



The Northeast Pacific Ocean and Northwest Coast of North America within the global climate system, 29,000 to 11,700 years ago

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ABSTRACT

The Northwest Coast of North America stretches 4000 km from Bering Strait to Washington State. Here we review the history of glaciation, sea level, oceanography, and climate along the Northwest Coast and in the subarctic Pacific Ocean during the Last Glacial Maximum and deglaciation. The period of interest is Marine Isotope Stage 2 between ca. 29,000 calendar years ago (29 ka) and 11,700 calendar years ago (11.7 ka). The glacial history of the Northwest Coast involved multiple glacial systems responding independently to latitudinal variations in climate caused by changes in the North American ice sheets and in the tropical ocean-atmosphere system. Glaciers reached their maximum extents 1–5 kyrs later along the Northwest Coast than did large sectors of the Laurentide and Fennoscandian Ice Sheets. Local, Last Glacial Maxima were reached in a time-transgressive, north to south sequence between southwestern Alaska and Puget Sound. The history of relative sea level along the Northwest Coast during Marine Isotope Stage 2 was complex because of rapid isostatic adjustments by a thin lithosphere to these time-transgressive glacial fluctuations. Multiple lines of evidence suggest Bering Strait was first flooded by the sea after 11 ka and that it probably did not assume its present-day oceanographic functions until after 9 ka. The coldest intervals occurred during Heinrich Event 2 (ca. 26–23.5 ka), again between ca. 23 and 21.5 ka, and during Heinrich Event 1 (ca. 18–15 ka). During these times, mean annual sea surface temperatures cooled by 5° to 8° C in the Gulf of Alaska, and glacial equilibrium-line altitudes fell below present sea level in southern Alaska and along the Aleutian Island chain. Sea ice episodically expanded across the subarctic Pacific in winter. Oceanographic changes in the Gulf of Alaska tracked variations in the vigor of the Asian Summer Monsoon. The deglaciation of the Northwest Coast may have served as the trigger for global climate changes during deglaciation. Starting ca. 21 ka, marine-based glaciers there were increasingly destabilized by rising eustatic sea level and influxes of freshwater and heat associated with the rejuvenation of the Asian Summer Monsoon. Rapid retreat of marine-based glaciers began ca. 19 ka and released large numbers of ice bergs and vast amounts of freshwater into the Northeast Pacific. Resultant cooling of the North Pacific may have been tele-connected to the North Atlantic through the atmosphere, where it slowed Atlantic Meridional Overturning Circulation and initiated the global effects of Heinrich Event 1, ca. 18–15 ka. During the Younger Dryas, ca. 12.8–11.7 ka, mean annual sea surface temperatures were 4° to 6° C cooler than today in the Gulf of Alaska, and sea ice again expanded across the subarctic Pacific in winter. Conditions of extreme seasonality characterized by cold, dry winters and warm, steadily ameliorating summers caused by the southward diversion of the Aleutian Low in winter may explain the previously enigmatic records of Younger Dryas climate along the Northwest Coast.

1. Introduction

The energy gradient between low and high latitudes which fuels the general circulation in the atmosphere and ocean implies that the dynamics of glacial-interglacial cycles cannot be understood without the tropics.

Berger et al. (2006)

The ice-age history of the Northwest Coast of North America (Fig. 1) is important because this 4000-km coastline is the interface between North America and the North Pacific Ocean. As a result, its climate is largely a function of the ocean/atm system of the North Pacific. Because the Northwest Coast lies upwind from much of North America, its paleoenvironmental history strongly influenced that of the rest of the

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continent. Our purpose here is to update and expand an early review of Northwest Coast paleoenvironments (Mann and Hamilton, 1995) with the wealth of new information that has emerged from multiple fields of inquiry over the intervening thirty years.

The focus here is on the last glacial cycle, which corresponds roughly to Marine Isotope Stage 2 (MIS 2), the Last Glacial Maximum and deglaciation, considered here as the interval 29,000 to 11,700 calendar years Before Present (hereafter 29 ka to 11.7 ka). This was a period of repeated, global changes in glaciers, sea ice, ocean circulation, and storm tracks (Clark et al., 2012; Shakun et al., 2012). These changes afford an opportunity to understand how the planet's ocean/atm/cryosphere systems respond to forcing from a variety of external drivers and internal interactions, some of which are either absent or of minor importance in the present-day system. MIS 2 also saw dramatic shifts in the distributions of plants and animals, including the earliest dispersal of people from Eurasia into North America. Although still debated, the route taken by the First Americans may have followed the Northwest Coast (Fladmark, 1979; Willerslev and Meltzer, 2021). Because of space limitations, this review concentrates on the physical aspects of the Northwest Coast's paleoenvironments.

Today, the ocean/atm system of the subarctic Pacific and the Northwest Coast is linked to tropical systems through a complex system of teleconnections (SI Section 1). These teleconnections operate through both oceanic tunnels (e.g., the Kuroshio Current) and atmospheric bridges (e.g., the Aleutian Low). Understanding how these connections worked in the past may help predict their future behaviors. The tropics are the heat engine of the global ocean/atm system, and the underlying premise of this review is that changes at high latitudes can only be understood through their connections with the tropics.

2. Paleoenvironmental records from the Northwest Coast and Subarctic Pacific

2.1. Glacial history

2.1.1. “Cordilleran Ice Sheet” or “Cordilleran Glacier Complex”?

It is useful to define some terminology before reviewing the extent and timing of glaciation along the Northwest Coast. During the global

Last Glacial Maximum (hereafter, LGM), the Northwest Coast was lined by marine-based glaciers that drained ice masses accumulated over the western Cordillera of North America (Fig. 2). Chamberlin (1895) referred to this assortment of ice caps, valley glaciers, and piedmont glaciers as the “Cordilleran Ice Sheet”. Although often depicted as a single, confluent body of ice extending from Washington State to southwestern Alaska, in fact this accumulation of ice consisted of a myriad of glaciologically independent glaciers. This was particularly



Fig. 2. Distribution of glaciers and ice sheets (blue) during the Last Glacial Maximum at high latitudes in the northern hemisphere. Dashed lines show extent of subaerial Arctic continental shelves at times of lowest relative sea level. Redrawn from Ehlers et al. (2011) and Simms et al. (2019). The numbers are estimates of the meters of eustatic sea-level draw-down contained in different ice sheets. Estimates of sea-level drawdown are from Simms et al. (2019) and Stokes et al. (2012). “CGC” = Cordilleran Glacier Complex, “LIS” = Laurentide Ice Sheet, “FIS” = Fennoscandian Ice Sheet.

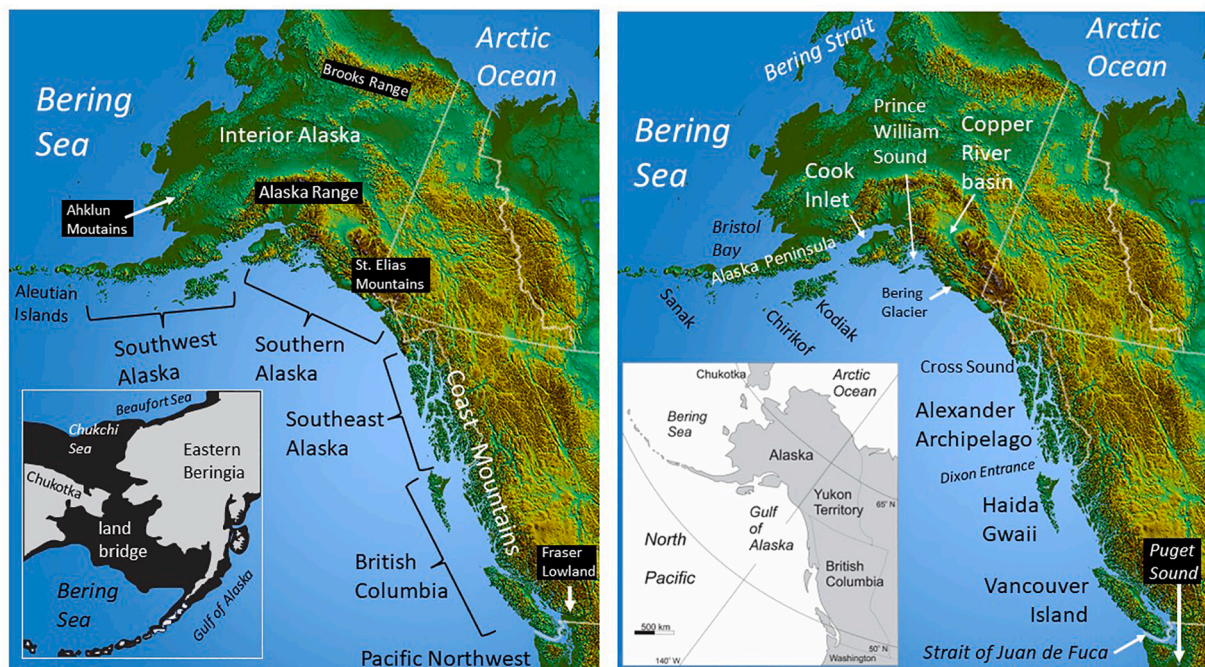


Fig. 1. The Northwest Coast of North America. The Bering Land Bridge (lower left) is shown as it existed at the height of the last ice age.

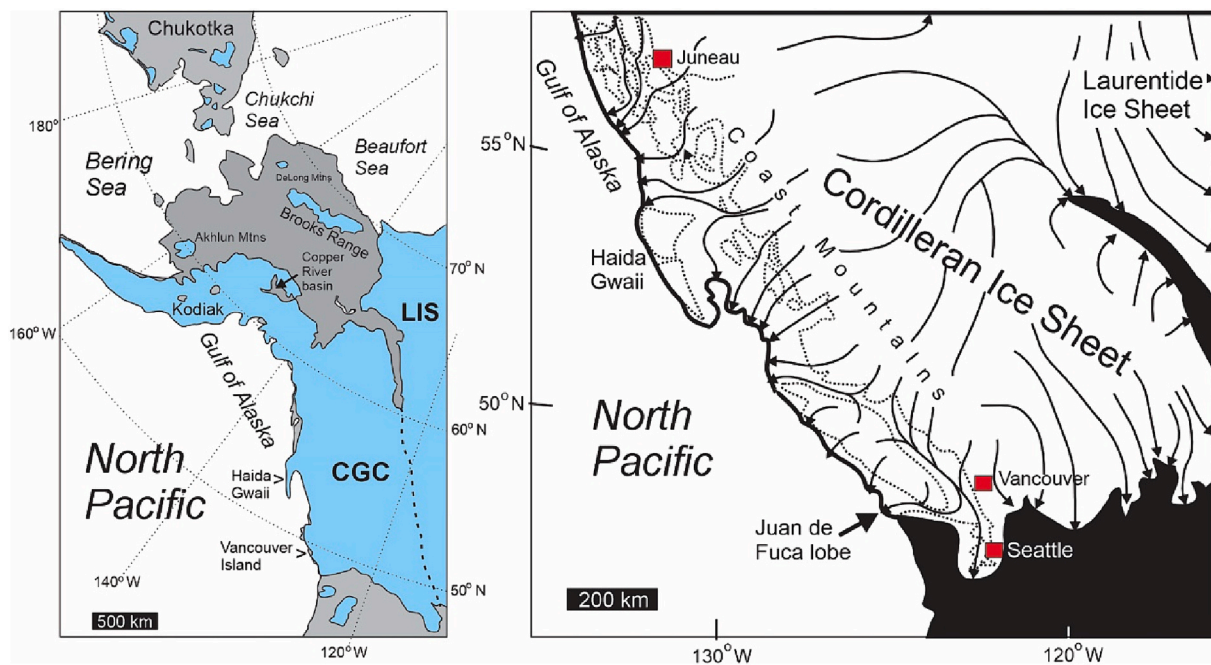


Fig. 3. **LEFT** The Cordilleran Glacier Complex (CGC) consisted of numerous, glaciologically independent glacier systems. The extent of glacial ice in northwestern North America ca. 21 ka is from [Dalton et al. \(2020\)](#). Ice extent in Chukotka is from [Barr and Clark \(2012\)](#), and ice extent in the DeLong Mountains is from [Hamilton \(2010\)](#), and in the Brooks Range from [Kaufman et al. \(2011\)](#). “LIS” = Laurentide Ice Sheet. **RIGHT** The only fully integrated, ice-sheet portion of the CGC occupied the interior highlands of British Columbia and Alberta, and this was only for brief intervals during Marine Isotope Stage 2. Generalized flow patterns shown as arrows. Redrawn from [Clague and James \(2002\)](#).

true in the high ranges of the southwest Yukon and southern Alaska, where the dynamics of different glaciers were coordinated only in the sense of responding to shared climate drivers, and, in the case of glaciers reaching tidewater, by changes in relative sea level that affected how much ice was lost by calving icebergs into the sea. Only in south-central sector of the Cordilleran Glacier Complex in British Columbia ([Fig. 3](#)) where bedrock plateaux allowed the formation of coalescent ice domes during the local LGM was there a degree of glaciological integration comparable to that occurring in the Laurentide Ice Sheet ([Clague, 1989; Clague and Ward, 2011; Perkins and Brennand, 2015; Seguinot et al., 2016; Menounos et al., 2017; Eyles et al., 2018](#)).

The assortment of glaciers present over northwestern North America during Marine Isotope Stage 2 is more appropriately called the Cordilleran Glacier Complex than the Cordilleran Ice Sheet. The term “complex” is more appropriate because an ice sheet is glaciologically integrated ([Bates and Jackson, 1987](#)), while a glacier complex is not. The Laurentide Ice Sheet (LIS), for example, at its maximum extent flowed radially from a 3 km-high ice dome centered over the lowlands of the Canadian Shield ([Marshall et al., 2000; Dyke et al., 2002; Dalton et al., 2020](#)). The different sectors of the LIS were dynamically integrated at a continental scale ([Winsborrow et al., 2004; Stokes et al., 2016](#)). In contrast, large sectors of the Cordilleran Glacier Complex (CGC) consisted of relatively thin ice whose flow was topographically segregated into independent ice bodies ([Clague, 1989; Clague et al., 2011; Eyles et al., 2018](#)). This was particularly true during deglaciation as mountain ridges emerged from the down-wasting ice ([Fulton, 1991; Margold et al., 2013; Menounos et al., 2017](#)). An immediate benefit of recognizing the CGC as a “complex” rather than an “ice sheet” is to recognize the high potential for asynchronous glacier fluctuations ([Darvill et al., 2018](#)). This tendency that was accentuated further along the Pacific coast by the presence of numerous marine-based glaciers whose dynamics were susceptible to non-climatic drivers ([Benn et al., 2007; Stokes et al., 2014](#)).

2.1.2. Major features of the Cordilleran Glacier Complex

The Cordilleran Glacier Complex (CGC) developed when alpine glaciers expanded and coalesced ([Kerr, 1934](#)). Infrequently during the most glaciogenic phases of the late Pleistocene, glaciers thickened enough to form one or more ice domes over the interior of British Columbia ([Clague and James, 2002](#)) ([Fig. 4](#)), and the formation of these domes caused the flow axis to shift eastward of the Coast Mountains ([Stumpf et al., 2000](#)). Even in this southern, ice-sheet portion of the CGC, deglaciation was geographically complex compared to much of the Laurentide Ice Sheet because of the alpine topography ([Clague, 1989; Clague and Ward, 2011; Margold et al., 2013; Perkins and Brennand, 2015](#)).

Salient features of the Cordilleran Glacier Complex (CGC) include: 1) Its wide latitudinal range. Its northernmost glaciers terminated in the subarctic landscapes of Interior Alaska, while its southernmost glaciers overrode forests in Washington, Idaho, and western Montana. 2) Its 4000-km long marine margin. Many of the CGC’s outlet glaciers and ice streams flowed onto the continental shelf where they were marine-based, which meant their beds were positioned at or below contemporary sea level. 3) Its North Pacific moisture source. Unlike the Laurentide Ice Sheet (LIS), the CGC was nourished almost entirely by North Pacific moisture. 4) Its numerous warm-based glaciers. Because of its maritime position and relatively low altitudes and latitudes, significant portions of the CGC were at the pressure-melting point ([Booth and Hallet, 1993; Clague and James, 2002](#)). 5) Its complexity of flow. In contrast to much of the LIS, the CGC developed over mountainous terrain ([Clague and James, 2002](#)). 6) Its pronounced dynamism. The relatively small sizes and warm basal temperatures of many of the glaciers comprising the CGC made them respond rapidly to changing climate. Glaciers flowing into the sea were vulnerable to rapid retreats driven by iceberg calving.

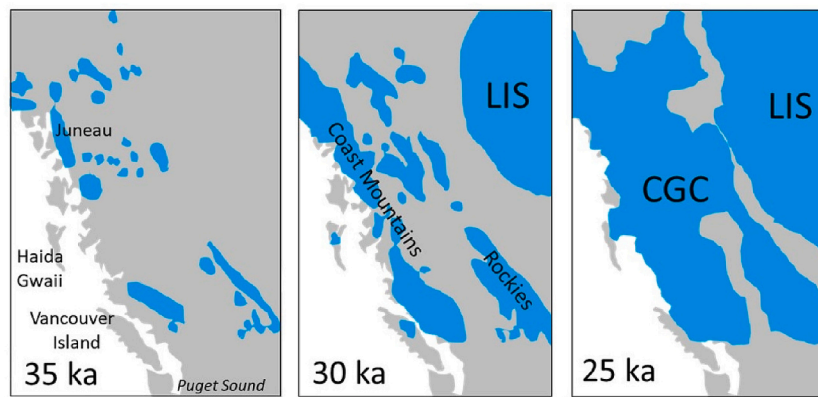


Fig. 4. The expansion of the Laurentide Ice Sheet (LIS) and the Cordilleran Glacial Complex (CGC) during the onset of Marine Isotope Stage 2 as inferred by Clague and Ward (2011). Note that by 30 ka the LIS was expanding westward as an integrated ice sheet, while the CGC was still coalescing from multiple alpine ice caps.

2.1.3. Timing and extent of the Marine Isotope Stage 2 glaciation along the Northwest Coast

2.1.3.1. Puget Sound and southwestern British Columbia. Following a prolonged interstadial during Marine Isotope Stage 3 (ca. 57–29 ka), glaciers coalesced and advanced out of the southern Coast Mountains and the highlands of Vancouver Island beginning ca. 30 ka (Clague, 1981; Clague and James, 2002; Clague and Ward, 2011) (Fig. 5). Ice first reached the Fraser Lowland and northern Puget Sound during the Coquitlam Stage, accompanied by an advance of alpine glaciers in the Cascade Mountains (Booth et al., 2003; Porter and Swanson, 2008). After a standstill or a minor retreat between 23 and 21 ka, the Puget Lobe advanced rapidly into Puget Sound, crossing the site of Seattle ca. 17.6 ka and reaching its maximum extent near present-day Olympia, Washington ca. 17 ka (Porter and Swanson, 1998). The maximum extent of the Puget Lobe lasted <500 years (Menounos et al., 2009). Meanwhile, another ice lobe flowed westward down the Strait of Juan de Fuca to terminate on the continental shelf (Hendy and Cosma, 2008; Taylor et al., 2014). During this Vashon Stage, alpine glaciers descending from the Cascade and Olympic Mountains coalesced with the main flow of ice originating in Canada (Riedel et al., 2010), while east of the Cascade Mountains, ice lobes advanced down the Okanagan valley and the valleys further east (Porter, 1976; Booth et al., 2003; Balbas et al., 2017). Some of these ice lobes, including the Purcell Lobe near the present Idaho/Montana border, dammed lakes whose repeated outburst floods

may have affected the oceanography and climate of the entire North Pacific (Section 4.1.9).

The Vashon Stage ended with the rapid retreat of ice out of Puget Sound beginning before 16 ka (Fig. 5). This rapid retreat probably began when the Juan de Fuca Lobe was dislodged from its terminal moraine shoal by rising sea level (Clague and Ward, 2011; Taylor et al., 2014). By 15.5 ka, Puget Sound was ice free, and a large calving embayment had formed in the Strait of Georgia near the International Border (Menounos et al., 2009; Clague and Ward, 2011). Abrupt warming at the onset of the Bølling ca. 14.7 ka reduced the ice volume of the Cordilleran Glacier Complex (CGC) in western Canada by approximately half in <500 years (Menounos et al., 2017). In inland regions where the CGC existed as an integrated ice sheet, rapid melting gave rise to an assortment of independent alpine glaciers and ice caps by the end of the Younger Dryas, ca. 11.7 ka (Menounos et al., 2017).

As the ice withdrew into the Coast Mountains and the North Cascades, marine waters invaded the isostatically depressed landscapes of Puget Sound and the Fraser Lowlands (Thorson, 1989; Dethier et al., 1995; Clague and James, 2002; Mosher and Hewitt, 2004). In southern Puget Sound, short-lived proglacial lakes formed and then drained as their outlets were progressively uncovered as the ice margin retreated northward and down-wasted.

2.1.3.2. Western coast of Vancouver Island. Alpine glaciers advanced from the mountainous interior of Vancouver Island ca. 30 ka, prior to the island being overtopped by mainland ice flowing west out of the Coast Mountains (Clague and Ward, 2011). The local Last Glacial Maximum (ILGM) on Vancouver Island occurred between 20 and 15 ka (Darvill et al., 2018). The outer, western coast of the island was glaciated last and deglaciated first, which resulted in relatively brief periods of glacial cover (Hebda et al., 2022). Grounded ice reached the outer coast at different times in different places. For example, Topknot Lake on the northwestern outer coast was overrun by ice before 17.1 ka (Hebda et al., 2022), while Port Eliza on the central, outer coast was not overrun until after 16.3 ka (Al-Suwaidi et al., 2006). The seaward extent of glaciation remains unclear (Darvill et al., 2018), and some locations on the northwest coast of Vancouver Island may have escaped glaciation (Hebda, 1997; Hebda et al., 1997; Hebda et al., 2022). Areas further south along the western coast of Vancouver Island that were covered by ice were deglaciated prior to 16 ka (Al-Suwaidi et al., 2006).

Marine records off the western coast of Vancouver Island add valuable details to the record of glaciation (Fig. 6). Glaciomarine sedimentation began ca. 29.5 ka (Cosma and Hendy, 2008). Episodes of iceberg rafting became increasingly frequent after ca. 19.5 ka, with a major peak in the deposition of ice-berg rafted debris (IRD) occurring ca. 17–16, which was coeval with the Vashon Stage maximum in Puget Sound and its initial retreat. A later spike in IRD deposition occurred off the western

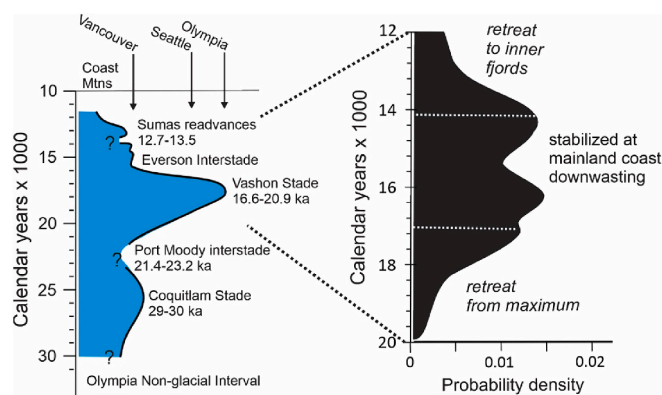


Fig. 5. **LEFT** Time/distance diagram for southwest British Columbia and Puget Sound during Fraser Glaciation (Porter and Swanson, 1998; Booth et al., 2003; Darvill et al., 2018) modified from Cosma and Hendy (2008). **RIGHT** The timing of glacial retreat along the central British Columbia coastline between Vancouver Island and Southeast Alaska expressed as the probability density of exposure ages (Darvill et al., 2018; Darvill et al., 2022).

