, its duration and detailed character remain subjects of continuing debate, and its noteworthiness as a glacier event in the context of the entire Neoglacial period has been questioned (**Clague et al., 2009**). Although it is widely agreed that this interval was confined to the past millennium, some place its beginning in the 17th century, whereas others place it as early as the 13th century. Furthermore, accumulating evidence has shown that this interval did not always include the most extensive advance or advances of the middle and late Holocene.

The Hypsithermal Interval

By the mid-19th century, European pollen analysts had identified a series of pollen zones spanning Holocene time, which they designated zones IV–IX. **Deevey and Flint (1957)** recognized an interval (zones V–VIII) of generally mild climate within this series and named it the Hypsithermal interval. The Hypsithermal followed the cool climate of the earliest Holocene time (pollen zone IV ¼ Preboreal) and preceded an interval of cool late Holocene climate (pollen zone IX ¼ Subatlantic). The ages of the zonal boundaries are based on radiocarbon dating (**Mangerud et al., 1982**).

Definition of Neoglaciation

A middle to late Holocene interval marked by repeated episodes of glacier advance has been given various names (e.g., Hypothermal, Katathermal, Medithermal, and Neoglaciation). As a result of its increasing use in the North American Cordillera, **Porter and Denton (1967)** proposed to define Neoglaciation as "the climatic episode characterized by rebirth and/or growth of glaciers following maximum shrinkage during the Hypsithermal interval." They argued that the maximum shrinkage probably coincided with the maximum

Hypsithermal warmth, which, based on evidence available to them, appeared to have occurred between 8000 and 5000 years ago. Further, they called attention to pollen studies in western North America that implied a regionally non-synchronous transition from Hypsithermal to post-Hypsithermal climate, implying that this boundary was latitudinally time transgressive rather than isochronous. They attempted to resolve this problem by defining Neoglaciation as a geological-climate unit (a unit that may lack isochronous boundaries) and suggested that evidence of the initial Neoglacial advance in a given area might fall at any time within the past five millennia. For sure, there is sparse evidence that glaciers advanced at discrete times during the early Holocene (e.g., ca. 11.3, ca. 9.2, ca. 8.2 ka, etc.), but in most mountain ranges, phases of glacier expansion that resulted in net glacier growth following the time of minimal glacial extent initiated during the middle Holocene (8200–4200 cal year BP) and persisted through the late Holocene (4200–0 cal year BP; Walker et al., 2012). As such, this paper focuses on evidence for glacier activity following the early/middle Holocene transition at 8200 cal year BP. In some areas, the early part of Neoglaciation may overlap the later part of the Hypsithermal interval. The Little Ice Age constituted the youngest, and sometimes the only, recognized Neoglacial episode.

Establishing Neoglacial Chronologies

The establishment of a reliable chronology of Neoglaciation depends on accurate dating. Whereas in Europe and Iceland, historical data (e.g., written observations, geographic and topographic maps, paintings, sketches, lithographs, and photographs) that record the position of accessible glacier margins span hundreds of years, in the Western Hemisphere such records seldom extend back more than a century (**Porter, 1981**). For many inaccessible glaciers, historical records began only in the era of aerial photography and satellite imaging. Therefore, geologists have had to rely substantially on several physical, chemical and biological dating methods to develop chronologies, and these have varying degrees of reliability.

Radiocarbon dating commonly provides only maximum or minimum limiting ages for alpine moraines and glacial drift. However, a stacked succession of moraines may include buried soil, peat, or wood that provides bracketing radiocarbon ages for successive moraines (**Fig. 2**). Radiocarbon chronologies can also be developed by dating organic matter in lakes and bogs lying on, behind, or beyond a moraine. The temporal variation in atmospheric radiocarbon means that for Holocene radiocarbon dates to be useful for correlation they should be calibrated using standard calibration curves (Stuiver et al., 1998). Radiocarbon ages in this article are expressed as calibrated ages in ^{14}C cal year BP.

Dendrochronology has been used to date late Holocene deposits particularly effectively in northwestern North America where glaciers terminated in forested areas. The life span of most forest trees is generally less than a millennium, so tree-ring dating based on the oldest tree is mainly applicable for dating middle to late Little Ice Age moraines. Minimum ages for advances have been obtained by coring the oldest trees growing on moraines. Sources of potential error include uncertainty as to whether the oldest tree has been found, the time between moraine construction and germination of the first seedlings, and the time for a seedling to grow to the height at which the tree was cored. Although these factors may lead to underestimating the age of a morainal substrate, in most cases the error range probably is no more than a decade or two. In some circumstances, the culmination of a glacier advance may be determined by coring trees at the ice margin that were tilted but not killed and noting a marked change in the pattern of ring growth due to tree disturbance. One additional use of dendrochronology is to apply cross-dating to glacially transported logs and sheared trees (**Fig. 2**). The age of outer rings of in situ

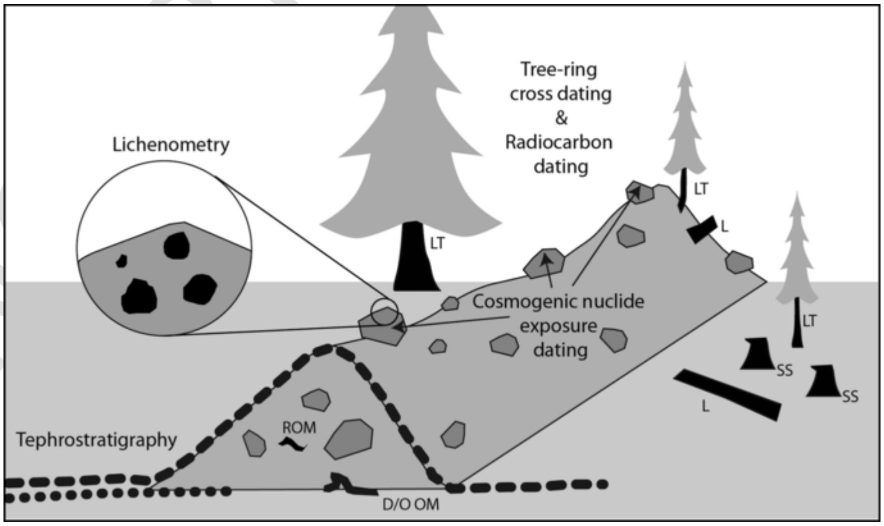

Fig. 2 Common methods used to date moraines. Targets for radiocarbon and tree-ring cross dating are labeled: LT living tree, L log, SS sheared stump, ROM reworked organic material, D/O OM deformed/overridden organic material. *Dashed* and *dotted* lines represent tephra layers.

glacially sheared stumps can provide the year of death, and as such is more precise than radiocarbon dating subfossil wood. Cross-dating the outer rings on multiple glacially mobilized logs can also provide close constraints on the times of past glacier advance, although it is more challenging to build glacier time-distance histories with reworked logs than with in situ stumps.