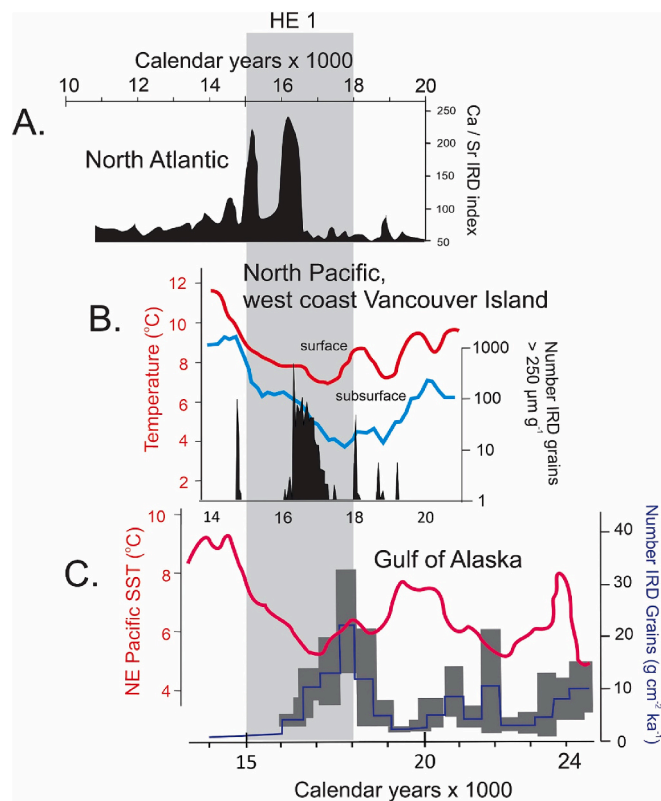


Fig. 6. Marine records of deglaciation inferred from ice-rafted debris (IRD) and sea surface temperature (SST). **A.** The IRD record from Site U1308 in the North Atlantic (Hodell et al., 2017). **B.** IRD concentrations and ocean temperatures inferred from planktonic foraminiferal Mg/Ca records in Core MD02–2496 from the continental slope of Vancouver Island, British Columbia (Taylor et al., 2014). **C.** IRD accumulation rates in Core U1419 from the northeastern the Gulf of Alaska (Walczak et al., 2020). The red line shows the mean annual SST in the Gulf of Alaska as estimated by Praetorius et al. (2023).

coast of Vancouver Island ca. 14.8 ka at the beginning of the Bølling interstadial (Cosma and Hendy, 2008; Taylor et al., 2014) (Fig. 6).

2.1.3.3. Central British Columbia coast and Haida Gwaii. The central British Columbian coast extends from Vancouver Island to Dixon Entrance (Fig. 3). Haida Gwaii (Queen Charlotte Islands) has been a focus of research concerning glaciation and relative sea level because of its unique geography and biogeography. The archipelago lies on the outer edge of the continental shelf and is separated from the mainland by 50–150 km of shallow marine waters (Hecate Strait and Queen Charlotte Sound) (Fig. 7). Its biogeography is unusual because of the occurrence of endemic, genetically unique, and disjunct species (Heusser, 1989; Godbout et al., 2008; Shafer et al., 2010; Pruett et al., 2013; Mathewes et al., 2015; Fedje et al., 2021). The occurrence of some of these unique taxa may relate to the presence of ice-free areas that afforded biological refugia during Marine Isotope Stage 2. Reconstructions of glacier extent and timing are necessary to identify where and when these ice-free areas and biological refugia might have existed (Heusser, 1960; Clague, 1981; Mathewes and Clague, 2017; Shaw et al., 2020; Fedje et al., 2021).

During an extended period of interstadial climate between 50 and 31 ka, temperate rainforest vegetation grew in the lowlands of Haida Gwaii under a climate only slightly cooler than today (Warner et al., 1984; Mathewes et al., 2015). The western edge of the Cordilleran Glacier Complex advanced into Hecate Strait ca. 30 ka, and after ca. 24 ka merged with alpine glaciers flowing eastwards from the uplands of Haida Gwaii (Blaise et al., 1990; Barrie and Conway, 1999; Mathewes and Clague, 2017). This coalescence was probably short-lived because of

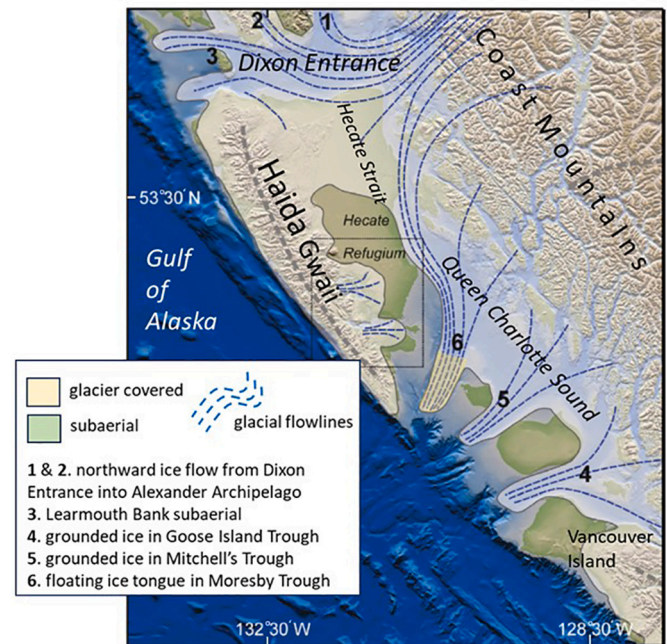


Fig. 7. Glacier extent and locations of possible ice-free areas around Haida Gwaii and in Queen Charlotte Sound during the local Last Glacial Maximum between ca. 24 and 18 ka. Modified slightly from Shaw et al. (2020).

the relatively small size of glacier catchments on Haida Gwaii and because the proximity of the open Pacific Ocean prevented the buildup of thick glacial ice over the islands. As a result, areas on the western coast of Haida Gwaii, which borders the outer shelf edge, possibly remained ice-free and subaerial during the local LGM (Barrie et al., 2021).

During the local Last Glacial Maximum (ILGM) ca. 24 to 18 ka, multiple ice streams flowed onto the continental shelf north and south of Haida Gwaii through Dixon Entrance and eastern Hecate Strait (Eyles et al., 2018). Ice reached thicknesses of ~400 m in Queen Charlotte Sound (Barrie and Conway, 1999) and ~700 m in northern Hecate Strait and Dixon Entrance (Hetherington et al., 2004). These ice streams calved into the open Pacific along the outer shelf edge (Fig. 7), leaving only thin and transient glacier margins to advance westward across Hecate Strait to merge with the glaciers flowing eastwards from Haida Gwaii (Barrie et al., 2021). The steep gradient in ice thickness between the inner fjord zone of the mainland and the outer shelf generated an isostatic forebulge that caused relative sea level to fall below –150 m along the eastern coastline of Haida Gwaii prior to 14 ka (Hetherington et al., 2004) (Section 2.2). This resulted in large areas of Queen Charlotte Sound lying above sea level until this forebulge collapsed and eustatic sea level flooded the area ca. 10 ka (Fedje and Josenhans, 2000; Fedje et al., 2005; Shaw et al., 2020).

Lowland areas on Haida Gwaii and the adjacent continental shelf may have become ice-free before ca. 19.4 ka (Blaise et al., 1990; Mathewes and Clague, 2017; Darvill et al., 2018), although alpine glaciers persisted in the uplands. Minimum-limiting ages from cosmogenic exposure dating indicate that ice derived from the Coast Mountains had retreated eastward to the mainland coast by 17 ka (Barrie and Conway, 1999), and perhaps as early as 18 ka (Darvill et al., 2018; Barrie et al., 2021). Upon reaching the mainland coast, the ice margin paused and possibly readvanced between ca. 17 and 14 ka (Fig. 5) (Darvill et al., 2018; Darvill et al., 2022). During this 17–14 ka readvance or standstill along the central British Columbia coast, the interior portions of the Cordilleran Glacier Complex continued to downwaste and thin (Darvill et al., 2022). Glaciers underwent a final, fluctuating retreat into the inner, mainland fjords between 14 and 13 ka (Hetherington et al., 2004;

Eamer et al., 2017; Barrie et al., 2021; Darvill et al., 2022).

2.1.3.4. An ice-free area / refugium on Haida Gwaii? Building on the studies of Barrie and Conway (1999, 2002), Barrie et al. (2009), Hetherington et al. (2004), and Josenhans (1994), Josenhans et al. (1997), Shaw et al. (2020) and Barrie et al. (2021) reconstructed the paleogeographies of Dixon Entrance, Hecate Strait, and Queen Charlotte Sound during the local Last Glacial Maximum (ILGM) and subsequent deglaciation (Fig. 7). Their reconstructions suggest that grounded ice from the mainland flowed southwards in the coast-parallel trough along the eastern (mainland) side of Hecate Strait. Upon reaching Queen Charlotte Sound, this ice stream split and flowed through three, cross-shelf troughs to empty into the open Pacific. In a pattern familiar from glaciated continental shelves elsewhere (Wellner et al., 2001; Nielsen et al., 2005; Batchelor and Dowdeswell, 2014), the cross-shelf troughs in Queen Charlotte Sound were separated by low-relief banks, which Shaw et al. (2020) suggest remained unglaciated and subaerial. With relative sea level lowered by >150 m (Josenhans et al., 1997; Shugar et al., 2014) (Section 2.2), an ice-free, subaerial area measuring roughly 150 km long and 10–50 km wide may have existed along the eastern side of Moresby Island, the southern major island of the Haida Gwaii group. This potentially ice-free area, which Shaw et al. (2020) relate to the “Hecate refugium” inferred to exist by Mathewes and Clague (2017) based on paleoecological evidence, would have consisted of an outwash plain criss-crossed by proglacial rivers. During the ILGM, the borders of this ice-free area would have repeatedly shifted in response to changes in glacier positions and sea level (Josenhans et al., 1997). It remains to be demonstrated whether this ice-free area provided a biological refugium. If it did, the biota it sheltered were probably limited to arctic-alpine species.

More certain is the existence of extensive ice-free and subaerial

surfaces in Hecate Strait and Queen Charlotte Sound between ca. 18 and 10 ka. When by 17.6–16.6 ka, mainland ice had retreated to the present coastline (Darvill et al., 2018, 2022), and the ice cap over Haida Gwaii had retreated into the island highlands, some 40×10^3 km² of present-day Queen Charlotte Sound and Hecate Strait were ice-free and subaerial (Shaw et al., 2020). This extensive lowland remained subaerial until ca. 10 ka when the sea transgressed the area (Josenhans et al., 1997; Shugar et al., 2014) (Section 2.2).

2.1.3.5. Southeast Alaska (Alexander Archipelago). The Alexander Archipelago (Fig. 1) extends 500 km northward from Dixon Entrance to Cross Sound and 200 km westward from the Coast Mountains to the Gulf of Alaska. The archipelago consists of island massifs bordered by strandflats along the outer Gulf of Alaska coastline (Fig. 8). During the local Last Glacial Maximum (ILGM), island ice caps coalesced with glaciers originating in the Coast Mountains and sent ice streams seaward through fjords to calve on the continental shelf (Capps, 1931; Holtedahl, 1958; Carrara et al., 2007; Lesnek et al., 2018; Lesnek et al., 2020; Barrie et al., 2021). Since the 1930s, biologists have speculated that ice-free areas were present in the Alexander Archipelago and sheltered biota during the last ice age (Hultén, 1937; Heusser, 1960; Klein, 1965; Heusser, 1989; Heaton et al., 1996; Cook et al., 2001; Carrara et al., 2007; Ager, 2019); however, the existence of biological refugia in Southeast Alaska remains controversial (Walcott et al., 2022), much as it is on Vancouver Island (Hebda et al., 2022) and Haida Gwaii (Mathewes and Clague, 2017; Fedje et al., 2021).

A major advance in understanding the glacial geology of the Alexander Archipelago occurred when Lesnek et al. (2018) showed that cosmogenic dating was feasible in this temperate-rainforest setting by using ice-scoured bedrock surfaces and glacially transported boulders above present tree line. These exposure ages indicate that regional

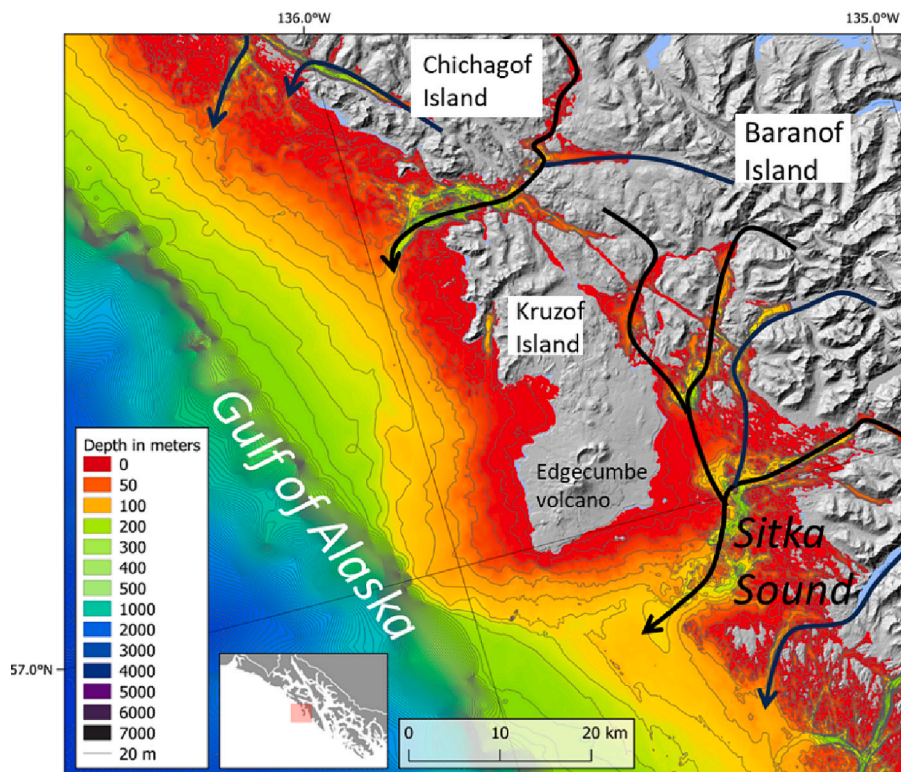


Fig. 8. A representative area of the outer coast of the Alexander Archipelago showing the relatively narrow (20–40 km) continental shelf and the well-developed strandflat (< 50 m water depth). This strandflat was incised by glaciers issuing from the fjord systems that crisscross the archipelago. The strandflat is less-developed near southern Kruzof Island because of the Quaternary volcanic deposits of Mount Edgcombe. Arrows show the inferred flow patterns of major outlet glaciers. The geomorphic imprint of glaciation is relatively light along this coastline compared to farther northwest along the Gulf of Alaska. Bathymetric data are from Zimmermann and Prescott (2015); the map is generated in QGIS v3.26.2. The onshore digital elevation model is from Zabihi et al. (2021).

deglaciation was underway by 17.7 ± 0.7 ka (Lesnek et al., 2018). Additional exposure-age dating has narrowed the timing of ice retreat from the outer coastline to between 17 and 15 ka and showed that ice had retreated eastward to the coast of the mainland before 14 ka (Lesnek et al., 2020).

Mountainous, fjord-land topography complicates interpretation of the chronology of glacial dynamics in the Alexander Archipelago. The fjords may have been deglaciated first through the calving retreats of marine-based glaciers, leaving island ice caps perched on the intervening uplands (Baichtal et al., 2021). On the other hand, in similar terrain along the outer coast of Norway, high-altitude surfaces were deglaciated early and remained subaerial for millennia before adjacent fjord became ice free (Regnéll et al., 2022). Deciphering the pattern of deglaciation in Southeast Alaska will require cosmogenic dating of surfaces ranging in elevation from sea level to mountain ridges.

Additional cosmogenic dating by Walcott et al. (2022) suggests that ice retreated from the outer coast of the northern Alexander Archipelago (Chichagof and Baranof Islands) ca. 15.1 ± 0.9 ka, and from the outer coast of the southern archipelago ca. 16.3 ± 0.8 ka. The cessation of ice-rafted debris deposition in the Gulf of Alaska ca. 14.8 ka suggests that most marine-based glaciers had retreated onto land by then (Davies et al., 2011; Praetorius and Mix, 2014). These estimates for deglaciation timing are consistent with the basal ages of freshwater lakes (Engstrom et al., 1990; Ager and Rosenbaum, 2009; Ager et al., 2010; Ager, 2019) and with the ages of marine shells associated with glacio-marine deposits at various locations in the Alexander Archipelago (Mann and Streveler, 2008; Baichtal et al., 2021).

More closely limiting ages on the local Last Glacial Maximum (LLGM) in the southern Alexander Archipelago come from the ^{14}C ages of bones recovered from On Your Knees Cave (in Tlingit language: *Shuka Káa*) (Heaton et al., 1996; Heaton and Grady, 2003; Lesnek et al., 2018). This cave is located at 56° N on northern Prince of Wales Island approximately 125 m above present sea level, 40 km east of Chatham Strait, 60 km inland from the outer coastline, and approximately 140 km from the outer edge of the continental shelf. *Shuka Káa* was the den of Arctic foxes (*Vulpes lagopus*) and contains the abundant bones of ringed seal (*Pusa (Phoca) hispida*), an ice-dependent seal species now restricted to the

northwest Pacific, the Arctic Ocean, and parts of the North Atlantic. Twenty-six ring seal bones from the cave range in age from 30 to 14 ka. The only time interval when the error terms of consecutive ^{14}C ages do not overlap is between 19.8 and 17.2 ka, suggesting this was the only time when the cave was sealed off from the ocean, presumably by overriding glacial ice (Lesnek et al., 2018). This unique chronostratigraphic evidence suggests the LLGM was brief and of limited extent in the southern Alexander Archipelago. The *Shuka Káa* record constrains the LLGM in Southeast Alaska to at most a 2.6-kyr interval that occurred 3 to 4 kyr after the Laurentide Ice Sheet reached its maximum in the Great Lakes region (Heath et al., 2018), 0.5 to 1 kyr after the time of maximum glaciation in the northwestern Alaska Range (Tulenko et al., 2022) (Section 2.1.3.12), and 0.5–1.5 kyr prior to the LLGM in Puget Sound (Porter and Swanson, 1998) (Section 2.1.3.1).

It remains unclear how complete ice cover was over the Alexander Archipelago. Prior to the advent of exposure-age dating, it was thought that ice buried all but the highest summits of the Alexander Archipelago and terminated in a continuous, calving margin along the outer continental shelf (Mann and Hamilton, 1995). Carrara et al. (2007) and Lesnek et al. (2020) suggested that certain areas along the outer coast remained ice-free throughout the Last Glacial Maximum. The ring-seal chronology from *Shuka Káa* is consistent with limited, short-lived ice cover; however, Walcott et al. (2022) suggest that even outer coast areas were glaciated until 16.3 to 15.1 ka. These latter authors imply that ice extended onto the continental shelf along the entire seaward margin of the archipelago, an interpretation that is consistent with the reconstruction of ice flowing to the shelf break in Queen Charlotte Sound and Dixon Entrance (Shaw et al., 2020; Barrie et al., 2021).

In summary, the local Last Glacial Maximum (LLGM) occurred in Southeast Alaska between 19.8 and 17.2 ka, which is later than the southern margins of the Laurentide and Fennoscandian Ice Sheets, but prior to the LLGM in Puget Sound. Because the LLGM occurred in Southeast Alaska after 20 ka when eustatic relative sea level was rising, marine-based ice streams draining the Alexander Archipelago would have been increasingly destabilized, even in the absence of major shifts in climate. Deglaciation proceeded quickly and involved rapid calving retreats beginning ca. 17 ka and intensifying after 16 ka. As with the

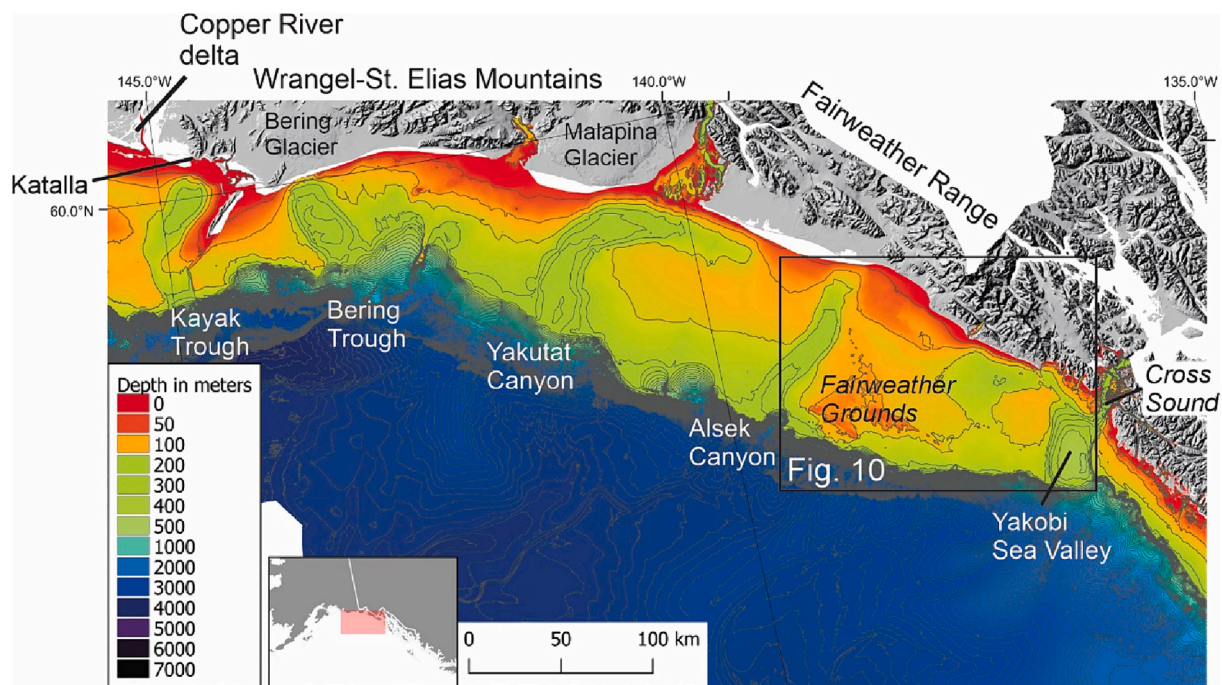


Fig. 9. Cross-shelf troughs attest to prolonged, intense glaciation of the continental shelf between the Yakobi Sea Valley and the Copper River delta. Bathymetric data are from Zimmermann and Prescott (2015); the map is generated in QGIS v3.26.2. The onshore digital elevation model is from Zabihi et al. (2021).

calving retreats of other marine-based ice complexes (Small et al., 2018), fjord topography/geometry in some cases superseded climate in determining the spatial and temporal pattern of glacier retreat in the Alexander Archipelago. The western margin of the Cordilleran Glacier Complex had retreated to the inner fjords of the Coast Mountains by 14 ka. If ice-free areas did exist in Southeast Alaska during the ILGM, they were located on outer coast mountainsides and/or near the outer edge of the continental shelf where the presence of an isostatic forebulge (Hetherington et al., 2004; Shaw et al., 2020; Baichtal et al., 2021; Barrie et al., 2021) allowed them to persist during deglaciation despite rising sea level. Striking progress has been made in deciphering the extent and timing of the LGM in Southeast Alaska. The next step is to sample exposure ages along topographic gradients in order to reconstruct glacier flowlines, trimline altitudes, equilibrium-line altitudes, and the seaward extent of ice on the continental shelf.

2.1.3.6. Southern Alaska: Cross Sound to the Copper River delta. The coastline between Cross Sound and the Copper River delta (Fig. 9) is backed by glaciated peaks rising to 6000 m asl. Rapid tectonic uplift since the Oligocene (Lease et al., 2021) has outstripped topographical lowering by glacial erosion (Merrand and Hallet, 2001). Embayments are widely separated and consist of fjord mouths, some still occupied by glaciers, including the piedmont lobes of the Malaspina and Bering Glaciers. Repeated glaciations have left widespread evidence of glacial erosion and glaciomarine sedimentation on the continental shelf (Carlson et al., 1982; Molnia, 1986; Eyles and Lagoe, 1990; James et al., 2009a; Gulick et al., 2015). These glacial features include moraines, mega-scale glacial lineations, drumlins, trough-marginal moraines, cross-shelf troughs, inter-trough banks, trough-mouth fans, grounding-zone wedges, ice-proximal fans, and thick accumulations of glaciomarine sediment (Swartz et al., 2015; Zimmermann and Prescott, 2015; Montelli et al., 2017; Clary et al., 2021). The accumulation of these glaciogenic features over a 23-million year history of marine-based glaciation makes it challenging to identify the glacial limits reached during Marine Isotope Stage 2.