Lichenometry has been a commonly applied method for dating moraines, particularly in the Brooks Range and the Canadian Arctic. Because of the slow growth rate of the ubiquitous species Rhizocarpon geographicum at high latitudes, the method is applicable to most Neoglacial deposits (albeit with increasing and substantial uncertainty beyond the last millennium). In lower latitude mountains (e.g., the Rockies and Cascades), growth rates are more rapid, permitting high-resolution dating for the past century or two, but the effective range of lichenometry is generally placed within the Little Ice Age. The method has proved somewhat less useful in South America, where long radiocarbon-controlled growth curves are difficult to construct.

Tephrochronology has been used in dating Neoglacial moraines on and downwind from active volcanoes (e.g., in southern Alaska, the Cascade Range, and the Andes). Holocene tephra layers have been dated by means of bracketing radiocarbon dates, and their presence or absence on and/or beneath moraines permits limiting ages to be assigned to glacier advances (**Fig. 2**). In Mt. Rainier National Park, for example, Holocene tephras from eruptions of Mt. Rainier, Mt. St. Helens, and Mt. Mazama provide bracketing ages for Neoglacial moraines.

Radiocarbon-dated sediment records from glacially fed lakes provide continuous records of Neoglaciation. Increasingly used, lake sediment archives of Holocene glacier change are now available from many mountain ranges across the globe, including at many sites throughout the American Cordillera. Although time-distance information is not available in lake sediment records, their continuous nature is valuable for addressing the presence or absence of glaciers in a catchment during the Holocene and the timing of the onset of Neoglaciation. This information is otherwise often difficult to obtain due to the obliterative nature of glacier advances combined with glacier maxima achieved in the last millennium at most locations.

In situ cosmogenic nuclides (e.g., ^{3}He, ^{10}Be, ^{14}C, ^{26}Al, and ^{36}Cl) have been widely used to obtain surface-exposure ages of alpine moraine boulders, especially those of the last glaciation. Chronologies of Holocene deposits based on cosmogenic nuclide exposure dating are being increasingly reported. Advances in analytical capabilities and laboratory procedures allow for surfaces as young as the late Holocene to be more routinely dated. This chronometer allows users to obtain direct ages of moraine boulders, often interpreted to represent the culmination of a glacier advance, in locations where the other methods described above are not applicable due to the absence of appropriate materials. There are caveats to cosmogenic nuclide exposure dating. Although surface erosion and snow shielding commonly are negligible for such young surfaces, other factors that make ages too young might apply. One such factor may be landform degradation, as late Holocene moraines can still be ice cored, and thus are still stabilizing or slowly moving downhill. An additional complication is isotopic inheritance, which yields surfaces with higher ages than their true timing of deposition. Reworked boulders or rock fall deposits are especially prone to inheritance, which sometimes can be revealed by being statistically older than other samples. Inheritance may be more common in cirque glacier systems where rockfall debris comprises a large portion of moraine boulders. In some cases inheritance might be represented by only slightly elevated nuclide concentrations, perhaps stemming from low glacier erosion rates following exposure during the Hypsithermal.

Several of the above dating techniques require moraines (e.g., lichenometry, cosmogenic nuclide exposure dating), and in the absence of moraines, dating methods (e.g., radiocarbon) require the intersection of glaciers and treeline or peat-rich ecosystems. Thus, the existing record of Neoglaciation in the American Cordilleras partly reflects where various dating methods (some that produce more reliable results than others) are suitable to the environment. In most locations, Neoglacial moraines are absent from prior to the Little Ice Age, ruling out exposure dating methods for dating anything but Little Ice Age moraines. High-resolution records of Neoglaciation exist in southern Alaska and western Canada due to the use of dendrochronology, despite glaciers being largest during the Little Ice Age. Radiocarbon dating glacier-overrun wood and peat has led to detailed knowledge in western Canada and in certain locations in the Andes Mountains. These are some reasons why existing knowledge of Neoglaciation in the American Cordilleras is incomplete, which is something to keep in mind when making regional comparisons.

Neoglacial Chronology in the American Cordilleras

Most chronologies of Neoglaciation in Cordillera mountain ranges are from selected areas, spanning from Alaska's Brooks Range to the southern Andes Mountains. A selection of studies, including both classic and recent articles, is reviewed here. In low latitudes, where the snowline is very high, modern glaciers and their Neoglacial predecessors terminated on land and were confined to high cirques, mostly well above 4000 m. In middle latitudes, small valley and cirque glaciers lay at altitudes of 3000–4000 m, with the largest glaciers sometimes on high stratovolcanoes. At higher latitudes, many glaciers terminate in tidewater and experienced advance/retreat cycles, such as those in south-coastal Alaska.

Alaska

Glaciers cover ca. 5% of the state of Alaska, equating to ca. 75,000 km^2 by area (**Molnia, 2007**). Numerous cirque glaciers and small valley glaciers are located in the highest sectors of the Brooks Range, Arctic Alaska. All glaciers lie above or beyond the treeline in a landscape of herbaceous tundra vegetation. Although radiocarbon ages have been obtained for some middle to late Neoglacial moraines, the glacial chronology is based mainly on lichenometric data obtained near the margin of > 100 glaciers, mostly in the central part of the range (**Fig. 3**; **Calkin, 1988**; **Pendleton et al., 2017**). A lichen growth curve that is controlled by radiocarbon dates back to 1300 cal year BP was extrapolated to 8000 years BP, thus spanning all of Neoglaciation. The estimated error range of the ages is ± 20% (i.e., ± 1000 years for the earliest Neoglacial time). Moraines postdating 5000 cal year BP tend to be closely nested and often lie within < 100 m of moraines deposited during the Little Ice Age. Adding to the lichenometry-constrained pattern of Neoglaciation are cosmogenic ^{10}Be exposure ages from seven Holocene moraines (**Pendleton et al., 2017**; **Fig. 3**). Outermost Holocene moraines date to as early as ca. 4500 cal year BP. Other pre-Little Ice Age Neoglacial moraines (ca. 3500, 2500–2000, 1600–1300, and 1100–900 cal year BP) have also been dated. Little Ice Age moraines that border nearly every glacier terminus have lichenometric ages that cluster at 600–900, 300–500, and 90 cal year BP.

Southern Alaska and the Yukon Territory are the most extensively glacierized sector of the Americas and include thousands of small to large land-terminating glaciers, as well as numerous large tidewater-calving glaciers. Holocene chronologies are based mainly on radiocarbon and dendrochronology of logs in glacier forefields, and in a few instances on proglacial sediment records. Away from the coastline, the onset of Neoglaciation is constrained by lake sediments to be ca. 3100 cal year BP in the Ahklun Mountains, and to 4500–4000 cal year BP in the Chugach Mountains (**Levy et al., 2004**; **McKay and Kaufman, 2009**). Neoglacial advances in the northeastern St. Elias Mountains of Yukon Territory culminated 2800, 2600, and 1230–1050 cal year BP and were followed by the most extensive advances of the Holocene during Little Ice Age (**Denton and Karlén, 1977**). In the Wrangell-St. Elias Mountains, Alaska, glaciers advanced at 2700, 1700, and 800 cal year BP, in addition to an advance from the mid-1600s through the 1800s AD (**Wiles et al., 2002**).

In the Kenai Mountains and other ranges that border the Gulf of Alaska, pre-Little Ice Age advances are dated to between 3300 and 2900 cal year BP, around 2000 cal year BP and between approximately 1550 and 1300 cal year BP; this latter advance is referred to as the "First Millennium AD" advance (**Barclay et al., 2009**; **Calkin et al., 2001**; **Wiles et al., 1999**). The First Millennium AD advance, although less extensive than subsequent advances during the last millennium, has been recorded throughout southern Alaska and the Coast Mountains of British Columbia (**Reyes et al., 2006**). Land-terminating glaciers experienced major periods of expansion during the Little Ice Age in the middle 13th, early 15th, middle 17th, and last half of the 19th centuries.

By contrast, large calving tidewater glaciers in this region experience advance/retreat cycles that differ from glacier to glacier: some glaciers advanced while others retreated or were stable. Nevertheless, on the scale of millennia, a gross correspondence can be seen among phases of expansion, which may last nearly 1000 years, and intervals of rapid retreat (**Barclay et al., 2009**; **Calkin et al., 2001**; **Fig. 4**). The record of calving glacier activity has mainly been reconstructed from wood- and peat-bearing deposits exposed by ice recession. Rooted tree stumps, sheared off by advancing ice, have been used to develop ring chronologies that help assess the rate of glacier advance and time of glacier maxima. Around the Gulf of Alaska, episodes of calving glacier expansion seem to have occurred throughout the Holocene. The most extensive advance of calving glaciers coincided with the Little Ice Age, although previous advances achieved similar extents (**Fig. 4**). Several very large glacier systems (e.g., Hubbard, Icy Bay, Glacier bay) retreated significantly (10s–100 km) by the 20th century. Columbia Glacier is the most recent of the major calving glaciers to begin retreating and its terminus is now receding rapidly upfjord; its dramatic retreat follows a relatively stable front since an advance dating to ca. 1000 cal year BP (**Carlson et al., 2017**).

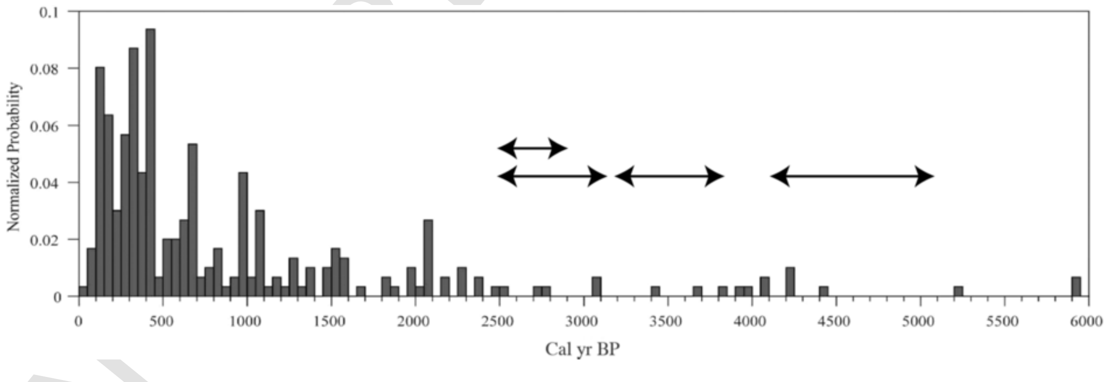

Fig. 3 Histogram of lichenometrically-dated moraines in the Brooks Range, Arctic Alaska. Double-headed arrows represent spread of ^{10}Be ages on pre-Little Ice Age moraines (each *arrow* represents a single dated moraine with multiple ^{10}Be ages). Modified from Pendleton, S.L., Briner, J.P., Kaufman, D.S. and Zimmerman, S.R. (2017). Using Cosmogenic ^{10}Be exposure dating and Lichenometry to constrain Holocene glaciation in the Central Brooks Range, Alaska. *Arctic, Antarctic, and Alpine Research* **49**, 115–132. https://doi.org/10.1657/AAAR0016-045.