The extent of glaciers on the continental shelf of the northern Gulf of Alaska during the Last Glacial Maximum (LGM) has been the topic of continued speculation (Capps, 1931; Karlstrom, 1964; Coulter et al., 1965; Péwé, 1975; Molnia, 1986; Hamilton, 1994; Manley and Kaufman, 2002; Dyke, 2004; Kaufman et al., 2011; Dalton et al., 2020; Haeussler et al., 2022). Based solely on the geomorphology of the continental shelf, which remains largely undated, LGM ice probably flowed to the outer shelf edge throughout the region. Previous reconstructions show glacier tongues extending seaward through the cross-shelf troughs, with the inter-trough banks remaining ice free (Molnia, 1986; Kaufman et al., 2011; Dalton et al., 2020); however, based on what is known from glaciated continental shelves in Iceland (Geirsdóttir et al., 2009) and western Norway (Laberg et al., 2000; Ottesen et al., 2005; Batchelor and Dowdeswell, 2014; Montelli et al., 2022), these inter-trough banks were probably also ice covered, albeit by thinner and less-dynamic ice than the ice streams in the troughs.

Recent compilations of the bathymetry of the continental shelf (Zimmermann and Prescott, 2015), together with the mapping of fish habitats (Greene et al., 2011), reveal moraines and possible glacial trimlines on the inter-trough banks between the Yakobi Sea Valley and the Alsek Canyon (Fig. 10). The presence of multiple moraines there suggest a complex glacial history during Marine Isotope Stage 2 (MIS 2). Of particular interest are the Fairweather Grounds, a 540-km² area of exposed bedrock that protrudes as much as 80 m above the surrounding continental shelf and shoals at a depth ~ 24-m (Greene et al., 2011). Acoustic mapping suggests the presence of an erosional trimline (Greene et al., 2007) that could delineate the seaward extent of inter-trough, glacial ice during MIS 2. If this interpretation is correct, then glaciers did not reach the outer shelf edge here during the local Last Glacial Maximum.

Much of what is known about the glacial history of this sector of the Gulf of Alaska coastline during Marine Isotope Stage 2 comes from marine cores. Basal organics in a core from the Yakobi Sea Valley date to ca. 15 ka, suggesting deglaciation occurred around that time (Barron et al., 2009). Multiple peaks in ice-rafted debris in the northeastern Gulf of Alaska indicate a complex pattern of glacier retreat interrupted by either stillstands or readvances of marine-based ice. Bouts of iceberg-rafted debris (IRD) deposition occurred offshore of the Bering Glacier ca. 25–23, 22, and 21 ka, followed by a peak in deposition between 18.5 and 16.5 ka, which was immediately before or possibly during the early stages of Heinrich Event 1 (HE 1) (Walczak et al., 2020) (Fig. 6). In a sediment core taken closer to the Bering Glacier, Cowan et al. (2020) found broad peaks in IRD deposition between 26.5 and 24 ka and again between 18.5 and 17 ka. Freshening of ocean surface waters occurred ca. 16.7 ka, probably in response to widespread melting of ice during regional glacial retreat (Davies et al., 2011). A transition to hemipelagic, laminated sediment in the same cores ca. 14.8 ka indicates that most of the formerly marine-based glaciers retreated onto land by that time, causing iceberg calving to cease (Davies et al., 2011; Praetorius and Mix, 2014).

Onshore, Sirkin and Tuthill (1987) dated basal peat near Katalla near the eastern edge of the Copper River delta to 15.8–17.9 ka. Chapman et al. (2009) dated a basal peat on Wingham Island, also near Katalla, to 13.8–14 ka, while Peteet (2007) obtained basal peat dates from the Bering Glacier foreland as old as ca. 16 ka. Taken together, these minimum-limiting ¹⁴C dates indicate the Bering Glacier had retreated from the present coastline between 16 and 14 ka. The Bering Glacier had retreated even further inland than its present terminal position before 12 ka, possibly as early as 14 ka (Molnia and Post, 1995).

2.1.3.7. Prince William Sound. During the Last Glacial Maximum (LGM), glaciers from the Chugach and Kenai Mountains converged in Prince William Sound (PWS) and buried island massifs there under ~700 m of ice (Fig. 11). Two ice streams flowed out of PWS into the Gulf of Alaska, one on either side of Montague Island, and then crossed the continental shelf to terminate at the shelf break (Haeussler et al., 2015; Haeussler et al., 2022). Information about the chronology of glaciation in PWS is fragmentary. A minimum-limiting date of 14.1–15.0 ka on ice retreat comes from Upper Whitshed Lake near the western edge of the Copper River delta (Garrett et al., 2015). Another limiting date on deglaciation comes from the town of Valdez where Reger (1991) dated terrestrial plant remains to 15.6–12.7 ka. Exposure-age dating suggests ice had retreated from northwestern Prince William Sound before 14.3 ± 1.6 ka and from sites near sea level in west-central Prince William Sound before 12.9 ± 1.1 ka (Haeussler et al., 2022).

Farther west, the fjord-indented coastline of the Kenai Peninsula attests to a long history of erosion by marine-based glaciers (Fig. 11). Glacial troughs, inter-trough banks, and well-preserved end moraines suggest glaciers flowed to the outer shelf edge there during the local Last Glacial Maximum (Haeussler et al., 2022); however, these features remain undated. The presence of drowned cirques along this coastline suggests that glacier equilibrium-line altitudes fell below present-day sea level during the local Last Glacial Maximum (Péwé, 1975).

2.1.3.8. Cook Inlet Lowland. The glacial history of the Cook Inlet Lowland during Marine Isotope Stage 2 (MIS 2) was spatially and temporally complex and remains poorly understood (Briner et al., 2017). Much of what is known about the Quaternary history of this region comes from the work of Richard Reger and his colleagues (Reger et al., 1995; Reger and Pinney, 1997; Reger et al., 2008b), who in turn built on the exploratory work of Karlstrom (1964). The Cook Inlet Lowland occupies a structural trough surrounded by mountain ranges (Fig. 11). Its watershed drains some 100,000 km² of the southern flank of the Alaska Range into the Gulf of Alaska. During the local Last Glacial Maximum (ILGM), multiple piedmont lobes expanded into the Cook Inlet Lowland

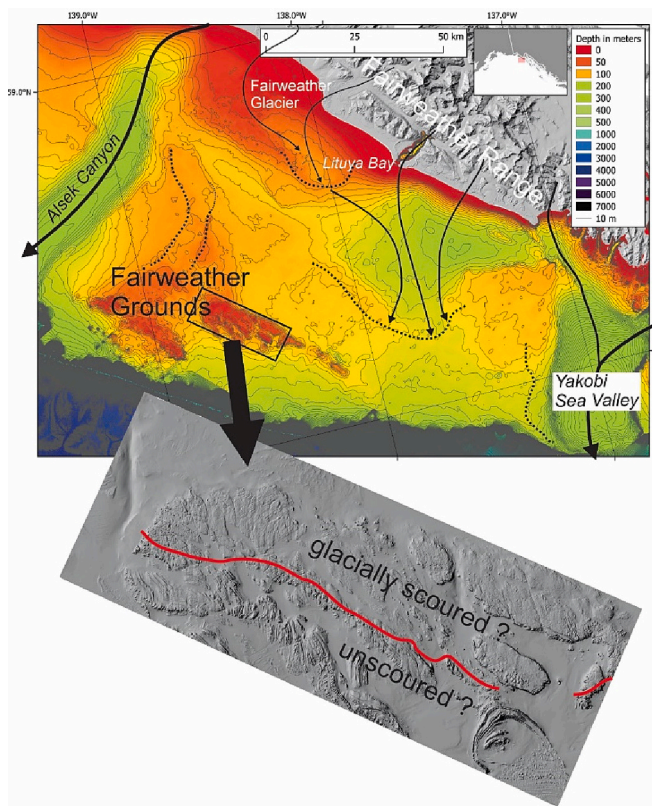


Fig. 10. The Fairweather Grounds on the outer continental shelf between the Yakobi Sea Valley and the Alsek Canyon may have escaped glaciation during Marine Isotope Stage 2. Hypothetical glacial flowlines are shown as solid arrows. Dashed lines show possible moraines. Ice streams probably flowed to the outer shelf edge through the cross-shelf troughs; however, moraines on the intervening banks suggest limited ice cover there. Mapping of fish habitats revealed a possible glacial trimline on the Fairweather Grounds (Greene et al., 2007; Greene et al., 2011). Age control over these submerged features is presently lacking. Bathymetric data are from Zimmermann and Prescott (2015); the map generated in QGIS v3.26.2. Onshore digital elevation model is from Zabihi et al. (2021).

from all sides. Because precipitation declined and equilibrium altitudes rose towards the north/inland (Péwé, 1975), glaciation was most intense at the seaward end of Cook Inlet (Fig. 11). Based on trimline altitudes and estimates of equilibrium-line altitudes, Mann and Peteet (1994) suggested that ice reached a thickness of at least 300 m at the mouth of Cook Inlet during the ILGM. The presence of high-level (410 m) glacial scouring on the Barren Islands in the mouth of Cook Inlet, together with the presence there of volcanic erratics transported from the Alaska Peninsula suggest that Cook Inlet ice flowed through the Amatuli Trough to reach the outer shelf edge (Fig. 11). Ice also overflowed low passes in the Aleutian Range to feed the ice lobe that filled the Iliamna Basin in the headwaters of Bristol Bay (Stilwell and Kaufman, 1996). During MIS 2, marine-based ice masses in lower Cook Inlet and on the inner continental shelf repeatedly dammed lakes in upper Cook Inlet (Karlstrom, 1964; Schmoll and Yehle, 1986).

Reger et al. (2008b) inferred that glaciers began to advance into the Cook Inlet Lowland from the surrounding ranges ca. 30 ka. The buildup of glacial ice at the mouth of Cook Inlet eventually formed an ice dam behind which a lake >100 m in depth formed in the upper inlet. Glaciers flowing from the western ranges crossed this lake to override the Kenai lowlands east of the inlet. Reger et al. (2008a) estimate that the local Last Glacial Maximum occurred between 24.2 and 22.8 ka during the Moosehorn Stade. Minimum-limiting dates on the Moosehorn Stade come from nine cosmogenic dates on erratic boulders that yielded an average age of 20.1 ± 1.4 ka (Tulenko et al., 2022). These exposure-age

dates are consistent with the ^{14}C ages of barnacle plates in glaciomarine sediments within the Moosehorn Stade's terminal moraine that range in age from 19.5 to 18.6 ka (Reger et al., 2008b).

Deglaciation triggered complex interactions between isostatic rebound, episodic seismic displacements, and rising eustatic sea levels (Schmoll and Yehle, 1986). A marine transgression began ca. 19.2–19.0 ka when rising marine waters breached the ice dam at the mouth of Cook Inlet and invaded the isostatically-depressed lowlands (Reger et al., 1995; Reger et al., 2008b). By 19 ka, marine waters extended some 200 km into Cook Inlet (Reger et al., 2008b) and by 17.6 ka reached upper Cook Inlet. By ca. 16.5 ka, marine waters extended >60 km north of present tidewater (Reger et al., 1995).

Three or more glacial standstills or readvances interrupted the course of the deglaciation of Cook Inlet (Karlstrom, 1964). The last of these deposited the 100-km long Elmendorf Moraine in the upper inlet ca. 16.8 ka (Kopczynski et al., 2017), although Reger (pers. comm., 2021) places the building of the Elmendorf moraine slightly later, between 16.8 and 16.0 ka. Retreat from the Elmendorf moraine was underway by 16.8, or possibly by 16.0 ka, and retreat accelerated at the onset of the Bølling/Allerød ca. 14.7 ka (Kopczynski et al., 2017). Ice had retreated from upper reaches of the Cook Inlet Lowland by 13.7 ka (Kopczynski et al., 2017) and from the eastern Kenai Lowland by 13.1 ka (Broadman et al., 2022).

In summary, the Cook Inlet Lowland remains a key, understudied region of the Northwest Coast. Preliminary studies have primed the area for detailed work in the future. For example, cosmogenic dating of the rich moraine record on both sides of Cook Inlet has just begun (Tulenko et al., 2022). The marine depositional settings in Cook Inlet provide numerous opportunities for reconstructing detailed ^{14}C chronologies of glacial history once the marine reservoir effect is better quantified. The mountainous topography surrounding the lowland and the high topography of islands near its mouth make it an ideal setting for glaciological modelling. To fully understand the glacial record of the Cook Inlet Lowland, detailed bathymetric surveys, marine coring, and onshore stratigraphic work are needed that are comparable to what has been done around Haida Gwaii (Section 2.1.3.4).

2.1.3.9. Kodiak Archipelago. Multiple ice caps developed over Kodiak and Afognak Islands during Marine Isotope Stage 2. Outlet glaciers radiating from Afognak Island flowed northward into Shelikof Strait and eastward into the Amatuli Trough (Fig. 11). Ice caps in the uplands of Kodiak Island sent outlet glaciers southwards to the outer edge of the continental shelf (Greene et al., 2016) as well as northwards into Shelikof Strait. During the local Last Glacial Maximum (ILGM), ice from the Kodiak Archipelago and the Alaska Peninsula converged in Shelikof Strait and flowed southwestward (Fig. 12). A suite of geomorphic features characteristic of fast flow within ice streams are preserved on the floor of the Skelikof Trough (Zimmermann et al., 2019). These include mega-scale glacial lineations, drumlins, and trough-marginal moraines (Batchelor and Dowdeswell, 2014). The detailed bathymetry compiled by (Zimmermann et al., 2019) and the very preliminary ice-flow modelling of Mann and Peteet (1994) suggest that the Shelikof Ice Stream terminated at the outer edge of the continental shelf during the ILGM.

Karlstrom (1964) suggested that an ice-free area existed on southwestern Kodiak Island during the Last Glacial Maximum. This was later confirmed by mapping moraines (Karlstrom, 1969) and by ^{14}C -dating glacial stratigraphy (Mann and Peteet, 1994). Much of this ice-free area consisted of interconnected proglacial lakes fed by ice-marginal streams whose courses and outlets probably shifted frequently. The subaerial, ice-free terrain on southwestern Kodiak Island during the local Last Glacial Maximum was limited to approximately 200 km² of alpine ridgelines that protruded above the level of these lakes and yet were below local snowlines. Because of its limited area, changeable nature, and the prevailing periglacial climate, this ice-free area on southwest

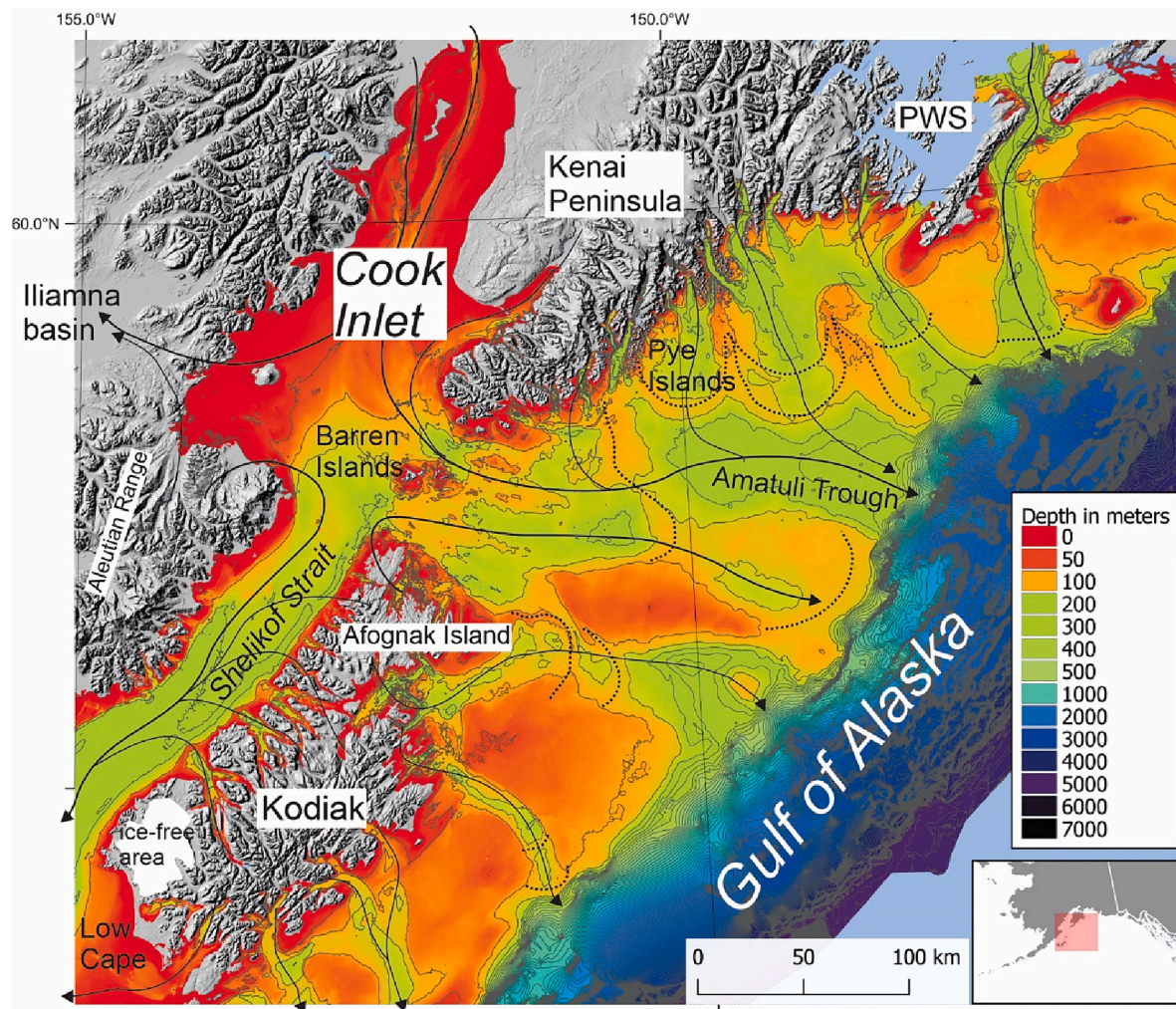


Fig. 11. Seafloor geomorphology suggests glaciers terminated at the outer edge of the continental shelf between Prince William Sound (PWS) and the Kodiak Archipelago during the Last Glacial Maximum. Prominent moraines are shown as dashed lines, and hypothetical glacial flowlines down troughs are shown as solid arrows. In the eastern part of the map, geomorphic interpretations are modified from [Haeussler et al. \(2015, 2022\)](#). Bathymetric data are from [Zimmermann and Prescott \(2015\)](#); the map is generated in QGIS v3.26.2. The onshore digital elevation model is from [Zabihi et al. \(2021\)](#).

Kodiak area probably provided a biological refugium for only a limited number of arctic-alpine biota.

^{14}C -dated stratigraphy along the margin of the ice-free area on southwestern Kodiak indicates that ice advanced down Shelikof Strait between 27.4 and 26.4 ka ([Mann and Peteet, 1994](#)). Deglaciation occurred prior to 18.2–17.4 ka at Low Cape (Beta-3958), which indicates the outer continental shelf was ice free prior to that time. A readvance of unknown extent occurred at Low Cape between 16.5 and 15.4 ka ([Mann and Peteet, 1994](#)).

Glacial equilibrium-line altitudes (ELAs) on the northwestern (leeward) side of Kodiak Island were 300–400 m above present sea level during the local Last Glacial Maximum (ILGM) ([Mann and Peteet, 1994](#)), but probably fell to present sea level or below on Afognak Island and in lower Cook Inlet. The presence of drowned cirques in the Shumagin Islands suggests the ELA there fell below present sea level. By analogy with the Antarctic Peninsula today ([Ferrigno et al., 2002](#); [Davies et al., 2012](#)), an ice cap whose ELA lay within 100 m sea level was sensitive to slight changes in ocean temperature, not to mention to changes in relative sea level. As discussed in [Section 2.3](#), sea ice was seasonally present in this region during the coldest intervals of Marine Isotope Stage 2.

Based on glacial features preserved on the seafloor between Kodiak and Sanak Island, [Zimmermann et al. \(2019\)](#) inferred that glaciers

flowed to the outer shelf edge during the local Last Glacial Maximum (ILGM). The occurrence of multiple moraine loops on the seafloor south of the Shumagin and Semidi Islands ([Fig. 12, 13](#)) suggests a complex history of standstills and/or readvances during deglaciation, and the presence of iceberg scours on the adjacent seafloor indicates these post-ILGM moraines were deposited by calving glaciers ([Greene et al., 2016](#); [Zimmermann et al., 2019](#)).

2.1.3.10. Sanak Island. Sanak Island (54.41°N, 162.64°W) lies 60 km offshore of the Alaska Peninsula and 30 km inboard of the continental shelf's outer edge ([Fig. 14](#)). Raised beaches and wave-planed, lowland surfaces attest to a postglacial marine transgression. [Mann and Peteet \(1994\)](#) inferred from trends in reconstructed snowlines that 100–300 m of ice covered Sanak during the local Last Glacial Maximum; however, [Misarti et al. \(2012\)](#) suggested that maximum ice thickness over Sanak was thin, < 70 m, although it is unclear what evidence this was based on. The oldest basal ^{14}C date from three lakes on Sanak Island indicates deglaciation occurred before 15.2–16.2 ka ([Misarti et al., 2012](#)). These authors extrapolated their lacustrine age/depth curve below the oldest ^{14}C date and asserted deglaciation occurred at “nearly 17 ka BP”. This conclusion is problematic because of the variability typical in sedimentation rates in proglacial areas. Because Sanak Peak rises to 530 m asl and consists of granodiorite ([Moore, 1974](#)), it may provide an

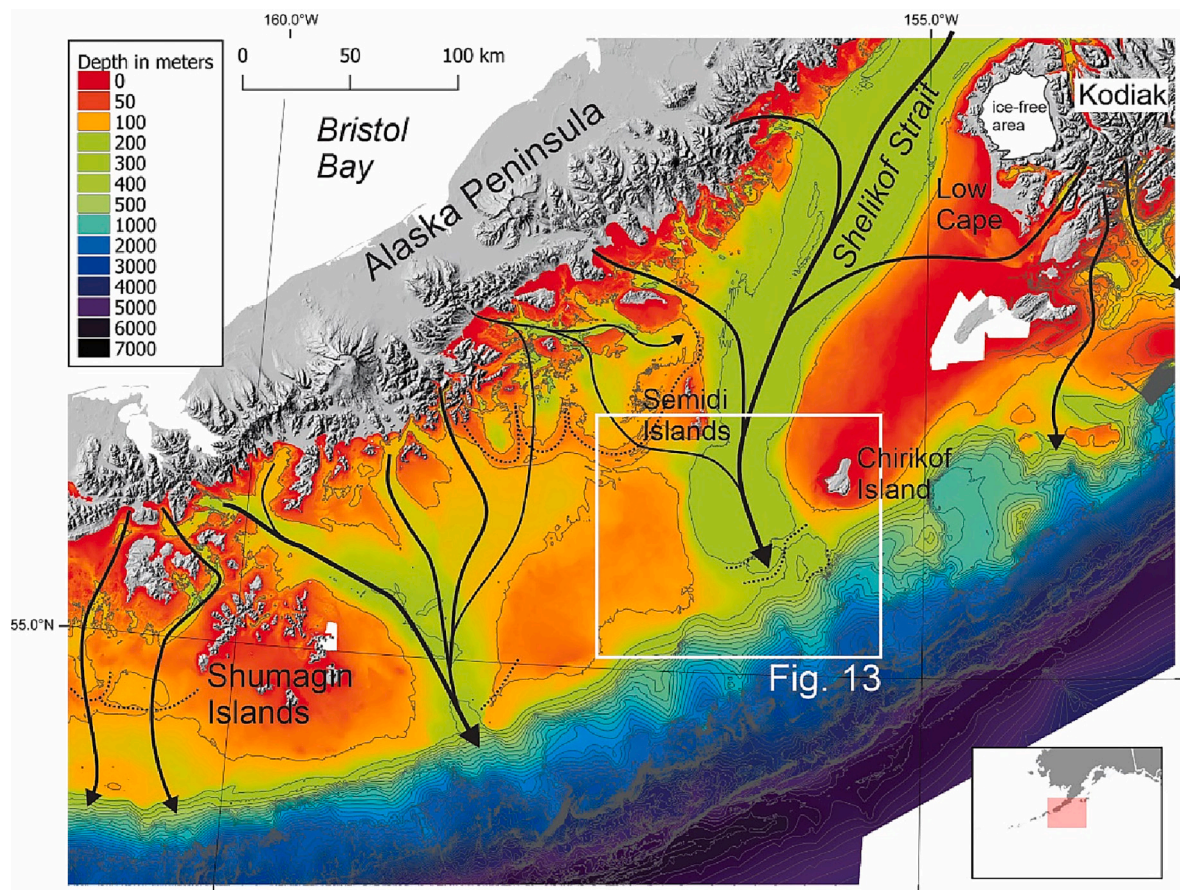


Fig. 12. Bathymetry of the continental shelf between the Kodiak Island and the Shumagin Islands. The interpretation of the seafloor geomorphology is based on Zimmermann et al. (2019). Hypothetical glacial flowlines (solid arrows) depict multiple ice streams originating on the Alaska Peninsula and Kodiak Archipelago and terminating along the outer edge of the continental shelf. Small ice caps were centered over the Semidi and Shumagin Islands. Multiple moraines located inboard of the shelf edge suggest a complex history of glacial stillstands and/or readvances during deglaciation. Bathymetric data are from Zimmermann and Prescott (2015); the map generated in QGIS v3.26.2. Onshore digital elevation model is from Zabihi et al. (2021). White box shows location of Fig. 13.

excellent site for using exposure-age dating to reveal the extent and timing of glaciation on the adjacent continental shelf.