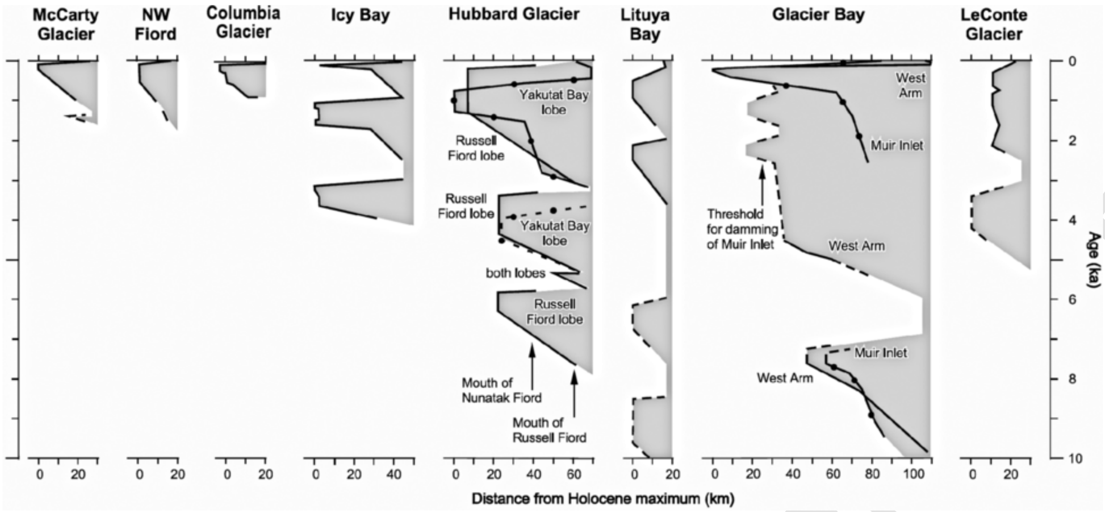

Fig. 4 Holocene records of marine glaciers in southern Alaska. Modified from Barclay, D.J., Wiles, G.C. and Calkin, P.E. (2009). Holocene glacier fluctuations in Alaska. *Quaternary Science Reviews* **28**, 2034–2048. https://doi.org/10.1016/j.quascirev.2009.01.016. Columbia Glacier history added from Carlson, A.E., Kilmer, Z., Ziegler, L.B., Stoner, J.S., Wiles, G.C., Starr, K., Walczak, M.H., Colgan, W., Reyes, A.V., Leydet, D.J. and Hatfield, R.G. (2017). Recent retreat of Columbia Glacier, Alaska: Millennial context. *Geology* **45**, 547–550. https://doi.org/10.1130/G38479.1.

Coast Mountains and Rocky Mountains of British Columbia

Glaciers cover about 27,000 km^2 of western Canada (**Clarke et al., 2015**). At present glacial reconstructions provide the most information about pre-Little Ice Age Holocene glaciation in the North American Cordillera. Middle Holocene advances between ca. 6900–5600 cal ka BP are dated from glacially overridden tree stumps in growth position at Garibaldi Park, southern Coast Mountains (**Fig. 5**; **Ryder and Thomson, 1986**; **Koch et al., 2007**). Evidence for advances during this “Garibaldi Phase” based on radiocarbon-dated wood and proglacial lake sediments are derived from additional sites in the Coast Mountains and in the Rocky Mountains (**Menounos et al., 2009**). The absence of moraines dating to the middle Holocene implies that these early advances were less extensive than later ones.

Following this interval of advancing glaciers during the early Neoglacial was the Tiedemann Advance, originally described in the southern Coast Mountains (**Ryder and Thomson, 1986**), and the Peyto Advance, described in the Rockies (**Luckman et al., 1993**), between 3500 and 1900 cal year BP (**Fig. 5**). Additional evidence for glacier advances during this interval has since been derived from additional radiocarbon-dated fossil wood and from proglacial lake sediments (**Menounos, 2002**).

Recent evidence from radiocarbon-dated fossil wood reveals episodes of glacier advance between the Garibaldi Phase and the Tiedemann-Peyto Advance, occurring at ca. 4900 and ca. 4200 cal year BP (**Menounos et al., 2009**). In the northern Coast Mountains, an advance that culminated 2300 cal year BP was equal to or more extensive than Little Ice Age advances, whereas an advance 1900 cal year BP was as extensive. Evidence of advances from 4400 to 3000 cal year BP and from 2300 to 1800 cal year BP has been found at Bugaboo

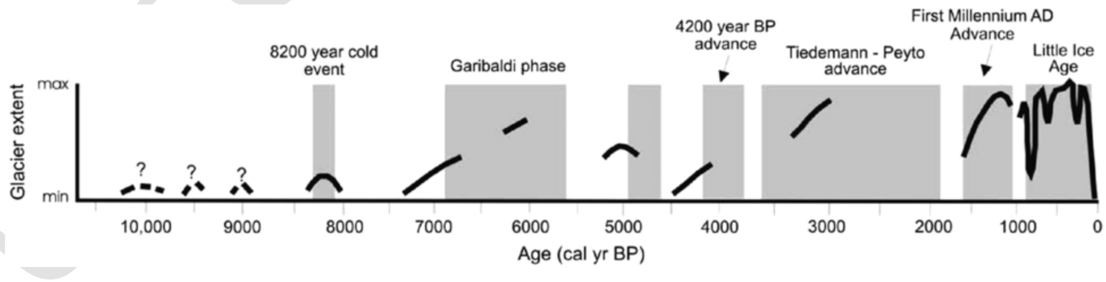

Fig. 5 The glacial record in western Canada. From Clague, J.J., Menounos, B., Osborn, G., Luckman, B.H. and Koch, J. (2009). Nomenclature and resolution in Holocene glacial chronologies. *Quaternary Science Reviews* **28**, 2231–2238. https://doi.org/10.1016/j.quascirev.2008.11.016.

Glacier in the Purcell Mountains (**Osborn and Luckman, 1988**). The First Millennium AD advance (1700–1300 cal year BP), described above, is described at many sites throughout western Canada (**Reyes et al., 2006**; **Menounos et al., 2009**).

The Little Ice Age glacier expansion began shortly before 900 cal year BP and culminated in the 18th or 19th century when most glacier termini reached their maximum Neoglacial limit (**Osborn and Luckman, 1988**; **Ryder and Thomson, 1986**).

Cascade Range

Many of the hundreds of glaciers in the Cascade Range terminate in vegetated terrain where radiocarbon dating of buried wood and soils, lichenometry, and tree-ring dating are feasible methods for dating Neoglacial deposits. Tephrochronology is also applicable, and in a few cases historical data extend back to the middle to late 19th century. Most Neoglacial Cascade moraines date to the 16th, 19th, and 20th centuries, and mark the most extensive position during Neoglaciation. An early advance (5400–5600 cal year BP) was based on in situ glacier-sheared trees that were exposed by ongoing retreat of the South Cascade Glacier, which resides in the North Cascade Range in Washington State (**Miller, 1969**); more recent radiocarbon ages from stumps in this glacier's forefield are 5900–5300 cal year BP (**Osborn et al., 2012**). No moraines of this advance have been identified beyond the Little Ice Age moraines, implying that middle Holocene advances were less extensive than those of recent centuries. Ring counts show that a tree growing on a nearby Chickamin Glacier moraine germinated before AD 1280; this moraine may record the onset of the Little Ice Age in the northern Cascades.

Tephra layers broadly bracket earlier Neoglacial moraines at Mt. Rainier, Washington between 3400 and 2200 cal year BP and 2200 and 450 cal year BP (**Crandell and Miller, 1965**). Elsewhere on Mt. Rainier, at Nisqually Glacier, a 3400-year-old tephra is found immediately adjacent to the outermost Little Ice Age moraine; the Little Ice Age moraine marks the most extensive Neoglacial advance (ca. AD 1825). Recent investigations of lateral moraine till stratigraphy at three Mt. Rainier glaciers led to 11 radiocarbon dated wood fragments indicating an advance of at least two of the glaciers at ca. 1700 cal year BP, potentially part of the First Millennium AD advance described elsewhere (**Samolczyk et al., 2010**); other advances occurred within the Little Ice Age.

Despite glaciers on Mount Baker, in the North Cascades in Washington, being longest during the mid-1800s, stratigraphic evidence combined with radiocarbon dating of buried wood and tephrochronology reveal the onset of Neoglaciation at ca. 6000 cal year BP, followed by advances at ca. 2200, 1600, 900, and 400 cal year BP (**Osborn et al., 2012**). A recent investigation of the central Cascades in Oregon State detailed a few moraines that lie beyond Little Ice Age moraines bracketed by tephra between 7600 and ca. 2000 cal year BP (**Marcott et al., 2009**).

US Rocky Mountains

With the exception of a very few areas, chronology for Holocene glaciation in the US Rocky Mountains is lacking (Davis, 1988). Although earlier workers hypothesized that pre-Little Ice Age moraines at many locations dated to the middle or late Holocene, it has now been confirmed by lake sediment coring and cosmogenic nuclide exposure dating that these moraines date to the latest Pleistocene or in rare cases perhaps the earliest Holocene (Davis, 1988; **Marcott, 2011**). There has yet to be a single location where pre-Little Ice Age Neoglacial moraines are reliably shown to exist, and the dendrochronological approaches used in western Canada are not applicable in the US Rockies where only small extant glaciers are present above treeline. Thus, information on Neoglacial history is sparse. Relative dating techniques and lichenometry applied to rock glaciers may support pre-Little Ice Age Neoglacial activity (Davis, 1988), but drawing conclusions about timing is tenuous. In Glacier National Park, Montana, characteristics of proglacial lake sediments were interpreted to indicate the phases of glacier expansion at ca. 6000, 3700, 2300, and 1500 cal year BP, followed by fluctuations since ca. 700 cal year BP (**Munroe et al., 2012**). These phases of glaciation overlap in timing with glacier expansions in western Canada.

Sierra Nevada

Although the Sierra Nevada might well be considered the "classic" area of the Little Ice Age and Neoglaciation, its geological record of Holocene glaciation, like elsewhere in the western United States, is sparse and rather poorly dated (**Clark and Gillespie, 1997**). The known moraine record is confined mainly to the Little Ice Age, although sediment cores from the Conness Lakes taken downvalley from cirque moraines suggest that Neoglaciation may have begun by 3200 cal year BP (**Konrad and Clark, 1998**; that is, remarkably close to Matthes' original estimate). Moraines of the Little Ice Age are, appropriately, referred to as Matthes-age moraines; on the basis of lichenometry, radiocarbon dating, and tephrochronology, they date to the past 700 years. Lichen ages of 970 and 1100 cal year BP for moraines in the east-central Sierra were reported more than three decades ago, but they have not been confirmed or replicated elsewhere in the range. The most recent effort to learn about Neoglaciation in the range involved rock flour records from multiple lakes downvalley from the Palisade Glacier (**Bowerman and Clark, 2011**). Increases in rock flour beginning ca. 3200 cal year BP indicates the initial growth of the glacier, which was followed by spikes in rock flour at ca. 2200, 1600, 700, and 250–170 cal year BP. It is difficult to know whether the growth of Palisades Glacier marks the onset of Neoglaciation in the Sierra Nevada, or if ca. 3200 cal year BP is when lowering snowline intersected this particular cirque basin.

Northern and Central Andes

Like elsewhere, moraines deposited during the Little Ice Age are ubiquitous throughout the Andes Mountains (**Rodbell et al., 2009**). In very few locations is there robust evidence that moraines lying beyond Little Ice Age moraines date to Neoglaciation. In Cordillera Blanca, northern Peru, radiocarbon ages of ice-pushed peat beyond the Little Ice Age glacier limit constrain an advance to ca. 1500 cal year BP (**Rodbell, 1992**; **Röthlisberger, 1987**), which is consistent with a nearby lacustrine record showing maximum glacier sediment flux at this time (**Rodbell et al., 2008**). There have been many studies on the Holocene history of the Quelccaya Ice Cap, Peru; a recent ^{10}Be dating study concluded that Little Ice Age moraines delimit the most extensive advance of the ice cap in the Holocene (**Stroup et al., 2014**). However, there are clastic sediment flux records (**Rodbell et al., 2008**) and radiocarbon ages on ice-killed vegetation in growth position (**Buffen et al., 2009**) and on ice-pushed peat (**Mark et al., 2002**) suggesting growth of Quelccaya Ice Cap to near its Little Ice Age extent at ca. 5100 cal year BP. Elsewhere in Peru, **Licciardi et al. (2009)** and **Stansell et al. (2015)** use ^{10}Be dating to confirm moraines dating to the Little Ice Age period, and additionally that no pre-Little Ice Age Neoglacial moraines exist. Based on proglacial lake sediment analysis, **Stansell et al. (2014)** indicate that glaciers were only active in the Venezuelan Andes during the Little Ice Age. Finally, in Bolivia, ^{10}Be ages on Little Ice Age and early Holocene moraines reveal that no pre-Little Ice Age Neoglacial moraine exist (**Jomelli et al., 2011**).