Glaciers emanating from one or more ice caps centered over the inner shelf near Sanak Island flowed northward across the Alaskan Peninsula to terminate in the Bering Sea, where they left moraine complexes at the heads of Cold Bay and Morzhovoi Bay (Fig. 14). For a shelf-based ice cap to exist at this location, the equilibrium-line altitude must have been at or below present sea level. By analogy with similarly positioned ice caps on the Antarctic Peninsula today (Ferrigno et al., 2002; Davies et al., 2012), sea ice was probably present in the adjacent ocean, at least in winter.

2.1.3.11. Alaska Peninsula (Bristol Bay). The glacial history of the Alaska Peninsula (Fig. 12) is of particular interest because during Marine Isotope Stage 2 it separated the unglaciated, subaerial portions of the Bering Land Bridge from the Northwest Coast Route along which the first people may have dispersed into lower latitude North America. Unfortunately, the glacial history of the Alaska Peninsula is understood only in general terms (Muller, 1952; Péwé, 1975; Detterman, 1986). A ^{14}C date on organics incorporated in outwash graded to an end moraine in the Kvichak River valley suggest a glacial advance occurred upstream in the Iliamna Basin sometime after 31–30 ka (Stilwell and Kaufman, 1996). In the Naknek valley, ^{14}C dates indicate moraine construction between 42 and 31.7 ka (Mann and Peteet, 1994). These limiting dates from the Kvichak and Naknek valleys suggest a major ice advance occurred late in Marine Isotope Stage 3 (MIS 3) and that advances during MIS 2 were less extensive. In the case of the Kvichak valley, the local Last

Glacial Maximum probably corresponds to the undated, prominent moraine system that now encloses Iliamna Lake. In the Ahklun Mountains north of Bristol Bay, proglacial sediment in Arolik Lake indicate the Last Glacial Maximum occurred between ca. 24 and 22 ka (Kaufman et al., 2003).

During Marine Isotope Stage 2 (MIS 2), multiple ice lobes flowed into the Bristol Bay lowland from ranges to the south, east, and north (Kaufman et al., 2011). Equilibrium-line altitudes were lowered by approximately 600 m on Kodiak Island, by 400 m along the northern flank of the Alaska Peninsula (Mann and Peteet, 1994), and by 200–400 m in the Ahklun Mountains (Manley et al., 2001). Snowlines assigned to the local Last Glacial Maximum (ILGM) parallel modern ones in the region, supporting previous suggestions that the geography of winter precipitation and summer temperature during the ILGM generally paralleled those of present (Péwé, 1975; Hamilton and Thorson, 1983).

2.1.3.12. Alaska Range. The Alaska Range arcs 650 km from the Yukon border to southwestern Alaska and contains some of the highest peaks in North America. The Alaska Range creates a barrier to the moisture carried by storms from the Gulf of Alaska and maintains the strongly continental climate of Interior Alaska. This rain-shadow effect was also prominent during Marine Isotope Stage 2 when glaciers south of the range flowed hundreds of kilometres onto the continental shelf of the Gulf of Alaska, while glaciers north of the range extended mere tens of kilometres into the lowlands of the Interior (Péwé, 1975; Hamilton and Thorson, 1983; Kaufman et al., 2011).

Beginning in the east in the Delta River watershed, an exposure age

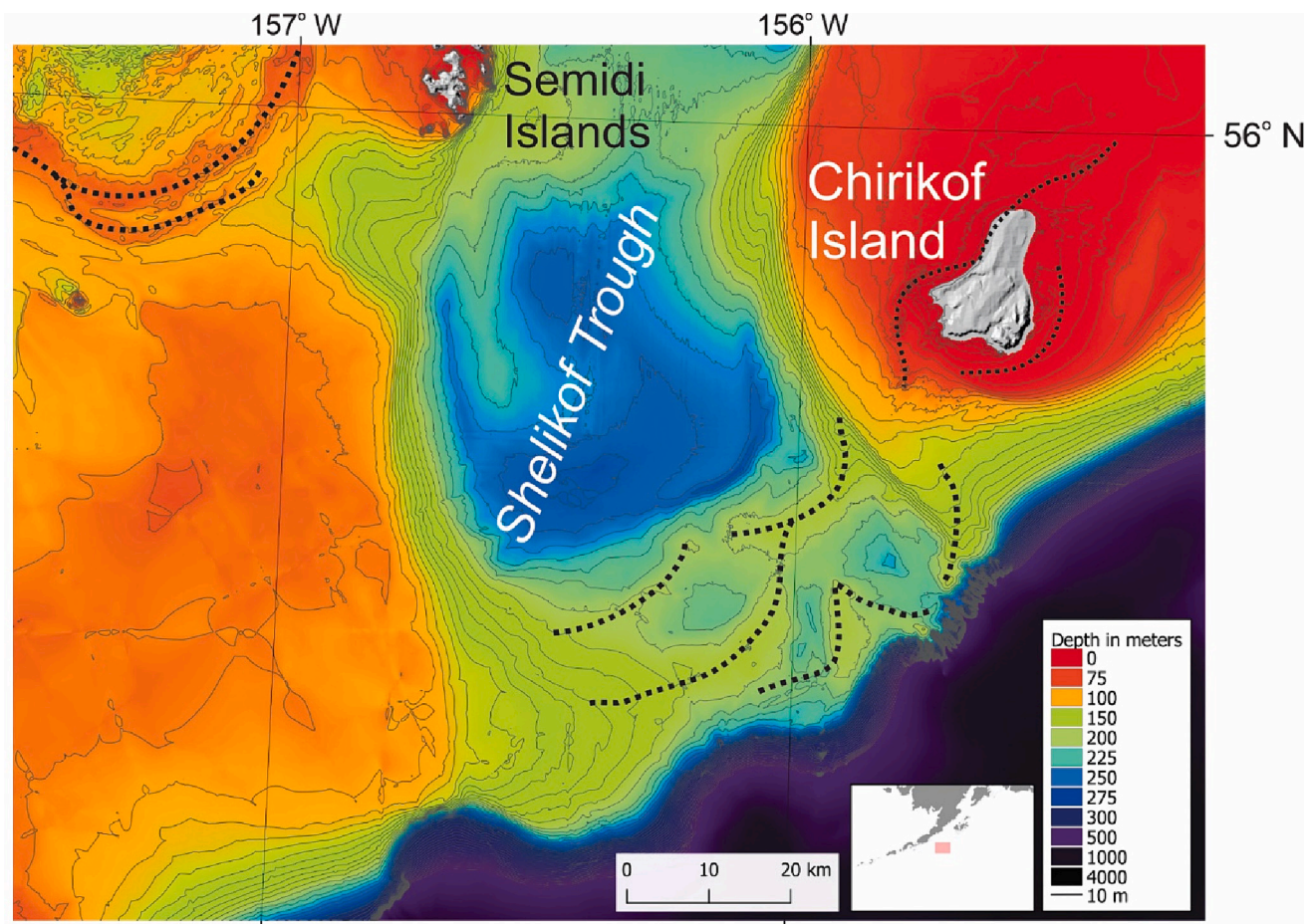


Fig. 13. Bathymetry of the seaward end of the Shelikof Trough. Dashed lines show moraines. Seafloor geomorphology is modified slightly from Zimmermann et al. (2019). Bathymetric data are from Zimmermann and Prescott (2015); the map is generated in QGIS v3.26.2. Onshore digital elevation model is from Zabihi et al. (2021).

from the Fish Lake valley ($63^{\circ} 31' \text{ N}$, $144^{\circ} 29' \text{ W}$, informal name) suggested the local Last Glacial Maximum (ILGM) occurred at $22.4 \pm 0.6 \text{ ka}$ (Young et al., 2009). Briner et al. (2017) reinterpreted a cluster of ca. 16.5-ka ages obtained by Young et al. (2009) as representing the true ILGM and revised these ages to $18.7 \pm 0.2 \text{ ka}$ using an updated ^{10}Be -production rate (Fig. 15). A readvance or standstill occurred in the Fish Lake valley at $11.6 \pm 0.3 \text{ ka}$ during the Younger Dryas chronozone (Young et al., 2009). Matmon et al. (2010) obtained several cosmogenic dates on boulders from a moraine previously identified as the ILGM limit (Péwé, 1975; Péwé and Reger, 1983) and suggested the ILGM occurred ca. 17 ka. Despite being the most accessible area in the Alaska Range, the glacial chronology of the Delta River area remains somewhat uncertain.

Scattered, maximum-limiting ^{14}C dates constrain the local Last Glacial Maximum (ILGM) in the central Alaska Range as occurring after 27 ka (Porter, 1983; Thorson, 1986). On the northern side of the range in Denali National Park, limiting ^{14}C dates constrain the ILGM between 22.2 and 21.1 ka (Ten Brink and Waythomas, 1985; Briner and Kaufman, 2008; Briner et al., 2017). Two readvances or standstills occurred there, one between 21.1 and 17.6 ka and another between 15.8 and 15.1 ka (Briner et al., 2017) (Fig. 15).

The most closely dated moraine sequence in the Alaska Range comes from the Revelation Mountains in the western Alaska Range where extensive cosmogenic dating of boulders in an iconic moraine sequence in the Swift River valley indicate the local Last Glacial Maximum (ILGM) occurred at $21.3 \pm 0.8 \text{ ka}$ (Fig. 15). Three readvances or standstills followed at $20.2 \pm 1.0 \text{ ka}$, $19.6 \pm 1.0 \text{ ka}$, and $17.7 \pm 0.8 \text{ ka}$ (Tulenko et al., 2018) (Fig. 15).

2.1.4. Glacier fluctuations during the Younger Dryas, 12.8 to 11.7 ka

In southwestern British Columbia and western Washington, several readvances of ice occurred between 14.5 and 11 ka, interrupting overall glacial retreat (Friele and Clague, 2002; Menounos et al., 2009). These included a readvance in the Fraser Lowland that may have coincided with the Younger Dryas (YD) (Kovanen, 2002; Kovanen and Eastbrook, 2002). Evidence is currently lacking for glacial advances along the Gulf of Alaska margin during the YD (Kaufman et al., 2010); however, glacial advances (or standstills) are documented during the YD chronozone in southwestern British Columbia and in the western Canadian Cordilleran (Lakeman et al., 2008; Menounos et al., 2009, 2017), as well as in the continental interior of southern Alaska (Young et al., 2019; Tulenko et al., 2022). The absence of YD glacial advances along the Gulf of Alaska coastline is reminiscent of their absence in coastal East Greenland (Levy et al., 2016) and Arctic Norway (Wittmeier et al., 2020). Like glaciers in coastal Greenland (Funder et al., 2021), maritime glaciers along the Gulf of Alaska margin may actually have been retreating during the YD. Limited evidence exists for an early-cold, late-warm pattern of climate changes during the YD in southern Alaska in the form of a moraine deposited ca. 12.5 ka in the Ahklun Mountains (Young et al., 2019) (Section 3.3). We return to the enigmatic nature of climate during the YD chronozone in Section 3.3.

2.1.5. Summary of glacial history along the Northwest Coast during Marine Isotope Stage 2

Glaciers in most sectors of the Cordilleran Glacier Complex reached their maximum extents relatively late during the Last Glacial Maximum (LGM), which is usually placed between 26.6 and 19 ka (Clark et al.,

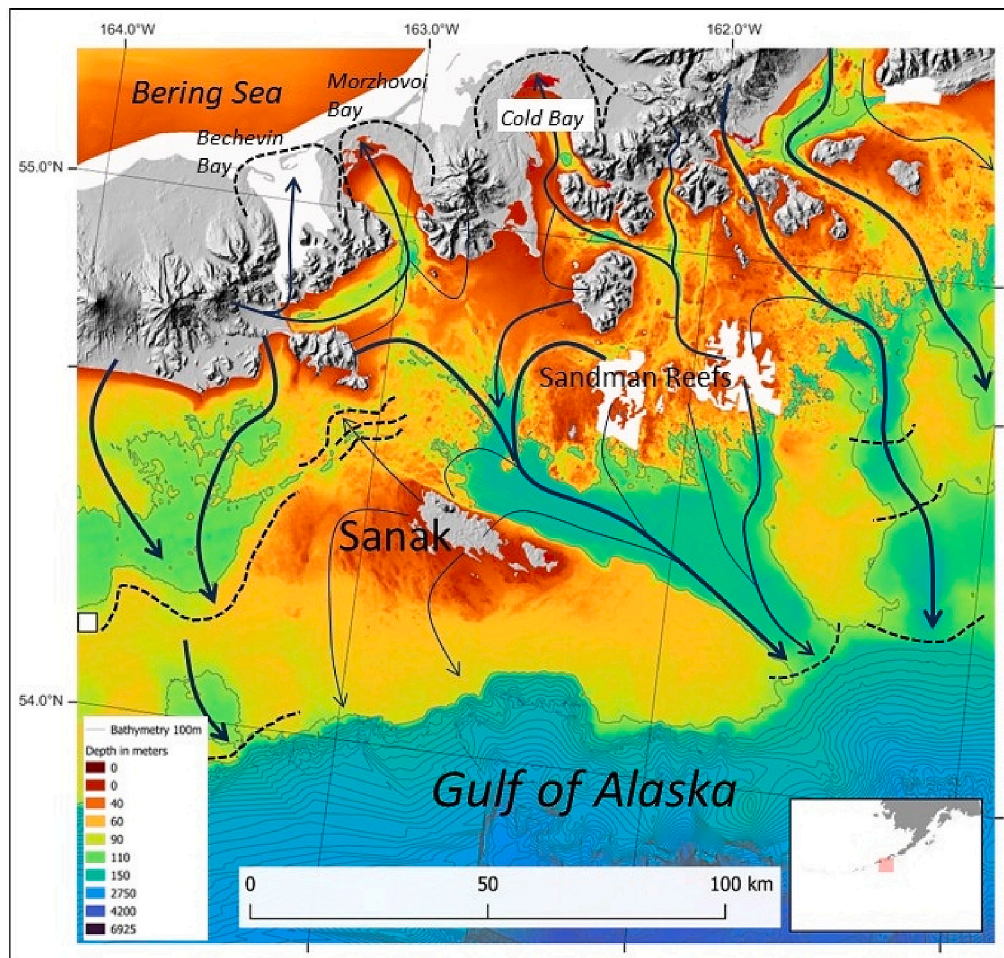


Fig. 14. Bathymetry on the continental shelf south of the outer Alaskan Peninsula near Sanak Island. Prominent terminal moraines were left by outlet glaciers that crossed the peninsula and terminated in the southern Bering Sea. Dashed lines show probable moraines on the sea floor. Black arrows are hypothetical glacier flow lines. Bathymetric data are from Zimmermann and Prescott (2015); the map is generated in QGIS v3.26.2. Onshore digital elevation model is from Zabihi et al. (2021).

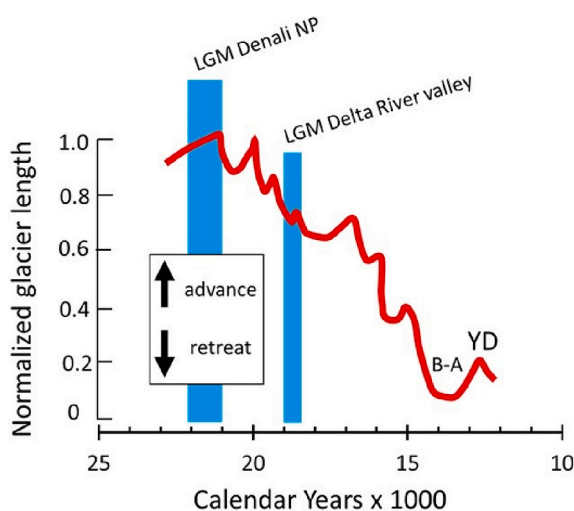


Fig. 15. Timing of the Last Glacial Maximum (LGM) in the Alaska Range. The red line depicts deglaciation of the Revelation Mountains. “Normalized glacier length” depicts the present-day glacier-terminus position as “0” and the LGM terminus position as “1”. Redrawn from Tulenko et al. (2018, 2022). The timing of the LGM in the Delta River valley and Denali National Park is from Briner (2017). “B-A” is the Bølling-Allerød. “YD” is the Younger Dryas.

2009) (Fig. 16). Many glacial systems along the Northwest Coast reached maxima after major sectors of the Laurentide and Fennoscandian Ice sheets. The local Last Glacial Maximum (ILGM) occurred earliest in northern sectors of the Northwest Coast. In the Swift River valley of the Alaska Range (Fig. 15) the ILGM occurred at 21.3 ± 0.8 ka, while the ILGMs in Puget Sound, the Strait of Juan de Fuca, Vancouver Island, and in eastern Washington/Idaho all occurred between 18 and 15 ka (Fig. 5). ILGMs in the southern sector of the Northwest Coast coincided with Heinrich Event 1 (HE 1) and were roughly in synchrony with a widespread episode of recessional moraine deposition in the western, conterminous USA (Laabs et al., 2020) (Fig. 16). In Southeast Alaska, the ILGM occurred at an intermediate time between 19.8 and 17.2 ka.

Like the timing of local Last Glacial Maxima (ILGM), the retreats of marine-based glaciers were time transgressive along the Northwest Coast. Rapid calving retreats began in the Strait of Juan de Fuca and along the western coast of Vancouver Island ca. 17.5 ka, but earlier, ca. 19 ka, in the northeastern Gulf of Alaska (Fig. 6) (though see Section 4.1.10). The timing of deglaciation of the continental shelf between Haida Gwaii and the Aleutian Chain remains largely unknown. Early work from southwestern Kodiak indicates that the outer shelf was ice free by 18.3–17.5 ka, although a readvance of unknown extent then occurred between 16.5 and 15.4 ka. In southern sectors of the Northwest Coast, glaciers had retreated to the inner-fjord zone by 13–14 ka. The timing of glacial advances during the Younger Dryas (YD) chronozone

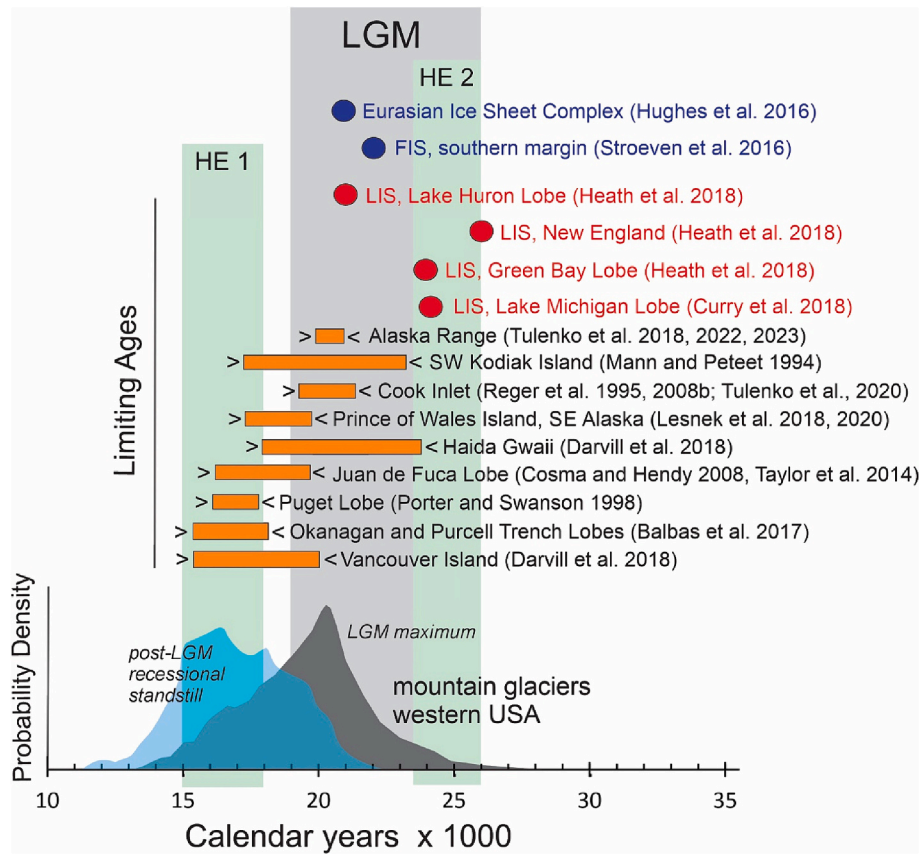


Fig. 16. ABOVE Limiting dates on the Cordilleran Glacier Complex (CGC) (orange bars), the Laurentide Ice Sheet (LIS, red balls), and the Fennoscandian Ice Sheet (FIS, blue balls). “LGM” = global Last Glacial Maximum. “HE 1” = Heinrich Event 1. “HE 2” = Heinrich Event 2. BELOW Probability density distributions of the minimum-limiting exposure ages of the moraines deposited by alpine glaciers in the western, conterminous United States (Redrawn from Laabs et al., 2020). In the western USA, “post-LGM recessional moraines” were deposited during a region-wide glacier standstill or readvance centered at 17.0 ± 1.8 ka during Heinrich Event 1.

remains obscure, probably because they were rare. What records do exist suggest advances occurred early in the YD chronozone, followed by retreats. The climatic regime responsible for this pattern is explored further in Section 3.3.

Along the Alaskan coast, newly available bathymetric data reveal numerous terminal moraines located at the mouths of cross-shelf troughs between Cross Sound and the inner Aleutians (Fig. 8–14). Although the troughs are composite features carved during multiple glaciations, the presence of well-preserved glacial features suggests they were probably reoccupied by ice streams during the local Last Glacial Maximum (ILGM). Bathymetric data also reveal complex sequences of recessional moraines bordering former island ice caps located south of the Alaska Peninsula. This is consistent with earlier inferences that equilibrium-line altitudes fell to near or below present sea level along the Gulf of Alaska coastline between Prince William Sound and the Aleutians during the ILGM.