Southern Andes

Little Ice Age moraines are found at all the glaciers investigated and fall within the range of 900–100 cal year BP, with the most extensive advances typically occurring between the 16th and 19th centuries (e.g., **Masiokas et al., 2009**). A majority of available ages provide only minimum limiting constraints on earlier phases of Neoglaciaiton, and the assumption commonly made is that these ages are closely limiting. However, some ages provide only broad age brackets (sometime within a 1500-year interval, or sometime after 3300 years ago, for example), making close age assignment and reliable correlations challenging. Furthermore, moraines deposited by tidewater- or lake-calving glaciers may be out of phase with the regional pattern, as is the case with such glaciers in coastal Alaska.

Numerous publications have led to a reasonable picture of Neoglaciation in the southern Andes. Moraines of the southern Andes that predate the Little Ice Age have been dated mainly by radiocarbon analysis of in situ or glacier-transported trees in nested moraine sequences and of basal peat in bogs on moraines or in meltwater channels. Tree-ring chronologies have been developed for some Little Ice Age moraine sequences. There seems to be some evidence from multiple locations for phases of glaciation more extensive than the Little Ice Age glacier limit during the middle Holocene. **Strelin et al. (2008)** suspect that ice extended beyond the Little Ice Age limit ca. 7000–6000 cal year BP, but cannot rule out that it occurred during the latest Pleistocene. **Douglass et al. (2005)** dated the Fachinal moraines using ^{10}Be and ^{36}Cl to ca. 8000 and ca. 6000 cal year BP, although there have been production rate and scaling updates since that time (e.g., Kaplan et al., 2011), and the ages calculated today would likely be somewhat older. **Rodbell et al. (2009)** concluded that due to wide age distributions and possible inheritance, a latest Pleistocene age of the Fachinal moraines could not be ruled out. **Espizua (2005)** interpreted minimum radiocarbon ages to suggest a glacier advance at ca. 5900 cal year BP, whereas **Harrison et al. (2012)** use optically-stimulated luminescence dating beyond the San Rafael Glacier, North Patagonia Icefield, to suggest phases of glaciation greater in extent than during the Little Ice Age at ca. 7.7 and ca. 5.7 ka. Finally, **Menounos et al. (2013)** found evidence in some, but not all, valleys that they studied for a glacier phase, slightly more extensive than the eventual Little Ice Age limit, dating between ca. 7500–5200 cal year BP. Collectively, although not well dated, there seems to be a body of evidence for a middle Holocene glacier phase more extensive than glaciers were during the Little Ice Age.

Heusser (1960) and Mercer (1970, 1976, 1982) pioneered research into the timing of Neoglaciation in the southern Andes, which largely took place around the Patagonian Ice Fields. Building from this pioneering threefold pattern of Neoglaciation, and based on a large amount of accumulated radiocarbon ages constraining the ages of glacier deposits, **Aniya (2013)** proposed five glacier phases at 4500–4000, 3600–3300, 2700–2000, 1600–900 cal year BP and from the 17th to 19th centuries. At the Southern Patagonian Icefield, **Strelin et al. (2014)** combined radiocarbon and ^{10}Be dating to provide relatively tight constraints on a sequence of Neoglacial moraines (**Fig. 6**). An early glacier phase smaller in extent relative to later phases occurred at ca. 7700–7200 cal year BP. This was followed by the deposition of three moraines, representing sequentially shorter glaciers, but all beyond the Little Ice Age limit, at 6000–5000, 2500–2000, and 1500–1000 cal year BP. Slightly upvalley are Little Ice Age moraines dating to ca. 700, > 400, and < 300 cal year BP. Farther south in Tierra del Fuego, **Strelin et al. (2008)** used radiocarbon dating to date pre-Little Ice Age advances at ca. 3400 and 1200–700 cal year BP, in addition to confirming the most extensive Neoglacial moraines belonging to the Little Ice Age period. **Glasser et al. (2002)** radiocarbon dated advances to just prior to the Little Ice Age, but within last millennium (between AD 1220 and 1340).

Onset of Neoglaciation

Because Neoglaciation is defined as the first phase of glacier growth following the Holocene minimum extent, the onset of Neoglaciation is expected to be spatially non-uniform. In addition, in mountainous areas not currently glaciated, a later onset for Neoglaciation may be

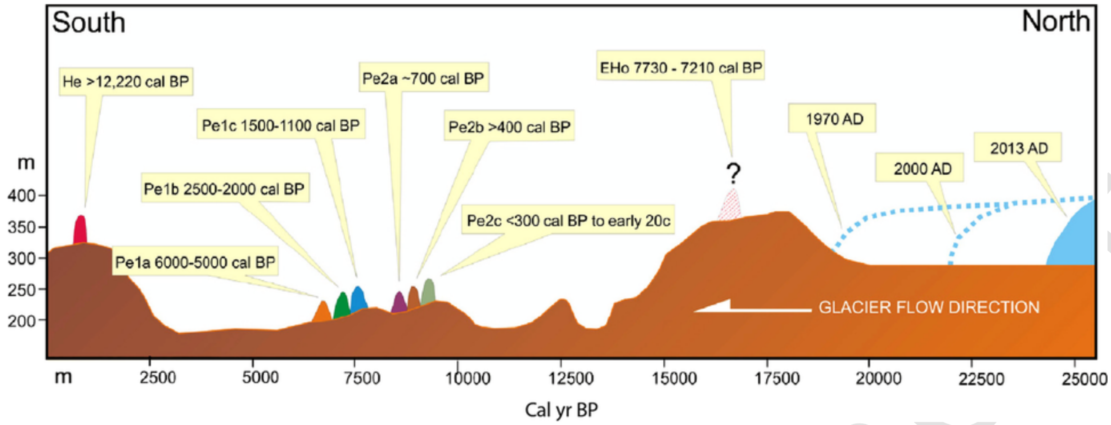

Fig. 6 The record of Holocene glaciation from the southern Patagonia Icefield. From Strelin, J.A., Kaplan, M.R., Vandergoes, M.J., Denton, G.H. and Schaefer, J.M. (2014). Holocene glacier history of the Lago Argentino basin, Southern Patagonian Icefield. *Quaternary Science Reviews* **101**, 124–145. https://doi.org/10.1016/j.quascirev.2014.06.026.

due to the simple fact that regional snowline did not lower across cirque floors until cooling had already progressed somewhat. Finally, the patchy geologic record itself, leading to an incomplete record of Holocene glaciation, further complicates interpretations of the onset of Neoglaciation.

In some locations in the American Cordilleras, there is morainal evidence for latest Pleistocene glacier phases, and moraines date to the early the Holocene in a few locations, such as the Andes Mountains (**Douglass et al., 2005**; **Jomelli et al., 2017**) and maybe in the US Rocky Mountains (**Marcott, 2011**), although the dating there is less secure. According to the definition of Neoglaciation, glacier phases that generally date between ca. 7000 and ca. 6000 cal year BP mark the onset of Neoglaciation. These occur in both the North American Cordillera (Garibaldi phase in western Canada) and at various locations in the South American Cordillera. In almost all locations, this glacier phase was less extensive than subsequent phases; perhaps at some locations in southern South America there are moraines dating to this phase, implying that glaciers were more extensive than during the Little Ice Age at this time (**Douglass et al., 2005**; **Harrison et al., 2012**; **Menounos et al., 2013**).

Temporal Pattern of Glacier Variations

Following the earliest glacier phase during the middle Holocene, data from throughout the American Cordilleras support the next glacier phases beginning ca. 5000 cal year BP. In fact, glacier advances between ca. 5000 and ca. 4000 cal year BP probably delimit the most widespread occurrence of Neoglacial activity throughout the Americas. Following this interval, there is evidence for glacier advances in almost every millennium. Given the fragmentary nature of the geologic record (most glacier advances in this time period were within Little Ice Age glacier extents), it is difficult to pinpoint discrete intervals of glacier advance and common time periods between glacier advances. Between 4000 and 2000 cal year BP, almost all mountain ranges contain evidence for advancing glaciers.

Examples are (1) the Tiedemann-Peyto advance(s) (ca. 3000 cal year BP) in western Canada, (2) the 3600–3300 and 2700–2000 cal year BP advances, and the 2500–2000 cal year BP moraine, from Patagonian glaciers, (3) spikes in glacier flour in Montana at 3700 and 2300 cal year BP, (4) a moraine on Mt. Rainier dating to 3400–2200 cal year BP, (5) ca. 3500 and 2500–2000 cal year BP moraines in the Brooks Range and (6) a 3300–2900 cal year BP advance in the Kenai Mountains.

In the last 2000 years there is increasing evidence for glacier advances. It is difficult to know if this is due to the fact that the record of glaciation is simply more complete, or if glaciers were nearer their eventual Little Ice Age extents, or both. Prominent among pre-Little Ice Age advances in this interval is the First Millennium AD advance, where glaciers in coastal Canada and Alaska experienced widespread, coherent advances ca. 1700–1300 cal year BP. This interval may be equivalent with the Dark Ages cool climate period in Europe. Glacier advances during this interval are also prevalent throughout the Andes Mountains. Moraines dating throughout the last millennium have been broadly assigned to the Little Ice Age cool period. In some locations, glacier advances date to the early portion of the last millennium, making it difficult to know whether or not to assign the advances to Little Ice Age cooling or not; this is a testament to the challenge of attributing glacier advances to a specific climate interval, and conversely, defining a climate interval based on the glacier record. Most glacier advances in the last millennium culminated within the well-accepted definition of the Little Ice Age.

In only few locations in the Northern Cordillera do middle or late Holocene moraines exist beyond the Little Ice Age extent of glaciers. These are at Mt. Rainier (one glacier; **Crandell and Miller, 1965**), some glaciers in Oregon (**Marcott et al., 2009**) and the Brooks Range (**Pendleton et al., 2017**). In the Brooks Range, cold, slow-moving cirque glaciers produced nested and superposed moraines that occasionally include early Neoglacial deposits. This limited older moraine record in the Brooks Range may in part be due to

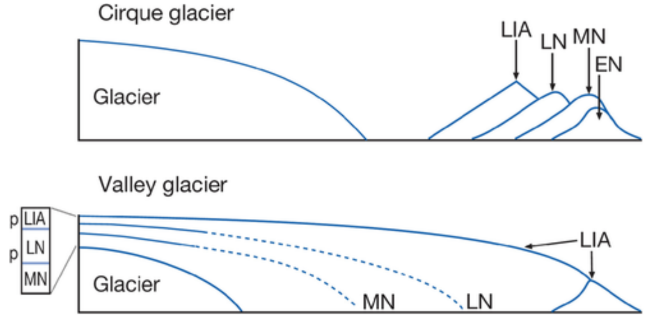

Fig. 7 Moraine records of cirque and valley glaciers. *Top*: Neoglacial moraine succession of a small cirque glacier in which the oldest moraine (EN, early Neoglaciation) has acted as a barrier to the glacier during later advances. Advancing ice may run up against older moraine barriers, developing a stacked sequence, and it may override them, burying the older deposits. MN, middle Neoglaciation; LN, late Neoglaciation; LIA, Little Ice Age. (*Bottom*) Successively more extensive advances of a valley glacier override earlier moraines (*dashed lines*) along the valley floor, with the Little Ice Age advance being the greatest of Neoglaciation. Evidence of earlier advances is preserved in lateral-moraine stratigraphy in which buried soils (p), sometimes log- and stump-bearing, separate deposits of successive advances.