2.2. Relative sea level (RSL)

2.2.1. The Northwest Coast between Puget Sound and Kodiak Island

The Northwest Coast of North America experienced relative sea level changes during MIS 2 that were markedly complex in space and time (Fig. 17) (Mosher and Hewitt, 2004; Mann and Streveler, 2008; Roe et al., 2013; McLaren et al., 2014; Shugar et al., 2014; Letham et al., 2016; Baichtal et al., 2021). This complexity resulted from the combination of time-transgressive glacier fluctuations and the region’s relatively thin lithosphere and low-viscosity asthenosphere, which made RSLs respond rapidly and sensitively to glacier loading (Larsen et al.,

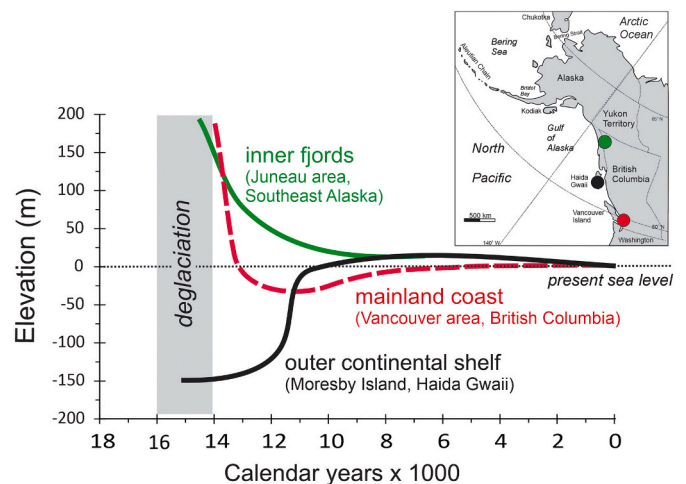


Fig. 17. Relative sea level (RSL) varied widely according to location. Shown here are representative RSL curves from positions along a coast-perpendicular transect spanning ~100 km from the outer continental shelf to the inner fjord zone. The curves for Haida Gwaii and Vancouver areas are from Shugar et al. (2014). The Juneau area curve is from Baichtal et al. (2021).

2005; James et al., 2009b; Hu and Freymueller, 2019). Further complexity arose from the region’s ongoing tectonism (Mann and Crowell, 1996; Shennan et al., 2014). The following overview of RSL history along the Northwest Coast is based largely on the review of Shugar et al.

(2014).

During the deglaciation, marine waters transgressed as high as 220 m across the isostatically depressed, western flank of the Coast Mountains in coastal British Columbia and Southeast Alaska (Miller, 1972, 1973, 1975; Clague and James, 2002). Areas within the zone of maximum ice loading (e.g., the inner-fjord zone) experienced steadily falling sea levels because the rates of isostatic recovery continuously exceeded the rates of eustatic sea-level rise (Fig. 17). Seaward of the zone of maximum ice loading, isostatic rebound initially surpassed rising eustatic sea level, but was later exceeded by it as uplift slowed. Between 14 and 12 ka in southwestern British Columbia, this pattern of relative sea level change resulted in lowstands of −11 m near Vancouver, B.C.; −30 m near Victoria, B.C.; and −46 m on western Vancouver Island (Shugar et al., 2014).

Offshore islands like Haida Gwaii experienced very different relative sea level (RSL) histories because relatively little isostatic depression occurred near the seaward limit of glacier extent (Fig. 17). At its lowest point, RSL fell below the typical, eustatic drawdown of around −120 m as the result of crustal forebulges developing in response to thick ice loads to the east. Deep accumulations of glacial ice over the western flank of the Coast Mountains squeezed the mantle seaward, where it elevated the crust of the outer continental shelf by some 20–30 m. This resulted in RSL in Haida Gwaii falling to around 150 m below present RSL just prior to deglaciation (Fig. 17). Then, as the forebulge migrated eastwards, RSL rose 5–10 m higher than present in the early and mid-Holocene, before falling back to its present level ca. 2 ka. This same pattern of post-glacial RSL change also occurred on the continental shelf bordering the Alexander Archipelago (Baichtal et al., 2021), and possibly along much of the coastline of the northern Gulf of Alaska. Records of RSL become increasingly fragmentary north of Cross Sound (Shugar et al., 2014) with the exception of Bering Strait.

2.2.2. Relative sea level history of Bering Strait

2.2.2.1. Existing data and inferences.

Whether Bering Strait is a land bridge or a seaway has important consequences for the climate of Eastern Beringia (Mann et al., 2001; Bartlein et al., 2015), for the functioning of the global ocean/atm system (Section 4.1.6), and for a diverse set of biogeographical concerns (Hopkins, 1967; Hoffecker et al., 2023). Multiple approaches have been used to reconstruct the history of the Bering Land Bridge. Comparisons between bathymetry and eustatic sea levels over the last 140 ka (Lambeck and Chappell, 2001; Siddall et al., 2003) suggest Bering Strait was subaerial between 140 and 130 ka, submerged between ca. 130 and 110 ka, intermittently submerged between 110 and 70 ka, and subaerial again between 70 and 11 ka (Fig. 18). Such comparisons ignore the possibility that the bathymetry of the strait has changed over the last 140 kyr (Section 2.2.2.2). Furthermore, comparing estimates of relative sea level to bathymetry is an

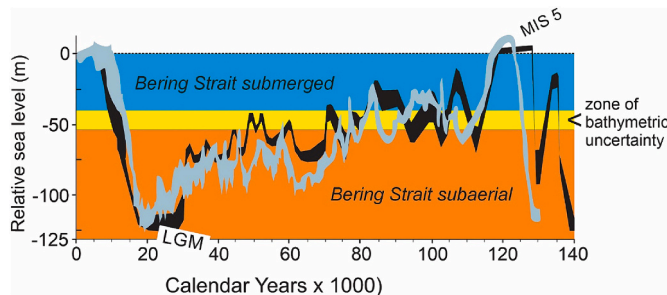


Fig. 18. The bathymetry of Bering Strait compared with eustatic sea level over the last 140,000 years based on far-field data of Lambeck and Chappell (2001) (black) and Siddall et al. (2003) (grey). Today, the shallowest sill in the strait lies around −53 m. “LGM” = global Last Glacial Maximum. “MIS 5” = Marine Isotope Stage 5, the last interglacial.

inherently fuzzy process because the elevation errors in eustatic sea level curves are generally between 2 and 10 m (Chappell et al., 1996; Keigwin et al., 2006; Abdul et al., 2016).

Based on the ^{14}C ages of terrestrial organic matter recovered in cores from the Chukchi Sea continental shelf, McManus and colleagues (McManus et al., 1983; McManus and Creager, 1984) estimated that Bering Strait was last flooded ca. 14,400 ^{14}C years, or roughly 17 to 18 ka (Fig. 19). As Elias et al. (1996) pointed out, this was a widely limiting, maximum-age estimate because ^{14}C -dead carbon was probably contained in the samples dated and because younger organic deposits were probably eroded away as marine waters rose. Working with sediment cores from the Bering Sea inner shelf, Elias et al. (1996) dated terrestrial peats to 16.1–12.8 ka at depths of 42 to 48 m below present sea level. Based on these ages, they suggested the initial flooding of Bering Strait occurred after 12.8 ka.

Keigwin et al. (2006) analyzed a marine core taken north of Bering Strait at a depth of −53 m and inferred that a major transition from estuarine to open-sea conditions occurred ca. 12 ka (Fig. 19). Also working on the Chukchi shelf north of the strait, Hill and Driscoll (2008) obtained an age of 10.9 ± 0.2 ka on a marine shell recovered one meter above what they interpreted to be a transgressive surface in −59 m water depth, suggesting that sea level neared the −53 m level on the northern side of Bering Strait about that time.

The dates when North Pacific whale and mollusk species first arrived in the Arctic Ocean have also been used to infer when Bering Strait first opened. Dyke and Savelle (2001) found the remains of bowhead whales (*Balaena mysticetus*) in the Canadian Arctic Archipelago as old as $10,850 \pm 140$ ka, which is consistent with Bering Strait opening ca. 11 ka (Fig. 19). Also consistent with a ca. 11 ka opening of the strait is the striking diversification of the molluscan fauna that occurred in the

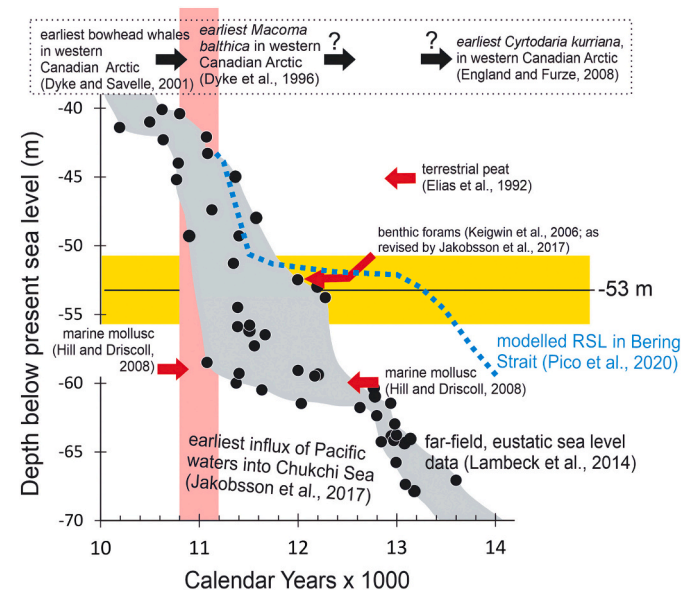


Fig. 19. Age constraints on the most recent flooding of Bering Land Bridge. Black dots are far-field, eustatic sea-level data (Lambeck et al., 2014). The grey shading encloses these data and their approximate errors. Arrows indicate whether a ^{14}C date is a maximum- or minimum-limiting age estimate, with the tips of arrow lying on the approximate calendar age of each sample. Samples marked with red arrows are plotted according to depth. The shallowest (highest) sill in Bering Strait today is around −53 m. The yellow band depicts an estimated 5-m band of uncertainty in the altitude of this sill at the time of initial flooding (Section 2.2.2.2). The pink, vertical bar marks the earliest influx of North Pacific waters into the Chukchi Sea according to Jakobsson et al. (2017). Black arrows in the upper panel show when marine species that are thought to have been restricted to the North Pacific prior to Bering Strait opening first appeared in the Arctic Basin. As discussed in the text, the arrival dates of these mollusk species may be red herrings.

western Arctic Archipelago after 10.3 ka (Dyke and Savelle, 2001).

More puzzling is the appearance of possible Pacific-endemic mollusk species in the western Arctic Archipelago prior to 12.5 ka. On Banks Island, Dyke et al. (1996) found *Macoma (Limecola) balthica* shells dating to 12.6 ka, while England and Furze (2008) discovered shells of *Cyrtodaria kurriana* dating to 13.5 ka (Fig. 19). Both these ages take into account an estimated marine-reservoir effect. One possibility is these species survived the Last Glacial Maximum in marine refugia somewhere in the North Pacific, and then reinvaded the Arctic Basin when their larvae/veligers drifted northward through the newly inundated and still shallow strait. These dispersal events could have occurred when water levels in Bering Strait were still quite shallow (Pico et al., 2020). If this were the case, the strait must have initially opened before 13.5 ka (England and Furze, 2008).

An alternative explanation is that the 13-ka *Macoma* and *Cyrtodaria* specimens from the western Arctic Archipelago in fact date to 10–11 ka, but the 0.5 ka correction for the marine-reservoir effect used by Dyke et al. (1996) and England and Furze (2008) is an underestimate. While some authors think that marine-reservoir effects (MARs) > 1 kyr are unlikely in the Arctic Ocean (England and Furze, 2008; Pico et al., 2020), MARs in polar seas are influenced by variations in sea-ice cover, ocean upwelling, and air-sea gas exchange, all of which can affect marine radiocarbon concentrations (Butzin et al., 2017; Heaton et al., 2020) (Section 4.1.10.2). Uncertainty surrounding the Arctic's marine reservoir effect during the deglacial continues to hamper sea-level reconstructions in Bering Strait.

A third explanation for 13-ka *Macoma* and *Cyrtodaria* from the western Arctic Archipelago is that the dispersal capabilities of these two, purportedly Pacific-endemic species have been underestimated, and in fact they reached the Beaufort Sea from the North Atlantic early in postglacial times via the Northeast Passage prior to the opening of Bering Strait. Although England and Furze (2008) think this unlikely, both *Macoma balthica* and *Cyrtodaria kurriana* have circumboreal distributions today. Moreover, *C. kurriana*'s distribution is strikingly discontinuous, so its absence from sediment cores along the Siberian continental shelf early in postglacial times (England and Furze, 2008) is not a convincing argument that their pelagic larvae were not carried into the Beaufort Sea by the same coastal currents that today carry Atlantic waters eastward along the Siberian continental shelf (Weingartner et al., 1999).

By modelling temporal patterns of crustal responses to transient loadings and un-loadings by glacial ice and ocean water, Peltier et al. (2015) suggested that Bering Strait flooded ca. 11 ka (Fig. 19). Elaborating on this approach, Pico et al. (2020) used varying scenarios of deglaciation timing over western North America to model relative sea level (RSL) history in Bering Strait, taking into account the complex interactions between eustatic sea-level history, distant isostatic effects, and the changing gravitational effects of the Cordilleran Glacier Complex (CGC) on RSL in the Bering and Chukchi Seas. Their modelling results suggest Bering Strait was initially flooded beginning ca. 13 ka, followed by a RSL standstill that lasted until ca. 11.5 ka. Prior to ca. 13 ka, Pico et al. (2020) think that RSL in Bering Strait was significantly higher (by ~10 m) than at far-field locations in tropical seas due to isostatic and gravitational effects from the CGC (Section 2.2.2.2) (Fig. 19, 20). Only after ca. 13 ka do Pico et al.'s (2020) models show RSL in Bering Strait converging with the global, eustatic sea-level curve of Lambeck and Chappell (2001) (Fig. 19).

Jakobsson et al. (2017) inferred that Bering Strait was flooded by the sea ca. 11 ka BP based on a combination of sedimentology, changes in the concentration of biosilica, and shifts in the $\delta^{13}\text{C}$ of organic matter in sediment cores from the Chukchi Sea (Fig. 19). Uncertainty about the local marine reservoir effect at this location during the late-glacial period (Hanslik et al., 2010; Butzin et al., 2017; Skinner et al., 2017) suggest 11 ka BP is a maximum-limiting age estimate.

Farmer et al. (2021, 2023) analyzed sediment cores taken north of Bering Strait for $\delta^{15}\text{N}$ in planktonic foraminifera (Fig. 20). Because $\delta^{15}\text{N}$

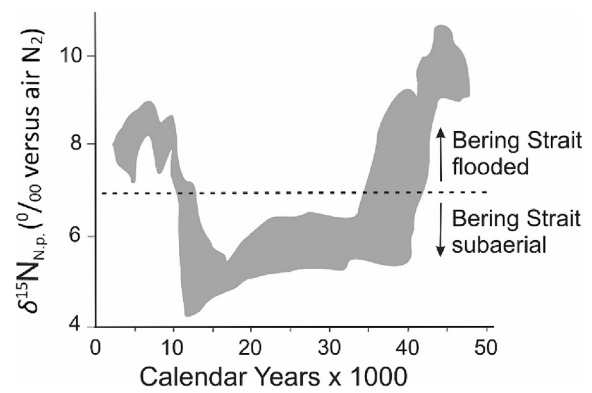


Fig. 20. Opening and closing of Bering Strait inferred from nitrogen isotopes in foraminifera in sediment cores from the western Arctic Ocean (Farmer et al., 2021; Farmer et al., 2023). The grey polygon encompasses the error-ranges of $\delta^{15}\text{N}$ values in three cores. The dashed line shows the maximum $\delta^{15}\text{N}$ value expected when the strait is closed to the ingress of North Pacific water.

is higher in the North Pacific than the Arctic Ocean, it provides a geochemical proxy for the presence of an open (flooded) Bering Strait. Their data suggest that relative sea level (RSL) dropped below the highest sill in the strait sometime between 40 and 35 ka, and that North Pacific water again flooded the strait starting ca. 11 ka. Because of uncertainties surrounding the marine reservoir effect during the Late Pleistocene, Farmer et al. (2021, 2023) refrain from calibrating their ^{14}C dates and instead interpret their data at millennial timescales.

Other proxy data that are consistent with initial flooding of Bering Strait ca. 11 ka include anoxic episodes on the Bering Sea shelf that ended ca. 11 ka, possibly as a result of enhanced circulation after Bering Strait first opened (Küehn et al., 2014), and the deposition of sand-rich layers on the Bering Slope ca. 11 ka, which suggest the present-day ocean current regime was established then (Wang et al., 2021).

2.2.2.2. Bathymetric uncertainties. Inferences about when Bering Strait was open/closed that are based on eustatic sea-level records are complicated by uncertainty surrounding the altitudes of bathymetric sills in Bering Strait when it was first inundated. This uncertainty comes from five sources, none of which are well-constrained. Based mainly on the effects of thermokarst deflation and erosion by currents, we speculate that the altitude of the shallowest sill in Bering Strait may have been as much as 5 m higher than today; however, factors including tectonism and far-field glacial effects could mean that the sill altitude was actually several meters lower than today.

1) Thermokarst deflation. When they were dry land during the Last Glacial Maximum, the surfaces of the Bering and Chukchi continental shelves were inflated by excess ice accreting in the underlying permafrost. Excess ice is the volume of ice in frozen ground that exceeds the pore volume present under thawed conditions (Harris et al., 1988). Today in unconsolidated deposits underlying coastal landscapes in northern Alaska and Yakutia, excess ice frequently comprises 40–80% of the uppermost 5 to 20 m of the ground by volume (Kanevskiy, 2003; Shestakova et al., 2021). Much of this ice takes the form of syngenetic ice wedges developed within deposits of ice-age loess (Kanevskiy et al., 2011; Murton et al., 2015; Gaglioti et al., 2018). Thick loess deposits accumulated in the Bering Strait region during Marine Isotope Stage 2 and 3 (Péwé, 1975; Muhs et al., 2003; Ager and Phillips, 2008). When excess ice comprises 50% of the uppermost 10 m of the ground, the overall ground surface can be elevated by approximately 5 m. When the sea transgresses across such a surface, it thaws the upper layers of permafrost causing subsea thermokarsting (Shakhova et al., 2017; Shakhova et al., 2019; Angelopoulos et al., 2020). Features consistent with such thermokarsting are visible in some of the seismic profiles from Bering Strait illustrated in Hill and Driscoll (2008).

2) **Erosion by bottom currents.** Strong currents run through Bering Strait today (Clement Kinney et al., 2022), and these currents have removed an unknown amount of sediment since the strait was initially flooded. Erosion was probably most intense when the transgressing sea first flooded the strait (Keigwin et al., 2006).

3) **Diastrophism.** The Bering Strait region is tectonically active in a spatially complex manner (Marlow et al., 1994). The Bering plate is now rotating clockwise at $4\text{--}8\text{ mm a}^{-1}$ (Cross and Freymuller, 2008). Along much of the coastline of western Alaska, the marine limit established ca. 100 ka during Marine Isotope Stage 5 now lies 6–10 m above sea level, but in certain places has subsided below sea level (Brigham-Grette and Hopkins, 1995). Ten meters of subsidence over 100 kyr suggests that the rate of vertical displacement due to tectonism has been $>1\text{ m}$ over the last 11 kyrs in certain areas of the Bering Strait region. Pico et al. (2020) estimate that $<3\text{--}4\text{ m}$ of vertical movement has occurred in the Bering Strait since 20 ka.

4) **Far-field glacial effects.** Although few glaciers existed in the immediate vicinity of Bering Strait during the Last Glacial Maximum (Brigham-Grette, 2001), relative sea level (RSL) in the Bering and Chukchi Seas was affected by the isostatic effects of distant ice loads over northwestern North America and by the gravitational effects of these ice masses (Pico et al., 2020). Uncertainties surrounding the chronology of the Cordilleran Glacier Complex (Section 2.1.3) limit the accuracy of modeling these far-field effects; however, they possibly caused 5–10 m of local variation in RSL changes across in Bering Strait region during the deglacial period (Pico et al., 2020).

5) **Mantle Dynamics (Dynamic Topography).** The flow dynamics of the mantle affect relative sea level (RSL) and complicate the effects of glacial isostasy and eustatic changes (Moucha et al., 2008). These mantle-induced changes can be significant over millennial time scales during the late Pleistocene (Austermann and Forte, 2019). The presence of multiple volcanic fields of Late Pleistocene age in western Alaska and on Bering Sea islands (Liang et al., 2024) attest to a non-quietest mantle, and the dynamic topography of the Bering Strait region may still be adjusting to the southward jump of the subduction zone from the northern Bering Sea to the Aleutian Trench that occurred after 55 Mya (Akinin et al., 2020).

In summary, North Pacific water probably first penetrated Bering Strait ca. 11.5 ka. The analyses of Pico et al. (2020) and Farmer et al. (2021, 2023) suggest the rate of relative sea level (RSL) rise slowed prior to this during the Younger Dryas chronozone, 12.9–11.7 ka. Multiple, unquantified factors make it uncertain how deep Bering Strait was at the time when it initially flooded, which complicates assigning an exact date to this event. Here we assign a $\pm 5\text{ m}$ uncertainty to the shallowest sill depth. The key question for oceanography and climatology is not when sea water first flowed through Bering Strait but when the strait became deep enough to assume its present-day oceanographic functions (Section 4.1.6). Only after ca. 9 ka did Bering Strait become deep enough to transmit significant amounts of ocean water from the North Pacific to the Arctic/Atlantic Oceans, and not until after ca. 7 ka did Bering Strait reach its present depth (Fig. 21).

2.3. History of sea ice in the subarctic Pacific during Marine Isotope Stage 2

Sea ice forms when sea surface temperature (SST) cools below -2°C . Glacial ice can also be widespread in the sea in the form of icebergs, and these two forms of ice mingle where marine-based glaciers border polar seas. Today in the Gulf of Alaska, sea ice is present only in winter and is restricted to inner fjords where surface waters are relatively fresh and cold air masses cross the coastal ranges from the continental interior. Even in the inner fjords, sea ice is ephemeral and thin today.

Current understanding of the timing and extent of sea ice in the high-latitude North Pacific during Marine Isotope Stage 2 (MIS 2) is sparsely distributed. In contrast to the North Atlantic, only a handful of deep-sea cores dating to the last 20 ka have been analyzed for sea ice proxies

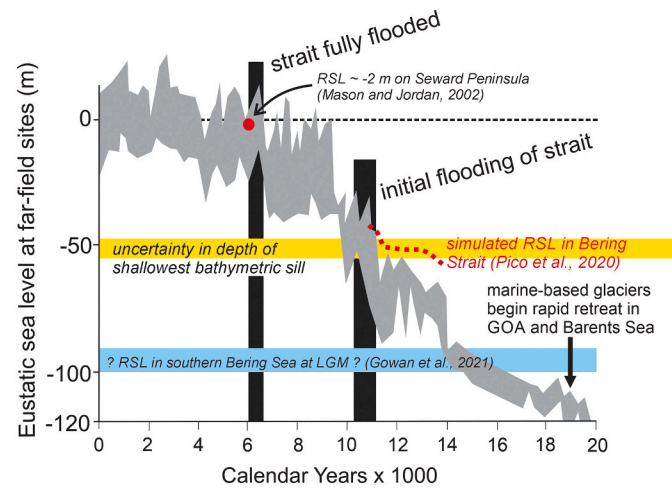


Fig. 21. Timing of the most recent flooding of Bering Strait based on the last 30 kyr of eustatic sea level recorded at far-field sites (Siddall et al., 2003; Lambeck et al., 2014). The grey area encloses these eustatic data and their approximate error terms. “GOA” = Gulf of Alaska. “LGM” = Last Glacial Maximum.

between Kamchatka and Southeast Alaska. A core from the Yakobi Sea Valley off of Southeast Alaska noted an increase in the abundance of sea ice diatoms during the Younger Dryas chronozone (Barron et al., 2009). Further north on the Gulf of Alaska continental shelf near the Bering Glacier, the sea ice diatoms in Core U1421 (Cowan et al., 2020; Praetorius et al., 2023) may record the presence of glacial ice in addition to sea ice (Fig. 26), at least prior to ca. 16.5 when intense iceberg calving was underway in the Bering Trough. This record suggests that ice of any kind was scarce on the continental shelf between 23 and 19 ka, increased during Heinrich Event 1 (HE 1) ca. 18–15 ka, and declined abruptly after ca. 14 ka. Throughout MIS 2 and 3, sea ice in the northeast Pacific was probably most abundant and seasonally persistent near the coast (Praetorius et al., 2023) and adjacent to calving glaciers (Taylor et al., 2014; Barrie et al., 2021).