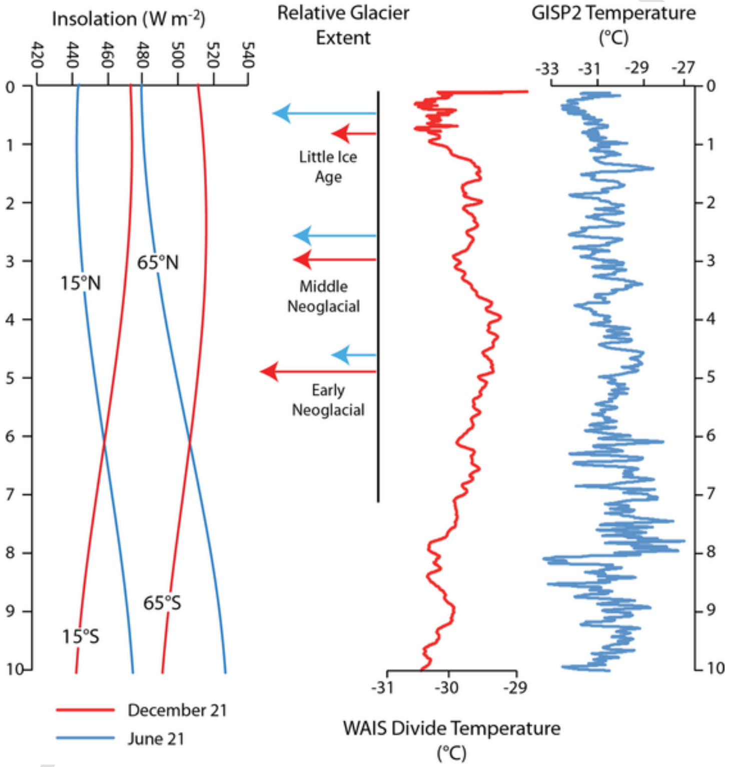

Fig. 8 Relative extents of Neoglacial moraines in the North and South American cordilleras compared with (A) the summer insolation received at different latitudes and (B) key paleotemperature records from the northern and southern hemispheres. According to the "orbital hypothesis" of Holocene glaciation, in northern North America, insolation was lowest and glaciers were most extensive during the Little Ice Age. And, in southern South America, glaciers were most extensive early in Neoglaciation when insolation was lowest, and glaciers shrank as insolation increased toward the Little Ice Age. In reality, it seems that southern insolation may not be the dominant control on southern Hemisphere temperature. GISP2 data from Kobashi, T., Menviel, L., Jeltsch-Thömmes, A., Vinther, B.M., Box, J.E., Muscheler, R., Nakaegawa, T., Pfister, P.L., Döring, M., Leuenberger, M., Wanner, H. and Ohmura, A. (2017). Volcanic influence on centennial to millennial Holocene Greenland temperature change. *Scientific Reports* 7. https://doi.org/10.1038/s41598-017-01451-7 and WAIS Divide data from Cuffey et al. (2015).

younger glacier advances being re-directed by older, bulky moraines, and not exclusively due to climate forcing of more extensive pre-Little Ice Age glaciation (**Fig. 7**). In the Southern Cordillera, the existence of pre-Little Ice Age moraines appears to be more common, particularly in the southern Andes Mountains. One example is glaciers draining the Southern Patagonian Icefield, where **Strelin et al. (2014)** dated several pre-Little Ice Age moraines to 6000–5000, 2500–2000, and 1500–1000 cal year BP (**Fig. 6**). This pattern of pre-Little Ice Age moraines existing beyond Little Ice Age moraines is mirrored at glacier fronts in New Zealand (e.g., **Putnam et al., 2012**).

In terms of climate forcing of glacier pulses, several mechanisms have been proposed. Millennial-scale forcing from summer insolation is thought to drive the broad pattern of net glacier growth or recession on the Holocene timescale, and is discussed further below. On centennial timescales, solar and volcanic forcing have been proposed to control changes in glacier length (**Denton and Karlén, 1973**; **Porter, 1981**), but making these correlations requires a level of precision in glacier chronologies that is the exception rather than the rule (cf. Wiles et al., 2004; **Miller et al., 2012**). In fact, a recent synthesis of Holocene glaciation concluded that attributing glacier length changes to solar and volcanic forcing remains somewhat ambiguous, and further research on mechanisms relating solar and volcanic perturbations to glacier length changes is needed (**Solomina et al., 2015**).

Hemispheric Contrasts in Relative Glacier Extent?

It has been hypothesized that the pattern of relative glacier extent during the Holocene relates to the hemispheric contrast in insolation (incident solar radiation) forcing. In the southern Andes, summer insolation (and perhaps summer temperature) was lowest in the early Holocene, when some glaciers reached maximum extents, but insolation became progressively higher approaching the Little Ice Age when glaciers were smaller (**Fig. 8**). By contrast, in the Northern Hemisphere, insolation was initially high during the early Holocene and decreased toward the Little Ice Age. The maximum Neoglacial ice extent would be predicted to occur during the Little Ice Age.

According to this "orbital hypothesis," valley glaciers in the southern Andes reached their greatest extent during early Neoglacial time, with successive subsequent limits diminishing in extent. And, in the northern Cordilleras, Little Ice Age moraines would represent the most extensive advances. Is this pattern supported by glacier reconstructions? It appears that pre-Little Ice Age moraines are indeed more often preserved in southern Andes, whereas in the northern Andes and throughout the northern Cordillera, pre-Little Ice Age moraines are rare. It is difficult to know whether the fact that there are exceptions to this (e.g., there are valleys in the southern Andes where Little Ice Age moraines mark the maximum Neoglacial extent, and there are valleys in the northern Cordillera where pre-Little Ice Age moraines exist) means that the orbital forcing hypothesis is not supported, or rather that it relates to noise within the system (glacier response time, moraine funneling).

To further investigate the likelihood of the orbital forcing hypothesis, one could draw on representative Holocene temperature reconstructions that only recently became available. Plotting GISP2 temperature (**Kobashi et al., 2017**) along side temperature reconstruction from the West Antarctic Ice Sheet (WAIS) Divide site (**Cuffey et al., 2016**), which arguably represents the high latitudes in both hemispheres, shows both similarities and differences (**Fig. 8**). What is not apparent is a simple opposite temperature history that pure insolation forcing would produce. One could investigate further by looking at temperature compilations from lower latitudes, such as the composite reconstructions from **Marcott et al. (2009)**. Taken together, these reconstructions all show that in the Southern Hemisphere there is late Holocene cooling compared with earlier millennia, beginning 4000–3000 cal year BP. The exercise also reveals the Little Ice Age as the coldest period within Neoglaciation, although the WAIS Divide record and the 30°S–30°N band from **Marcott et al. (2009)** display equally low temperatures prior to ca. 7000–8000 cal year BP. That early Holocene temperatures were as low as the Little Ice Age in these temperature reconstructions is consistent with the preservation of early Holocene moraines in parts of South America (e.g., **Licciardi et al., 2009**; Jomelli et al., 2011, 2017; **Strelin et al., 2014**), not to mention a similar moraine pattern in New Zealand (**Putnam et al., 2012**).

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