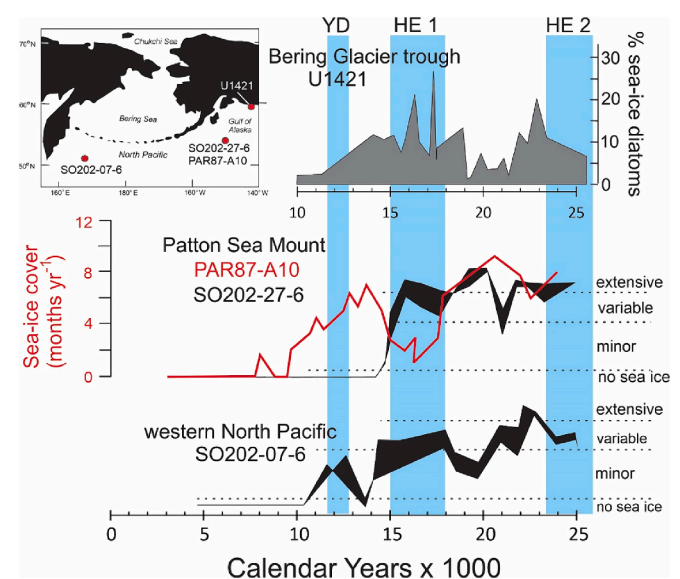


Fig. 22. Four records of sea ice from the subarctic Pacific. Core U1421 (Cowan, 2022) is from the continental slope near the Bering Glacier trough and may record iceberg-derived glacial ice in addition to sea ice. Core PAR87-A10 from the Patton Sea Mount was analyzed by de Vernal and Pedersen (1997). Core SO202-27-6 is also from the Patton Sea Mount (Méheust et al., 2018), and Core SO202-07-06 is from the northwestern North Pacific (Méheust et al., 2018). “YD” = Younger Dryas. “HE 1” = Heinrich Event 1. “HE 2” = Heinrich Event 2.

Analysis of Core PAR87-A10 (de Vernal and Pedersen, 1997) from the Patton Sea Mount in the southwestern Gulf of Alaska (54° 21.8' N, 148° 28' W) indicates that the Last Glacial Maximum (LGM) was a time of prolonged, seasonal ice cover, but counter-intuitively suggests that Heinrich Event 1 (HE 1) was a period of reduced sea ice cover (Fig. 22). These results are partly contradicted by another core from the Patton Sea Mount (Core SO202-27-6; Méheust et al. (2018) that suggests sea ice cover was sparse during the LGM, increased to “variable” ice cover during HE 1, declined during the Bølling/Allerød, and then increased slightly during the Younger Dryas chronozone.

Core 202-07-06 from the Detroit Sea Mount in the northwestern Pacific (51° 16.29' N, 167° 41.98'E) suggests an extensive sea ice cover at 23–22 ka followed by reduced coverage until ca. 20 ka, and then an increase in ice cover that peaked early during Heinrich Event 1 (Fig. 22) (Méheust et al., 2018). Sea ice disappeared from the area during the Bølling/Allerød but then reappeared during the Younger Dryas chronozone.

Sediment cores from the western Bering Sea and near southeastern Kamchatka suggest that between 20 and 10 ka the extent of sea ice repeatedly shifted across hundreds of kilometers (Max et al., 2012). Core SO202-18-6 was taken near the present southern edge of winter sea ice (Fig. 22) (Méheust et al., 2018). It suggests extensive sea ice cover during the Younger Dryas chronozone, ice-free conditions from 11.7 to 10 ka, followed by extensive ice cover thereafter. During the Last Glacial Maximum (LGM), perennial sea ice may have covered the Bering Sea (Sancetta, 1983; Sancetta et al., 1984; Caissie et al., 2010; Pelto et al., 2018). In the southern Bering Sea, the period between 17 and 11.3 ka saw a transition to seasonally ice-free conditions, followed after ca. 11.3 ka by ice-free conditions that lasted year-round (Caissie et al., 2010).

Méheust et al. (2018) made a speculative reconstruction of maximum sea ice extent during the Last Glacial Maximum (LGM) (Fig. 23). At its maximum in spring, pack ice may have arced across the North Pacific from Kamchatka to North America, possibly reaching latitudes as low as 55° N along the Northwest Coast near the British Columbia-Alaska border. The sea ice regime in the North Pacific during the LGM probably resembled that of subantarctic seas today (Maksym, 2019) rather than the present Arctic Ocean (Weeks, 2010). As in the Southern Ocean, North Pacific sea ice was highly exposed to storm winds and waves across enormous fetches. In this setting, sea ice tends to drift and eventually enter warmer water where it melts. Because of the

relatively low latitude and large wave fetch, most sea ice in the Gulf of Alaska was thin, first-year ice forming in autumn and melting by the following August. Thin, seasonally ephemeral ice like this tends to be highly unstable and undergo widespread deformation (Weeks, 2010). Fast ice would have existed along some shorelines, most likely in fjords not occupied by glaciers.

Potential insights into ice conditions near shore during Marine Isotope Stage 2 (MIS 2) come from faunal remains in On Your Knees Cave (*Shuka Káa*) on Prince of Wales Island (56° N) in Southeast Alaska (Heaton, 2003; Heaton and Grady, 2003). Among the bones recovered from this former fox lair are those of ring seal (*Pusa (Phoca) hispida*) and Arctic fox (*Vulpes lagopus*). Ring seals inhabit floating ice throughout the year, and Arctic foxes can live on both tundra and sea ice. In addition to these sea ice-indicating remains, the genes of polar bears (*Ursus maritimus*) occur in brown bear populations (*Ursus arctos*) on some islands in Southeast Alaska (Cahill et al., 2018), suggesting that they too inhabited the Northwest Coast during the local Last Glacial Maximum.

At first glance, the occurrence of ring seal, polar bear, and Arctic fox near On Your Knees Cave suggests that sea ice existed in the Alexander Archipelago and offshore in the Gulf of Alaska. On the other hand, polar bears and ice seals live today in southeastern Greenland in fjords where sea ice is present only seasonally (Laidre et al., 2022). Instead of pack ice, the ice seals and polar bears in these fjords utilize the mélange of glacial ice derived from icebergs. Similar iceberg-based habitats exist today at scattered locations along the Gulf of Alaska coastline, and they were probably extensive during deglacial phases of Marine Isotope Stage 2 (Shaw et al., 2020; Barrie et al., 2021). It follows that ice-dependent fauna from On Your Knees Cave does not provide conclusive evidence for sea ice as far south as Prince of Wales Island in Southeast Alaska. Interestingly, the bone fauna of the Port Eliza sea cave (49° 50'N) contains abundant salt-water fish but no ice-dependent marine mammals (Al-Suwaidi et al., 2006).

In summary, the history of sea ice in the North Pacific during MIS 2 remains poorly understood. At its greatest extents ca. 24–22 ka and 18–15 ka, winter sea ice covered an area of the high latitude North Pacific and its marginal seas that was some $\sim 3 \times 10^6$ km² greater than today. Together with the 1×10^6 km² of land exposed on the Bering Sea continental shelf by lowered eustatic sea level, this seasonal expansion of sea ice added some 4×10^6 km² of “terrestrial” surface to the sub-arctic Pacific region during late winter and spring. As sea ice does in subantarctic seas today (Watson et al., 2015), sea ice in the North Pacific during the Last Glacial Maximum undoubtedly had widespread impacts on overturning circulation and ocean ventilation.

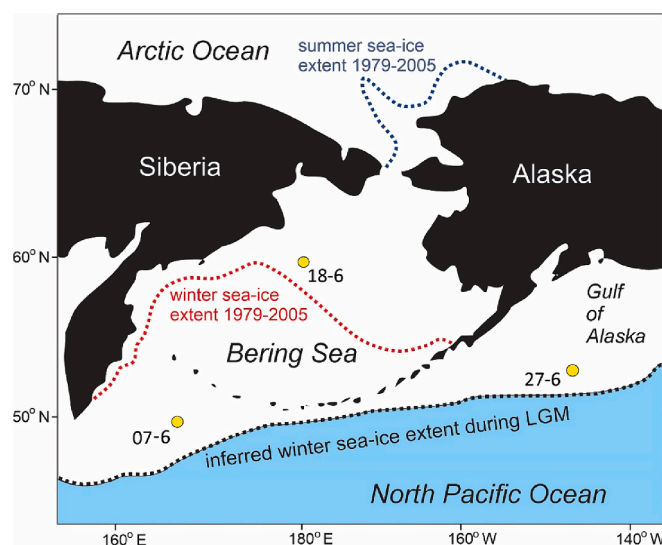


Fig. 23. The extent of winter sea ice during the last glacial maximum inferred from sea ice proxy biomarkers in marine cores (yellow dots). Modified slightly from Méheust et al. (2018). In the eastern Gulf of Alaska, sea ice may have extended in winter to ca. 55° N during the coldest intervals of Marine Isotope Stage 2.

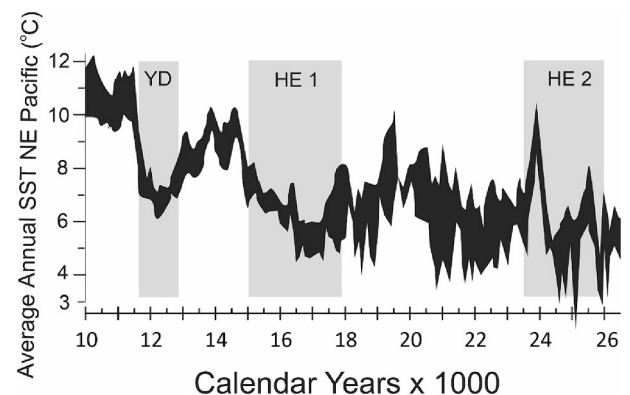


Fig. 24. Sea surface temperatures in the Northeast Pacific between 42° and 60° N. Redrawn from Praetorius et al. (2023). “YD” = Younger Dryas. “HE 1” = Heinrich Event 1. “HE 2” = Heinrich Event 2.

3. Synthesis: of the Northeast Pacific region during Marine Isotope Stage 2

3.1. Evidence from paleoceanography

Though still sparse compared to records from the North Atlantic, paleoceanographic data from the subarctic Pacific has accumulated rapidly over the last several decades. Oxygen isotope records from the continental slope near the Bering Trough in the northeastern Gulf of Alaska suggest sea surface temperatures (SSTs) there were 8° C cooler than today during Heinrich Event 2 (HE 2), ca. 23.5–26 ka (Fig. 24) (Praetorius et al., 2023). Three other cold periods followed, one at 23–21.5, another during Heinrich Event 1 (HE 1) between 18 and 16 ka, and the final one during the Younger Dryas chronozone. A record of planktonic foraminiferal Mg/Ca off the west coast of Vancouver Island suggests SSTs were 7° C cooler than today between 18 and 17 ka (Taylor et al., 2014) (Fig. 7). This is consistent with paleobotanical records from the coastline of the Olympic Peninsula in western Washington that suggest temperatures were $\geq 5^\circ$ C cooler than today and that precipitation was less than half of today's during the coldest part of Marine Isotope Stage 2 (Heusser et al., 1999).

A compilation of marine proxy data by Paul et al. (2021) suggests sea surface temperatures (SSTs) in the North Pacific cooled less than they did at similar latitudes in the North Atlantic (Fig. 25). Based on diverse proxy data, Margo Project Members (2009) inferred that summer SSTs were 2–4° C cooler in the southern and central Gulf of Alaska during the Last Glacial Maximum (LGM) than today. Tierney et al. (2020) estimated mean annual SSTs in the Gulf of Alaska during the LGM by combining data-based estimates of ocean temperature with integrative general circulation modeling. They concluded that nearshore SSTs were 5–15° C colder than today, with the coldest temperatures occurring nearest the coastlines of Southeast Alaska and British Columbia (Osman et al., 2021).

3.2. Inferences from general circulation models

Much of what we think we know about the climate of the Northeast Pacific region during Marine Isotope Stage 2 comes from the outputs of general circulation models (GCMs). Only the most relevant ones are mentioned here. Bromwich et al. (2004) inferred that July surface temperatures along the Gulf of Alaska coastline were at most 5° C cooler during the Last Glacial Maximum (LGM) than today. In accordance with earlier (e.g., COHMAP Members (1988)) and later modelling studies (e.g., Löfverström et al. (2014)), Bromwich et al. (2004) found that during the Last Glacial Maximum, the polar jet split around the topographic barrier formed by the Cordilleran Glacier Complex and the Laurentide

Ice Sheet (Fig. 26). The split jet stream caused storm tracks to be diverted away from Southeast Alaska and British Columbia, which then enhanced winter precipitation in northern (Prince William Sound) and northwestern sectors (Kodiak, Alaska Peninsula) of the Northwest Coast (Bromwich et al., 2004). Splitting of the polar jet during the LGM is not duplicated in some other GCM experiments, which predict only a southward shift and strengthening of the polar jet (Bartlein et al., 1998; Ullman et al., 2014).

Morée and Schwinger (2020) interpret their modelling results as showing that mean annual temperatures were 2.5–5° C cooler along the eastern Gulf of Alaska coast during the Last Glacial Maximum (LGM), with precipitation similar to today in the central and southern gulf, but slightly greater in the northwestern gulf. The modelling experiments of Ullman et al. (2014) suggest that at 21 ka strong cooling occurred over the North Pacific, and that the amount of this cooling responded sensitively to the changing height of the Laurentide Ice Sheet. Their results also suggest significantly less precipitation along in the eastern Gulf of Alaska during the LGM.

In contrast to paleoceanographic and modelling studies indicating that significant cooling occurred in the Gulf of Alaska region during the Last Glacial Maximum (LGM), the modelling study of Otto-Bliesner et al. (2006) suggested that mean annual sea surface temperatures (SSTs) were 1–1.5° C warmer. Even more warming is suggested by the modelling studies of Löfverström et al. (2014), Liakka and Löfverström (2018), and Tulenko et al. (2020). An LGM warming of 2° to 6.5° C in mean annual surface temperatures over the Gulf of Alaska and over Alaska as a whole is suggested by Liakka and Löfverström (2018) to have resulted from anticyclonic circulation induced by the orographic effects of the North American ice sheets. As foreshadowed by earlier modelling experiments (Kutzbach and Guetter, 1986; Broccoli and Manabe, 1987; Bartlein et al., 2015), this warming was caused by the poleward transport of energy within atmospheric stationary waves that developed along the western flanks of the ice sheets. The northward transport of energy was enhanced by positive feedbacks involving reduced surface albedo, decreased cloud cover, and enhanced transport of latent heat poleward along the Northwest Coast. Warming caused by the highest reconstructed heights of the Laurentide Ice Sheet would have caused glacier equilibrium lines to rise in northern sectors of the Northwest Coast, which Liakka and Löfverström (2018) and Tulenko et al. (2020) suggest is the reason why large parts of Alaska remained unglaciated during the last ice age.

3.3. Climate during the Younger Dryas (YD)

Oceanographic proxy data suggest that sea surface temperatures (SSTs) in the Gulf of Alaska cooled nearly as much between 12.9 and 11.7 ka during the Younger Dryas (YD) chronozone as during the Last Glacial Maximum (Barron et al., 2009; Walczak et al., 2020; Praetorius et al., 2023) (Fig. 24). Onshore, biological records also suggest that the climate cooled significantly around the Gulf of Alaska margin (Peteet and Mann, 1994; Hu et al., 1995; Hansen and Engstrom, 1996); however, vegetational responses to the YD varied across the region and were typically subtle (Kokorowski et al., 2008; Kaufman et al., 2010; Ager, 2019). For example, Mathewes et al. (1993) used palynology to infer that YD summers on Haida Gwaii were 2–3° C cooler than today and that the overall climate was wetter; however, reconstructions elsewhere in southern Alaska and British Columbia suggest a diversity of moisture regimes existed in different sectors of the Northwest Coast (Kokorowski et al., 2008; Jones et al., 2009; Fedje et al., 2011; Hebda et al., 2022).

Limited evidence from glacial geology in Southwest Alaska suggests the occurrence of an early-cold / late-warm pattern of climate change over the course of the Younger Dryas (YD) chronozone (Young et al., 2019). An early-cold / late-warm pattern is also suggested by changes in water chemistry and diatom abundance in Nimgun (Hu et al., 2002) and Arolik Lakes in Southwest Alaska, (Hu et al., 2007; Kaufman et al., 2010). This early-cold / warm-late pattern is absent from the Gulf of

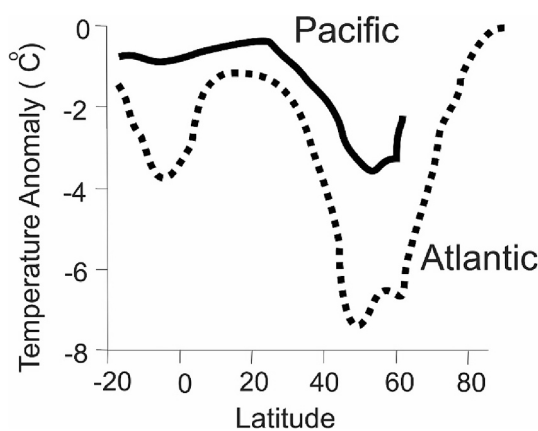


Fig. 25. Zonally averaged, annual-mean sea surface temperature anomalies between the Last Glacial Maximum and today as compiled from various sources by Paul et al. (2021).

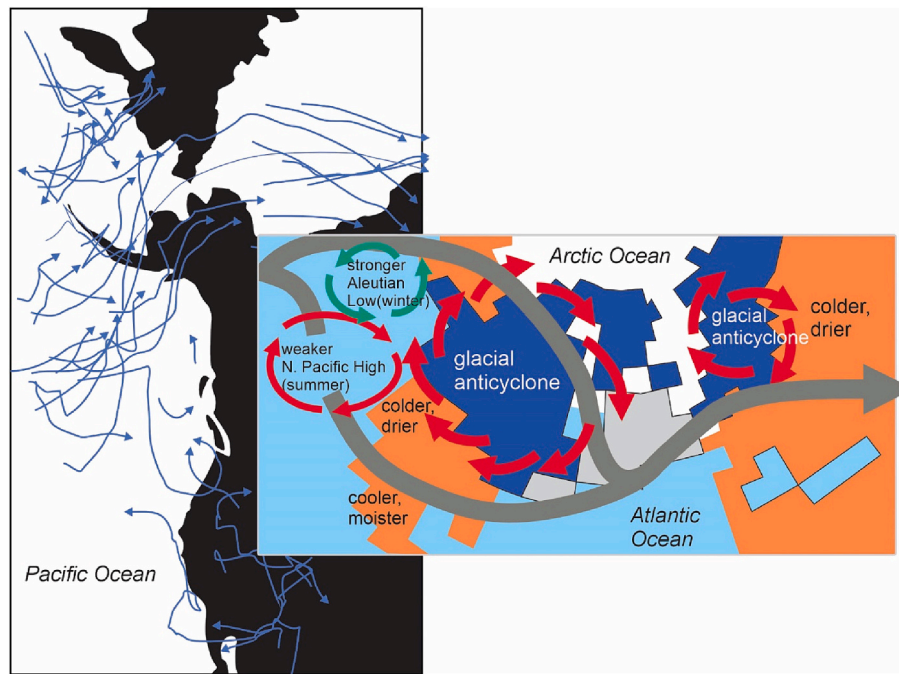


Fig. 26. At times during the Last Glacial Maximum, the presence of 3-km high ice sheets over northern North America created persistent anticyclonic flow. This probably split the polar jet in winter and diverted storm tracks (blue lines) around it. **LEFT** Storm tracks predicted in the modelling experiments of Bromwich et al. (2004). **RIGHT** The classic split-jet scenario resulting from the modelling experiments of COHMAP Members (1988).

Alaska sea surface temperature record (Fig. 24), nor is it reflected in the vegetation record of YD cooling from southwestern Kodiak Island (Peteet and Mann, 1994; Hajdas et al., 1998). Rising water levels in Discovery Pond on the Kenai Peninsula suggest increasing effective moisture beginning at 12.2 ka, some 500 years before the end of the YD chronozone (Kaufman et al., 2010).

Some of the enigmatic aspects of Younger Dryas (YD) climate along the Northwest Coast could relate to accentuated seasonality. YD winters along the Northwest Coast may have been cold and dry, while summers may have been warm and steadily growing warmer. This interpretation of YD climate has gained increasing consensus in the North Atlantic region (Levy et al., 2016; Schenk et al., 2018; Young et al., 2019; Rea et al., 2020; Funder et al., 2021; Putnam et al., 2023). The cause of accentuated seasonality in the North Atlantic region during both Heinrich Event 1 and the YD (Fig. 27) may have been the expansion of winter sea ice, which made winters colder but had little effect on summer conditions (Denton et al., 2005, 2021). Despite the colder winters, summer conditions in Greenland remained relatively mild and continued to warm over the course of global deglaciation, including during the YD chronozone (Putnam et al., 2023; Bromley et al., 2023) (Fig. 27).

The occurrence of cold and dry winters could explain the rarity of glacier advances along the Northwest Coast during the Younger Dryas (YD) chronozone. Because glaciers existing within a maritime climatic regime are typically more sensitive to winter precipitation (accumulation) than to summer temperature (ablation) compared to continental glaciers (Ohmura et al., 1992), the apparent absence of YD advances by glaciers bordering the Gulf of Alaska could have been the result of winters that were colder and drier than the preceding Bølling/Allerød Interstadial. Extreme winter conditions might also explain the replacement of ferns by ericaceous shrubs on the windswept tundra of southwestern Kodiak during the YD (Peteet and Mann, 1994). The limited vegetation responses to the YD along the Northwest Coast (Hansen and Engstrom, 1996; Ager et al., 2010; Ager, 2019) may reflect the fact that the most extreme climates of the YD occurred during the dormant season.

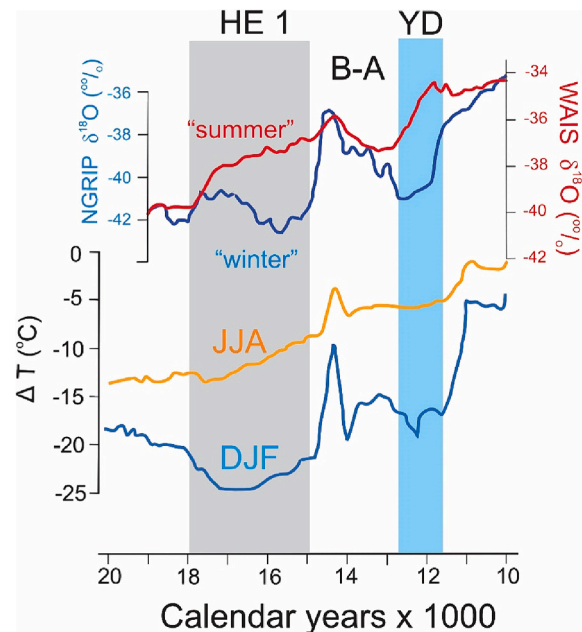


Fig. 27. The Extreme Winters Hypothesis asserts that high, northern latitudes experienced accentuated seasonality during Heinrich Event 1 and the Younger Dryas (Denton et al., 2005, 2022). Starting at 19 ka, winter temperatures cooled in response to the increased extent of seasonal sea ice, even while summer temperatures progressively warmed. **ABOVE** The Greenland NGRIP ice core $\delta^{18}\text{O}$ record (NGRIP Members, 2004) and the West Antarctic Ice Sheet Divide Ice Core (WAIS) $\delta^{18}\text{O}$ record (WAIS Divide Project Members, 2015) redrawn from Putnam et al. (2023). These authors argue that the WAIS record is a proxy for global, summer temperatures and that the NGRIP record is a proxy for winter temperatures in the North Atlantic region. **BELOW** Simulated summer and winter temperatures relative to sites near sea level in East Greenland today. “JJA” = June, July, August. “DJF” = December, January, February. Redrawn from Buizert et al. (2015).

3.4. Evidence from paleo-glacier mass balances

Estimates of the paleo-equilibrium line altitudes (ELAs) of glaciers are consistent with 4–5° C cooling in summer in the Gulf of Alaska region during the Last Glacial Maximum (LGM). A glacier's mass balance is an equifinal state resulting from different combinations of temperature and precipitation. That said, temperature tends to be paramount because it influences both the amount of precipitation arriving as snow and the amount of snow melting (Mackintosh et al., 2017). Summer temperatures are particularly important in controlling glacier mass balance through their effects on melt (Oerlemans, 2005; Zemp et al., 2015). The greater the precipitation and the warmer the temperature at the equilibrium line, the more sensitive is the glacier's mass balance to changes in either variable (Oerlemans, 1992; Anderson and Mackintosh, 2012). When in climate-sensitive phases of their advance/retreat cycles, marine-based glaciers that lose mass via iceberg calving tend to respond faster to temperature changes than do land-terminating glaciers of similar lengths (Jóhannesson et al., 1989). It follows that marine-based glaciers along the Northwest Coast during Marine Isotope Stage 2 responded sensitively and quickly to changing climate compared to glaciers located in the interior of the continent.

Using the accumulation-area ratio method (Porter, 2000) and reconstructions of paleo-equilibrium-line altitudes (ELAs), Tulenko et al. (2023) estimate that ~4° C of cooling occurred during summer in the western Alaska Range during the local Last Glacial Maximum (LLGM), and this is consistent with other paleo-proxy data from Interior Alaska (Péwé, 1975; Kurek et al., 2009). The presence of glacial cirques below sea level today on the coasts of the Kenai Peninsula and Alaska Peninsula suggests that ELAs there were > 800 m lower than today (Mann and Peteet, 1994). A similar estimate of ELA depression results from assuming a moist adiabatic lapse rate (Mackintosh et al., 2017) and an LGM marine-boundary layer 5° C cooler than today (Section 3.1). On the Shumagin Islands (Fig. 12, 28), where the mean summer temperature is now 10° C, the ELA probably fell ~900 m during the LLGM. This amount of ELA lowering brought it below present sea level, which is consistent

with the reconstructions of Mann and Peteet (1994) and agrees with what would happen within the present phase space of alpine glaciers in response to a 5° C cooling (Fig. 28). The fact that precipitation strongly modifies the effect of temperature within the glaciogenic phase space defined in Fig. 28 indicates that changes in winter precipitation were probably also important in controlling glacier dynamics along the Northwest Coast during the LGM.

3.5. Insights from the history of pluvial lakes in the Southwest USA

Some of the precipitation that was diverted southwards to pluvial lakes in the western USA occurred at the expense of the snow feeding glaciers in Alaska and British Columbia. For this reason, the chronology of these pluvial lakes provides insights into climate and glacier changes along the Northwest Coast. The western USA experienced higher effective moisture than today during the deglacial period, 21–11 ka (Reheis et al., 2014; Oviatt, 2015; Hudson et al., 2019). Closed topographic basins filled with water brought by extratropical cyclonic storms traveling in the Aleutian Low and being diverted southward around the southern margins of the Cordilleran Glacier Complex and the Laurentide Ice Sheet (Antevs, 1948). Abundant precipitation probably also arrived more directly from the central Pacific via atmospheric rivers (Lyle et al., 2012; Lora et al., 2017; Löfverström, 2020; Skinner et al., 2023).

Lakes began to fill in the Basin and Range region of the western USA at the beginning of Marine Isotope Stage 2 (Fig. 29). Most of these pluvial lakes there reached high stands between 18 and 15 ka, which is 5 to 8 kyrs after most sectors of the Laurentide Ice Sheet reached their Last Glacial Maxima. Many of these lake high stands occurred during Heinrich Event 1 (Munroe and Laabs, 2013) (Fig. 29), which was also when the Vashon Lobe reached its maximum extent in Puget Sound (Fig. 5). There are suggestions that northern basins like Lake Chewaucan in southeastern Oregon reached high stands later than did southern basins (Hudson et al., 2019), possibly as a result of storm tracks shifting northward as the ice sheets down-wasted (Oster et al., 2015). Most pluvial lakes dried rapidly after ca. 15 ka during the Bölling-Allerød interval (Fig. 29).

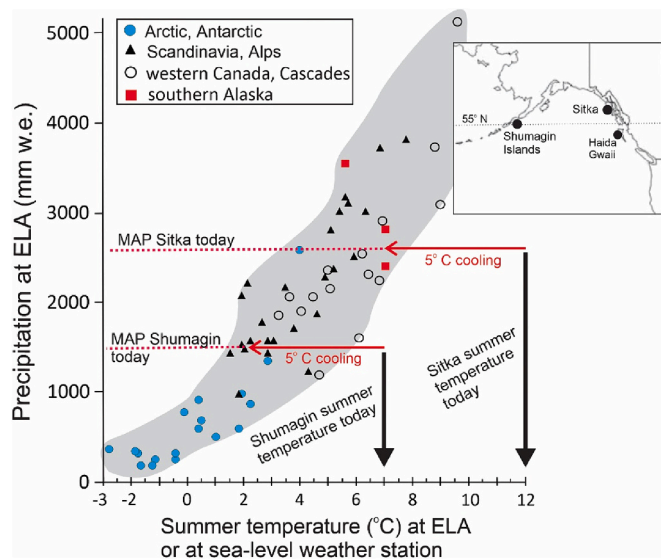


Fig. 28. The precipitation and temperature phase space of 70 existing glaciers (Ohmura et al., 1992) can be used to infer how cooling over the Gulf of Alaska during the Marine Isotope Stage 2 affected glaciers there. In response to the ~5° C cooling suggested by records of sea surface temperature from marine cores and general circulation models, equilibrium line altitudes (ELAs) would have lowered to near modern sea levels on the Shumagin Islands and near Sitka, even without increases in precipitation. The modern climate data are from the Alaska Climate Research Center, <https://akclimate.org/data/air-temperature-normals/>. "MAP" = mean annual precipitation.

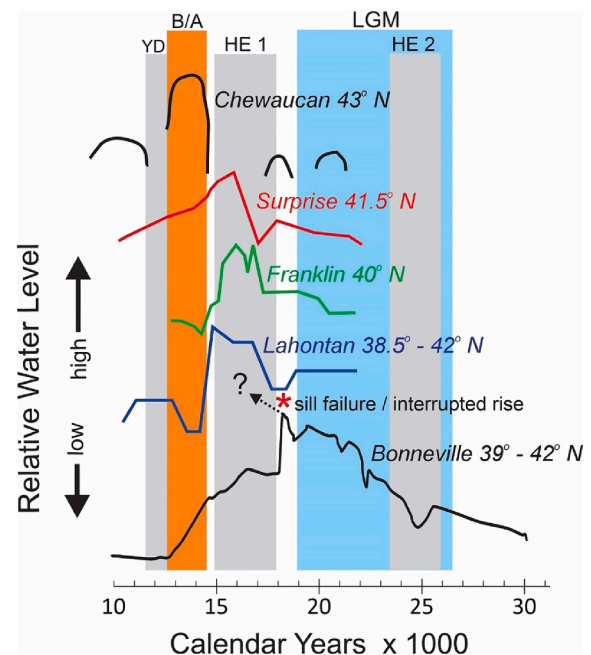


Fig. 29. Lakes began to fill closed basins in the western USA early during Marine Isotope Stage 2, but they only reached peak levels during Heinrich Event 1 ca. 18–15 ka. The water-level records for Lakes Chewaucan, Surprise, Franklin, and Lahontan are from Hudson et al. (2019). The Lake Bonneville curve is from Oviatt et al. (2015).

For decades, the cause of the pluvial interval in the western USA has been assigned to a southward shift of North Pacific cyclonic storms caused by the orographic effects of the North American ice sheets (Antevs, 1945, 1948; Broccoli and Manabe, 1987; Benson et al., 1995; Bromwich et al., 2004; Munroe and Laabs, 2013; Lachniet et al., 2017; Liakka and Löfverström, 2018). Recently, this “shift in the Westerlies hypothesis” has been challenged by more nuanced explanations, and these are relevant to what was happening at the same time further north along the Northwest Coast.

One variation on Antevs’ (1945) original idea is that rather than storm tracks uniformly shifting southwards, the polar jet stream along which these storms tracked was confined and steered into the western USA between an expanded subtropical high centered over Mexico and a semi-permanent high centered over the northern ice sheets (Oster et al., 2015). Another idea is that the deglacial wetting of the western USA resulted from a combination of the ice sheets’ orographic effects and from the effects of a southward shift in the thermal Equator caused by weakening of Atlantic Meridional Overturning Circulation (AMOC) (Broecker and Putnam, 2013; Lora et al., 2017; Hudson et al., 2019). According to this hypothesis, a southward shift in the thermal Equator altered zonal-mean meridional circulation globally (Bradley and Diaz, 2021) and locked storm tracks over western North America (Oster et al., 2015) into the north-dry, south-wet dipole pattern (Wise, 2010) that exists over the western USA today under El Niño conditions (Hudson et al., 2019) (SI Section 1.3.1). Support for this “ice sheet + AMOC-slowdown hypothesis” comes from the fact that the lake high stands occurred during Heinrich Event 1 (HE 1) and (most notably for Lake Lahontan (Fig. 29)) also during the Younger Dryas (Munroe et al., 2020), which were both times when slowing of AMOC caused equatorward shifts in the thermal Equator. Furthermore, the presence of cold steppe vegetation in southern Washington throughout MIS 2 (Whitlock and Bartlein, 1997) is consistent with a long-term persistence of the ENSO precipitation dipole (Wise, 2010). Lake basins in many parts of the western USA desiccated rapidly upon the rejuvenation of AMOC and the rapid down-wasting of the North American ice sheets during the Bølling-Allerød period (14.7–12.9 ka). The beginning of the Holocene saw a sweeping reorganization of atmospheric circulation over western North America in <1000 years, which may have been accompanied by a decline in the frequency of atmospheric river events (Lora et al., 2017).

Morrill et al. (2018) assert there was an additional cause for the wetting of the western USA during the deglacial period. Their modelling experiments suggest that regional cooling caused by the proximity of the ice sheets reduced the processes of moisture convection and divergent circulation that today cause drying of the region’s atmosphere. This explanation is consistent with the strong cooling effect that the ice sheets had in southeastern Washington (Lopez-Maldonado et al., 2023) and in the northern Rocky Mountains (Hostetler and Clark, 1997; Laabs et al., 2020; Quirk et al., 2022). Whatever the correct explanation, resolving these long-standing questions about the drivers of pluvial periods in the western USA will improve our understanding of the ocean-atmosphere-cryosphere interactions that occurred along the Northwest Coast during Marine Isotope Stage 2.

3.6. Summary of climate changes along the Northwest Coast during Marine Isotope Stage 2

The surface of the subarctic Pacific cooled less than the subarctic Atlantic at similar latitudes during Marine Isotope Stage 2 (MIS 2). Paleoclimatographic data suggest the coldest intervals of MIS 2 occurred in the Northeast Pacific at 26–23.5 ka (Heinrich Event 2), 23–21.5, 18–15 ka (Heinrich Event 1), and 12.8–11.7 ka (Younger Dryas chronozone). Minimum sea surface temperatures (SSTs) were probably 7° C colder than today off the western coast of Vancouver Island and 5–6° C colder in the northeastern Gulf of Alaska. Reconstructions of paleo-glacier equilibrium lines around the Gulf of Alaska during the Last Glacial Maximum are consistent with these estimates. Some modelling

experiments suggest similar amounts of cooling; others suggest that SSTs in the Gulf of Alaska were at times warmer than today (Otto-Bliesner et al., 2006; Tulenko et al., 2020). The predictions of warmer SSTs come from general circulation models (GCMs) that incorporate the topographic effects of the North American ice sheets on atmospheric circulation. When ice cover was thickest over northwestern North America, a semi-permanent blocking high may have diverted air masses and cyclonic storms to its north and south. The presence of this blocking high would have diverted warmer air masses northward along the Northwest Coast into southern Alaska and reduced both snowfall and cloudiness there. At the same time, the southward diversion of cyclonic storms and atmospheric rivers would have brought more precipitation into the western USA (Löfverström, 2020). Ice-topographic modulation of atmospheric circulation over the region may help explain the time-transgressive behavior of glaciers along the Northwest Coast.

During the Younger Dryas (YD) chronozone, sea surface temperatures (SSTs) in the northeastern Gulf of Alaska cooled by as much as 5° C. Paleoclimatographic data do not resolve seasonal differences in SST, nor is seasonality clearly distinguished by any of the terrestrial proxies for temperature now available. As a result, it is unclear what the millennial- and seasonal-scale timings of YD climate were along the Northwest Coast. The Extreme Winter Hypothesis that has emerged from studies in the North Atlantic region (Denton et al., 2005, 2022) may help explain the so-far enigmatic records of the YD along the Northwest Coast.

4. The Ice-Age Northwest Coast and Northeast Pacific in a global context

4.1. Key processes; global impacts

The ocean/atm/cryosphere systems of the Northeast Pacific and Northwest Coast participated in the rapid, global changes that characterized Marine Isotope Stage 2 (MIS 2). Based on the preceding review and on their importance today (Section 7.0), the following ten processes/phenomena were probably also of key importance along the Northwest Coast during MIS 2. This section describes how these processes may have affected the Northwest Coast and Northeast Pacific and in doing so linked them to the rest of the planet.

1. Orbital variations in insolation
2. Aleutian Low
3. Asian Summer Monsoon
4. Oceanic heat transport in the Kuroshio Current system
5. El Niño-Southern Oscillation
6. Opening and closing of Bering Strait
7. Extent and timing of sea ice in the North Pacific
8. Variations in overturning ocean circulation in the North Pacific
9. Glacial outburst floods entering the North Pacific
10. Sea surface cooling in the Gulf of Alaska possibly triggering Heinrich Event 1

4.1.1. Orbital variations in insolation

4.1.1.1. Were changes in low-latitude insolation important in the subarctic Pacific? The canonical Milankovitch view is that orbital variations drove the Pleistocene ice ages by reducing / increasing solar insolation at high northern latitudes (Fig. 30); however, the mechanisms involved remain unclear (Ruddiman, 2003; Raymo et al., 2006; Tabor et al., 2014). The fact that glaciers in the southern hemisphere fluctuated synchronously with those in the north, despite out-of-phase forcing by summer insolation in the two hemispheres, suggests that boreal, summer insolation was not the sole driver of the northern ice sheets (Broecker and Denton, 1989; Denton et al., 2021). The fact that summer insolation at low and high, northern latitudes varied in parallel (Fig. 31) suggests

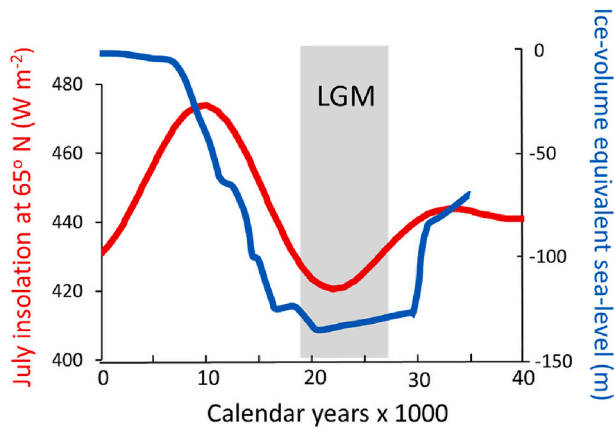


Fig. 30. Global ice volumes generally tracked Milankovitch orbital forcing at high, northern latitudes (red). Eustatic sea level (blue) is a proxy for the amount of glacial ice on land. At first glance, the synchrony between insolation and eustatic sea level suggests that boreal summer insolation was the ultimate driver of glaciation and deglaciation (Shakun and Carlson, 2010). “LGM” is the global Last Glacial Maximum. The sea level curve is from Lambeck et al. (2014). Milankovitch insolation data are from Laskar et al. (2011).

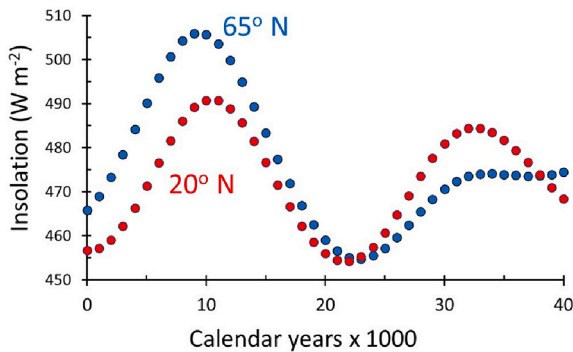


Fig. 31. Solar insolation at 65° N in summer varied in parallel with insolation at low, northern latitudes, suggesting that high-latitude insolation may not have been the sole driver of the boreal ice sheets. Insolation data from Laskar et al. (2011).

that low-latitudes processes could have played key roles. This is consistent with the low correlation between $\delta^{18}\text{O}$ records from southeast Asian speleothems and global ice volumes/eustatic sea level, which suggests that the chain of climate-change causation actually began in the tropics and went poleward rather than the other way around (Beck et al., 2018). Furthermore, an important role for low-latitude solar insolation in driving late Pleistocene events at higher latitudes is consistent with the planetary geography of energy receipt and dissipation (Pierrehumbert, 2000; Rodgers et al., 2003; Chiang, 2009).

4.1.1.2. A role for meridional insolation gradients? Raymo and Nisan-ciglu (2003) proposed that meridional insolation gradients modulated Milankovitch effects on ice-sheet volume to such an extent that during the early Pleistocene they were responsible for a 41-ka rhythm in sea surface temperatures (SSTs), despite the predominance of a 21-ka cycle in insolation at that time in Earth's history. The 41-ka periodicity of obliquity may have overwhelmed precession's effects on ice-sheet growth and decay by altering latitudinal gradients in insolation, which then changed the poleward flux of heat and moisture. In a similar way during Marine Isotope Stage 2 (MIS2) latitudinal gradients in seasonal solar insolation may have played key roles in the dynamics of high-latitude ice sheets. The occurrence of the Last Glacial Maximum during a peak in the insolation differences between 10° N and 60° N

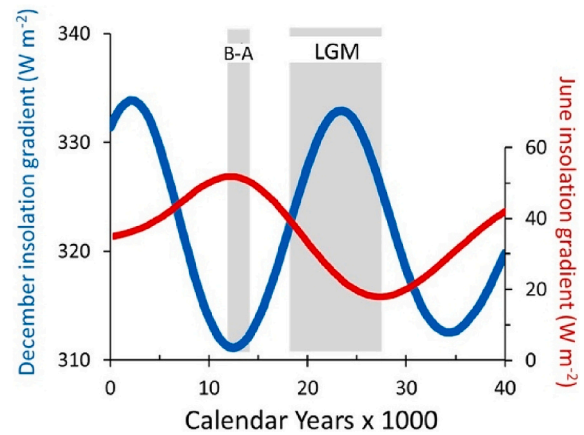


Fig. 32. Changing differences in solar radiation received at the Equator and 60° N. The steepness of this gradient affected the position of the Intertropical Convergence Zone (ITCZ), modulated the strength of the trade winds, and modified the pressure gradients responsible for generating extratropical cyclones. The onset of the Last Glacial Maximum (LGM) occurred when the winter gradient in insolation (blue line) between the northern tropics and the high, northern latitudes was steep and growing steeper, while the summer gradient (red line) was shallow and growing more so. Deglaciation accompanied a reverse in these seasonal gradients. The Bølling-Allerød (B-A) interstadial accompanied a minimum in the winter gradient. Insolation values are from Laskar et al. (2011).

(Fig. 32) is consistent with this meridional-gradient mechanism contributing to the inception, growth, and demise of the Cordilleran Glacier Complex.

How might insolation changes at low latitudes have affected the environments of the Northwest Coast through changes in the latitudinal gradient in solar insolation? Today, the most important atmospheric bridges (SI Section 1.3) between the tropics and the Northwest Coast are the Asian Summer Monsoon (ASM) and the Aleutian Low (AL), both of which are strongly influenced by conditions in the Equatorial Pacific. Today, steepening of meridional temperature gradients intensifies the jet streams, the mid-latitude Westerlies, and the subtropical ocean gyres (Lee and Poulsen, 2005; Molnos et al., 2017; Lutsko and Popp, 2018; Trenberth, 2022). In response, the ASM also tends to penetrate further north (Deininger et al., 2020). The net result is increased storminess over the North Pacific, particularly in winter (Liu et al., 2021), and it is these winter storms that provide the snow that nourishes glaciers along the Northwest Coast (McCabe et al., 2000; Meier et al., 2003; Malcomb and Wiles, 2013). The next two sections describe the effects that insolation-caused changes in latitudinal insolation gradients may have had on the ocean/atm/cryosphere system of the Northeast Pacific and Northwest Coast via the atmospheric bridges afforded by the Asian Monsoon and the Aleutian Low.

4.1.2. Aleutian Low

The glacial history of the Northwest Coast (Fig. 16) and the chronology of pluvial lakes in the western USA (Fig. 29), reflect shifting latitudinal gradients in climate over the North Pacific. In response to steepened latitudinal temperature gradients and the accompanying increase in the zonality of atmospheric circulation (Löffverström et al., 2014; Skinner et al., 2023), the Aleutian Low (AL) shifted southward during the coldest intervals of Marine Isotope Stage 2 (COHMAP Members, 1988; Munroe and Laabs, 2013). As they do today (SI Section 1.2.3), the AL's tropical teleconnections influenced the tracks these storms took, along with their seasonality and intensity. Changes in the strength and position of the AL affected glaciers by changing summer temperatures and winter precipitation. Under glacial conditions, atmospheric rivers probably increased in frequency and contributed larger proportions of annual precipitation along the Northwest Coast than

today (Löfverström, 2020). Modelling output hints that atmospheric rivers may have been particularly important in sustaining glaciers' mass balances in the Alaska Peninsula sector of the Cordilleran Glacier Complex (CGC) (Skinner et al., 2023). In response to the AL's southerly shift during Heinrich Event 1, the CGC advanced into western Washington between 17 and 16 ka. At that same time, pluvial lakes in the western USA reached their highest levels (Section 3.5), probably in response to a combination of increased winter precipitation and cooler, cloudier, less evaporative summer conditions.

Also during Heinrich Event 1, marine-based glaciers around Haida Gwaii (Section 2.1.3.4) and in the northern Gulf of Alaska and Alaska Range (Section 2.1.3) were retreating, possibly in response to declining precipitation. If the dipole pattern in winter precipitation that occurs today over the western USA during El Niño years also occurred at that time (SI Section 1.3.1), then glacial advances in southwestern British Columbia and in the western USA may have been responses to cooler summer temperatures rather than to increased winter precipitation.

Although changes in storm tracks within the Aleutian Low (AL) were probably instrumental in determining regional differences in the timing of glaciation between Alaska and the southwestern USA, how exactly teleconnection patterns (SI Section 1.3) such as the Pacific Decadal Oscillation (PDO), Pacific North American Pattern (PNA), and the Arctic Oscillation (AO) expressed themselves during Marine Isotope Stage 2 remains unclear. The presence of the North American ice sheets, combined with what were probably persistent Eastern Pacific Warm-El Niño (EPW-El Niño) conditions (Section 4.1.5), may have increased the frequency of the AO- and PNA+ patterns (SI Section 1.3). Because of these persistent EPW-El Niño conditions, PDO+ phases were probably also more frequent. Today, the conjunction of an EPW-El Niño with a PDO+ phase and winter PNA+ conditions tends to increase snowfall in southern and Southeast Alaska, while causing less snowfall in southern British Columbia and the Pacific Northwest, and bringing wetter conditions to the western USA. In contrast, the winter conditions that today are most favorable for glacier growth in the Pacific Northwest (and least favorable in southern Alaska) occur when PNA- patterns coincide with a PDO- phase and La Niña (SI Section 1.3). During the last ice age, similar anti-phase relationships in winter precipitation between southern/southeast Alaska and the Pacific Northwest may have caused time-transgressive glaciations in these different sectors of the Northwest Coast. That said, how exactly the AL's tropical teleconnections behaved when it shifted to its southernmost extreme along the Northwest Coast during Heinrich Event 1 remains to be deciphered.

4.1.3. Asian Summer Monsoon

Today, the Asian Summer Monsoon (ASM) transports large amounts of sensible and latent heat from the tropics into the subarctic Pacific (Wang et al., 2013) (SI Section 1.2.1). During Marine Isotope Stage 2

(MIS 2), the strength of the ASM generally tracked summer solar insolation (Fig. 33); however, several notable divergences occurred. After declining at the outset of MIS 2, monsoon vigor stabilized at a low level between ca. 25 and 20 ka, despite the continuing decline in summer insolation that occurred at 20° N. Even more radical divergences occurred during Heinrich Event 1 (HE 1) (ca. 18 to 15 ka) and the Younger Dryas chronozone (YD) chronozone (12.9–11.7 ka) when the ASM weakened despite increasing insolation. Sharp declines in ASM vigor during HE 1 and the YD were probably related to summer cooling over Asia (Chiang et al., 2014) and over the western tropical Pacific, which was probably a response to the combination of weakened Atlantic Meridional Overturning Circulation (Section 4.2) and persistent Eastern Pacific Warm-El Niño conditions (Section 4.1.5). The position of the Intertropical Convergence Zone (ITCZ) is a key factor in monsoon climatology today (Broecker and Putnam, 2013; Walker et al., 2015; Beck et al., 2018; Geen et al., 2020; Clemens et al., 2021), and southward shifts occurred in the ITCZ during both HE 1 and the YD (Chiang and Bitz, 2005; Bradley and Diaz, 2021) (Section 4.1.5).

Evidence for the changing influence of the Asian Summer Monsoon (ASM) on conditions in the subarctic Pacific during Marine Isotope Stage 2 (MIS 2) comes from records of sea surface temperatures (SSTs) (Walczak et al., 2020). SSTs in the Gulf of Alaska appear to have paralleled rainfall on the loess plateau in northern China (Fig. 34). Heinrich Events 1 and 2 (HE 1, 2) are clearly evident in both records, though a divergence occurred between 23.5 and 20 ka when the Gulf of Alaska's SSTs continued to cool while rainfall plateaued in northern China. The vigor of overturning circulation (ventilation) in the northeastern Gulf of

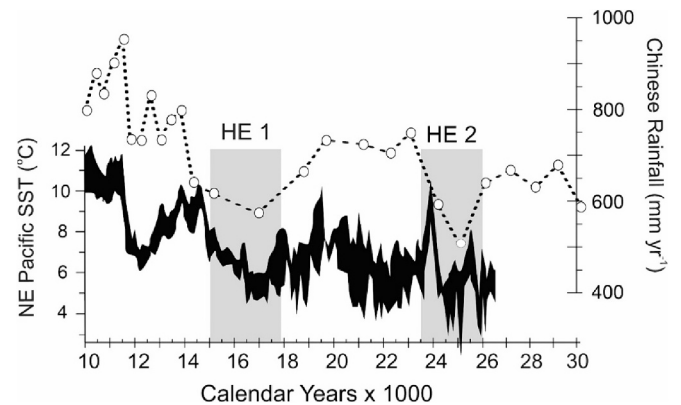


Fig. 34. During much of MIS 2, changes in sea surface temperature (SST) in the Gulf of Alaska roughly paralleled trends in summer rainfall in northern China. The SST record is from Praetorius et al. (2023), and the reconstruction of Chinese rainfall is from Beck et al. (2018).

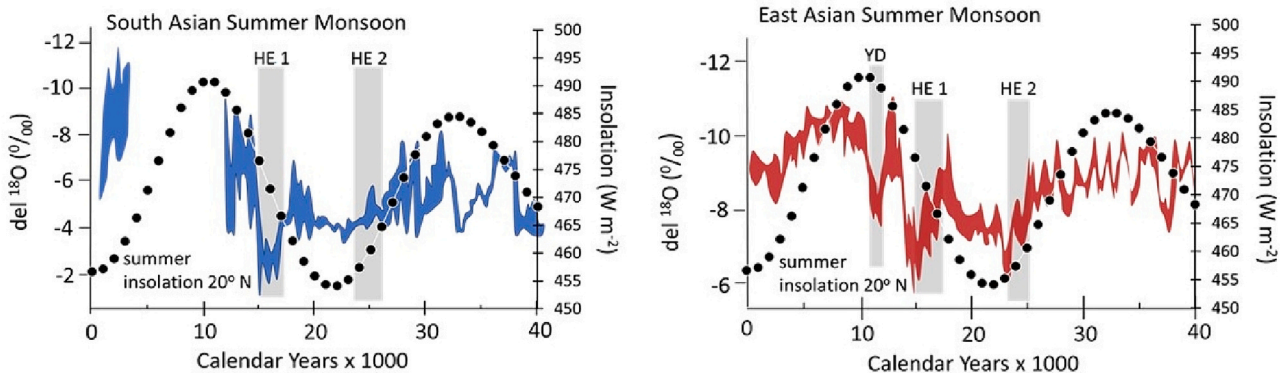


Fig. 33. Speleothem $\delta^{18}\text{O}$ records the changing vigor of two components of the Asian Summer Monsoon in northern India (RIGHT) (Kathayat et al., 2016) and in southeastern China (LEFT) (Cheng et al., 2016). The dotted line is Milankovitch insolation from Laskar et al. (2011). "YD" = Younger Dryas. "HE 1" = Heinrich Event 1. "HE 2" = Heinrich Event 2.

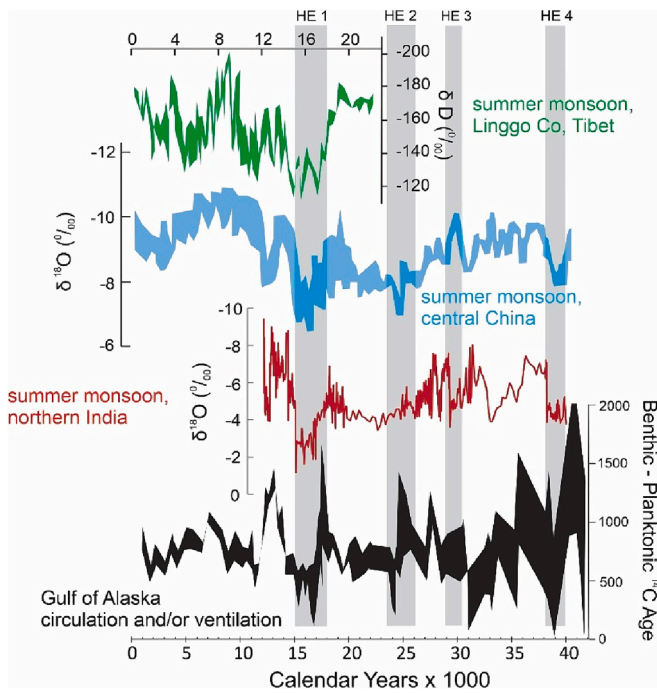


Fig. 35. A record of vertical mixing in the Gulf of Alaska (Walczak et al., 2020) (BOTTOM) compared to three records of the Asian Summer Monsoon (ASM). The Indian speleothem record is from Kathayat et al. (2016), the Chinese speleothem record is from Cheng et al., 2016, and the Tibetan lake-level record is from Hou et al. (2017). The slowdown of vertical mixing in the Gulf of Alaska was accompanied by a peak in ice-rafted debris deposition there (Fig. 6). “HE 1–4” = Heinrich Events 1–4.

Alaska also changed in parallel with the ASM, the latter recorded by $\delta^{18}\text{O}$ in speleothems in China and India, and by monsoon-fed lake levels in Tibet (Fig. 35). This correlation was especially pronounced during HE 1 and 2.

4.1.4. Oceanic heat transport

The Kuroshio current system transports tropical heat from Western Pacific Warm Pool (WPWP) to the high-latitude North Pacific (SI Section 1.1). The WPWP also exports heat to the Indian Ocean via the Indonesian Throughflow (ITF). ENSO affects the dynamics of the Kuroshio, the WPWP, and the ITF. What follows is an overview of how this system might have functioned during Marine Isotope Stage 2 and how it might have affected the Northwest Coast via the Asian Summer Monsoon and the Aleutian Low.

4.1.4.1. Western Pacific Warm Pool and Indonesian Throughflow.

Because it threads its way across the Maritime Continent of the Indonesian Archipelago, the Indonesian Throughflow (ITF) is sensitive to changes in sea level (Fan et al., 2018) (SI Section 1.1.5). Thus Kuhnt et al. (2004) estimated that the ITF was reduced by 31% when eustatic sea level reached its low point during the Last Glacial Maximum. This would have reduced oceanic heat transport from the Western Pacific Warm Pool (WPWP) into the Indian Ocean by some 23%. The oceanic heat not exported to the Indian Ocean via the ITF probably exited the WPWP into the eastern Pacific via the Equatorial Under Current (Rodgers et al., 1999).

Despite a significant decline in how much warm water was transported into the Indian Ocean by the Indonesian Throughflow (ITF), sea surface temperatures (SSTs) in the Western Pacific Warm Pool (WPWP) cooled by 4° to 5°C during the Last Glacial Maximum (LGM). This was accompanied by an eastward shift in the center of convective activity over the tropical Pacific (Xu et al., 2010; De Deckker, 2016) (Fig. 36). In response, the Asian Summer Monsoon (ASM) weakened. Also in

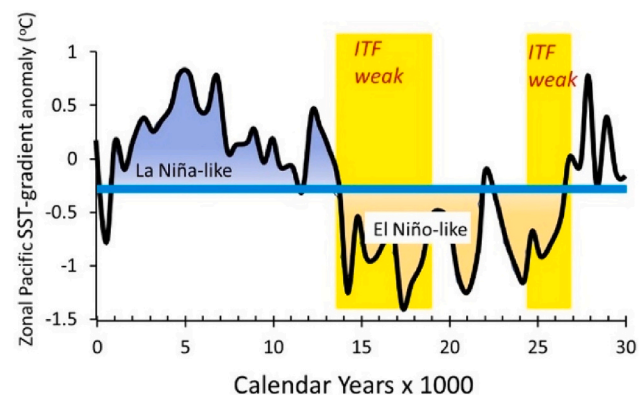


Fig. 36. Changes in the vigor of the Indonesian Throughflow (ITF), and the phases of the paleo-ENSO inferred from changes in the zonal sea surface temperature gradient across the tropical Pacific (Fan et al., 2018).

response to reduced convective activity over the western tropical Pacific, surface salinity increased there, while lowered eustatic sea level exposed large areas of the continental shelf (Voris, 2000), both of which contributed to a decline in convection and rainfall over the region (Di Nezio et al., 2016). The coolest interval in the WPWP occurred between 20 and 17.5 ka, which coincided with the maximum extent of glaciers bordering the northern Gulf of Alaska (Fig. 16). After ca. 17.5 ka, sea surface temperatures warmed in the WPWP by $3\text{--}5^\circ\text{C}$, and temperatures peaked during the early Holocene (Linsley et al., 2010). By 15 ka, rising sea level had re-submerged large parts of the Maritime Continent, and by 14–15 ka a vigorous ASM was reestablished over the region (Kuhnt et al., 2015). Along the Gulf of Alaska margin, reinvigoration of the ASM coincided with the majority of glaciers retreating out of tidewater (Fig. 16).

4.1.4.2. Kuroshio Current system. Surprisingly little is known about the ice-age history of the Kuroshio Current despite the key roles it plays in regional and global climates (SI Section 1.1.1). The coldest intervals along the southern coast of Japan occurred between 30 and 28 ka and again between 17 and 15 ka when sea surface temperatures (SST) off the southern coast of Japan were $\sim 3^\circ\text{C}$ cooler than today (Ujiié et al., 2003). During these coldest times, the Kuroshio and Kuroshio Extension carried less water and probably turned eastward at lower latitudes than today (Gallagher et al., 2015; Kubota et al., 2021). Lower eustatic sea level during the Last Glacial Maximum (LGM) excluded the Kuroshio Current from the East China Sea (Ujiié et al., 2003). Based on the recent dynamics of the Kuroshio-Oyashio convergence (Qiu, 2019), its southward shifts during ice-age stadials were probably in response to stronger winter monsoons associated with stronger Aleutian Lows, weaker summer monsoons, and increased flows of the Oyashio Current. By analogy with recent El Niño events (Hu et al., 2015), the Kuroshio and Kuroshio Extension probably experienced reduced flows during the coldest intervals of the LGM in response to persistent Eastern Pacific Warm-El Niño conditions. Consistent with the positive correlation seen today between SST in the subarctic Pacific and the strength of the Kuroshio Current (SI Section 1.3), cold intervals near Japan accompanied cooler SSTs in the Gulf of Alaska (Fig. 24).

4.1.5. The El Niño-Southern Oscillation (ENSO)

Today, teleconnections between ENSO and the Aleutian Low (AL) link the oceanography and meteorology of the tropical Pacific with those of the high latitude North Pacific (Kaboth-Bahr et al., 2021) (SI Section 1.3.1). Multiple studies suggest that El Niño-like conditions prevailed in the tropical Pacific during the Last Glacial Maximum (LGM). These include the work of Koutavas et al. (2002) who inferred that cooling of just 1.2°C occurred in the eastern equatorial Pacific during the LGM. This slight amount of cooling implies a weak zonal temperature gradient

across the equatorial Pacific, weak Hadley and Walker circulations, and a southward shift of the Intertropical Convergence Zone (ITCZ), all of which are suggestive of persistent Eastern Pacific Warm-El Niño conditions. Koutavas et al., 2002) found that the regime of most frequent El Niño conditions ended at 15 ka, while La Niña-like conditions prevailed between ca. 9 and 4 ka.

Additional evidence for a persistent El Niño-like state in the equatorial Pacific during the Last Glacial Maximum (LGM) comes from the modelling results of Han et al. (2020) that suggest the zonal gradient in sea surface temperature (SST) across the tropical Pacific declined during the LGM and thereby caused a weakening and eastward shift of Walker Circulation. Both the above studies are consistent with Ford et al.'s (2018) conclusion based on $\delta^{18}\text{O}$ in foraminifera from cores in the eastern equatorial Pacific that the zonal SST gradient was lower and that the thermocline was deeper there, both of which are consistent with a persistent El Niño-like state existing during the LGM. Fan et al. (2013, 2018) reached a similar conclusion by reconstructing the zonal SST gradient across the tropical Pacific between 30 ka and today (Fig. 36). Based on this they inferred that El Niño-like conditions existed from ca. 26 to 14 ka, whereas La Niña-like conditions dominated during the mid-Holocene. Finally, SST records from across the tropical Pacific compiled by Zhang, S. et al. (2022) also suggest a flattening of the zonal SST gradient from 30 to 19 ka consistent with El Niño-like conditions. The zonal gradient steepened between 19 and 16 ka, reached a peak at 11 ka, and then declined towards the present (Fig. 37).

In summary, the coldest intervals of Marine Isotope Stage 2 were probably spent under persistent Eastern Pacific Warm-El Niño (EPW-El Niño) conditions. By analogy with the present day (SI Section 1.3.2), the Northwest Coast probably experienced prolonged, positive phases of the Pacific Decadal Oscillation (PDO+) during the Last Glacial Maximum (LGM), although it is unclear how these PDO+ conditions were manifested when the polar jet was split and atmospheric flow was generally stronger and more zonal. By analogy with EPW-El Niño conditions today, cyclogenesis was probably increased in the North Pacific when EPW-El Niños were strongest and most persistent during the LGM, which would have deepened the Aleutian Low, increased the occurrence of atmospheric rivers, and generally increased the amount of moisture transported into mid-latitude North America. Opposing this trend were reductions in the amounts of moisture and heat being transported poleward by the Asian Summer Monsoon and by the Kuroshio Current. Obviously, there is much to learn about how ENSO, the Western Pacific Warm Pool, the Indonesian Throughflow, the Kuroshio system, and the Aleutian Low interacted during the alternating phases of MIS 2 climate.

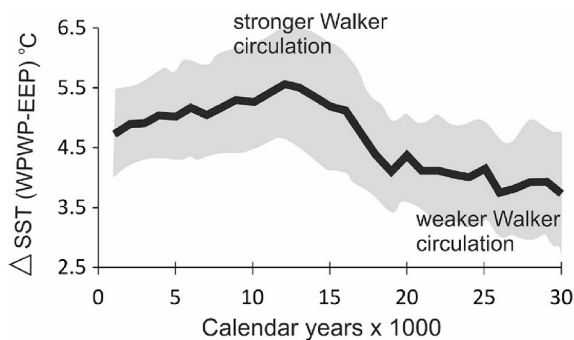


Fig. 37. Annual, zonal sea surface temperature differences between the Western Pacific Warm Pool and the eastern equatorial Pacific based on a compilation of deep-sea sediment records by Zhang et al. (2022). The grey-shaded area shows one standard deviation around the estimates of differences in east-to-west sea surface temperatures. Walker Circulation is strongest during La Niña conditions and weakest during El Niño conditions. El Niño conditions were more frequent during the Last Glacial Maximum. Redrawn from Zhang et al. (2022).

4.1.6. Opening / closing of Bering Strait

As noted in Section 2.2.2, the key question about the role of Bering Strait in global systems is not when the strait was first flooded at the end of the ice age, but when it became deep enough to assume its modern oceanographic functions. Without significant amounts of oceanic heat transport (OHT) through the strait (SI Section 1.1.6), the sea ice regime in the western Arctic Ocean probably remained in its full-glacial mode (Bradley and England, 2008), and without extensive open water in the Chukchi and Bering Sea, storm tracks probably remained farther south and followed more zonal tracks than today, which would have deprived the Arctic Basin of a large amount of the atmospheric heat it receives today (Section 7.1.2.1). Even if the initial flooding of Bering Strait occurred prior to 13 ka (Section 2.2.2), there would be little effect on the ocean-atmosphere system until near-modern sea levels were reached (Fig. 21). This point has been largely ignored in assessments of the paleoceanographic significance of Bering Strait (Hu et al., 2012; Praetorius et al., 2020).

Insights into the impacts of varying water depths in Bering Strait come from the analysis of Cessi (2020) who calculated the geostrophically balanced throughflow in Bering Strait today using this equation:

$$T_{BS} = H_{BS} \cdot g \cdot \Delta\eta / f_{BS}$$

Where H_{BS} is the average depth of Bering Strait (67 m today), g is gravity force, $\Delta\eta$ is the difference in sea surface height between the Arctic/North Atlantic Oceans and the North Pacific (~ 0.2 m), and f_{BS} is the Coriolis parameter at 66°N ($1.2 \times 10^{-4} \text{ s}^{-1}$). Solving for the throughflow yields an estimated throughflow of 1 Sv under present conditions, which is equivalent to the northward flow observed through the strait today (Woodgate, 2018).

If Pico et al.'s (2020) modelled relative sea level (RSL) curve for Bering Strait is correct, and assuming the shallowest sill in Bering Strait was indeed at -53 m, and if this sill was first transgressed ca. 13.2 ka (Fig. 19), then according to their model it would have taken until ca. 11.2 ka for RSL to rise an additional 10 m. Assuming the strait is a rectangular trough, and assuming the same difference in sea level between the North Pacific and Atlantic existed at 11.2 ka as today, Eq. 1 predicts that only ~ 0.2 Sv of northward flow would have occurred when the strait was 10 m deep. Even this modest flow is unlikely because Atlantic Meridional Overturning Circulation (AMOC) was reduced during the Younger Dryas (YD) chronozone (Hogg et al., 2016) between 12.9 and 11.7 ka. When AMOC slows, the difference in sea-surface heights between the North Pacific and Arctic/North Atlantic decreases, which removes a major cause of northward flow through Bering Strait (Cessi, 2020).

In summary, when Bering Strait initially flooded did not coincide with the initiation of its present-day oceanographic functions. Bering Strait is unlikely to have carried enough North Pacific water (Hu et al., 2007; Hu et al., 2010; Hu et al., 2012) or freshwater from glacial outburst floods (Praetorius et al., 2020) into the North Atlantic via the Arctic Ocean to have influenced Atlantic Meridional Overturning Circulation until after eustatic sea level reached near-modern levels sometime after 10 ka (Fig. 21).

4.1.7. Sea ice

Sea ice affects the atmosphere and ocean in diverse ways (Polyak et al., 2010; Bhatt et al., 2014; Watson et al., 2015). Most basially, it acts as a barrier to heat exchange between the colder atmosphere and the warmer ocean (Landrum and Holland, 2022), which means that its presence lowers air temperatures. Sea ice also affects ocean-atmosphere gas exchanges, overturning ocean circulation, storm tracks, and the routes of ocean currents (Walsh, 1983; Alexander et al., 2004; Ferrari et al., 2014). Because sea ice in subpolar seas forms and melts annually and is highly sensitive to changing patterns of heat transfer within both the ocean and atmosphere (Aylmer et al., 2022), its changing extent can act as a rapid, sensitive driver of hemisphere-scale climate changes

(Holloway et al., 2016; Wunderling et al., 2020). Modelling studies suggest that changes in the extent of Arctic sea ice affects the position of the Intertropical Convergence Zone (Chiang and Bitz, 2005) and the vigor of Atlantic Meridional Overturning Circulation (Liu and Fedorov, 2019). The responses of sea ice cover to changing climate are markedly non-linear because of the ice-albedo effect (Serreze and Barry, 2011), which means that both the decline and expansion of sea ice can occur suddenly. This rapidity of response is especially true for seasonal (winter) sea ice, which was the type widespread in the subarctic Pacific during Marine Isotope Stage 2 (Section 2.3).

Based on its seasonal cycle in the Arctic Ocean today, sea ice in the subarctic Pacific during Marine Isotope Stage 2 (MIS 2) began forming in October and reached its maximum extent in March, which means its effects on regional climate were greatest in late winter and spring. Based on how reductions in sea ice cover are affecting the Arctic and Antarctic today (Bhatt et al., 2014; Zhang et al., 2023), expansion of sea ice during MIS 2 would probably have steepened north-south temperature gradients over the North Pacific region, and as a result, strengthened upper-level westerly winds and intensified zonal atmospheric flow. When sea ice was at its maximum extent, the Aleutian Low and the Polar Jet would have been displaced southward and directed more zonally, which would have reduced winter precipitation in Alaska and increased it in the Pacific Northwest and the western USA (Section 4.1.2).

Changes in the extent of sea ice in the subarctic Pacific may have been a key driver of climate changes at regional and global scales during Marine Isotope Stage 2. Widespread sea ice expansion during winter in the North Atlantic underlies the Extreme Seasonality Hypothesis proposed to explain some aspects of climate during Heinrich Event 1 and the Younger Dryas (Broecker and Denton, 1989; Denton et al., 2022; Putnam et al., 2023) (Fig. 27). This same hypothesis can be applied to the high-latitude North Pacific. As explored in Section 4.1.10, the 3500 km marine-based margin of the Cordilleran Glacier Complex may have been a hair trigger for Heinrich Event 1 by virtue of the large masses of marine-based glacial ice that were located on the Northeast Pacific's continental shelf ca. 19 ka (Section 2.1.3). When these glaciers retreated, icebergs and meltwater probably fueled the expansion of winter sea ice across the subarctic Pacific. Reconstructions of the extent of sea ice during MIS 2 (Section 4.1.7) suggest it episodically expanded and contracted over a region approximately twice the size of the Gulf of Mexico and at its maximum extended as far south as 55° N (Fig. 22). In response, the Aleutian Low (SI Section 1.2.3) would have shifted southward and deepened, diverting storm tracks into the Pacific Northwest and western USA. By this means, changes in sea-ice extent may have contributed to the time transgressive nature of glacier fluctuations along the Northwest Coast (Fig. 16). Sea-ice generated cooling of the high-latitude North Pacific might then have teleconnected via the atmosphere to the North Atlantic region (Peteet et al., 1997).

4.1.8. Overturning circulation in the North Pacific

Today, overturning circulation in the North Pacific is restricted to the production of North Pacific Intermediate Water (NPIW) in the northwestern Pacific (SI Section 1.1.2). This limited amount of deep circulation is one reason the abyssal North Pacific contains large amounts of ^{14}C -depleted CO_2 (Shackleton et al., 1988; Lund et al., 2011; Du et al., 2018; Walczak et al., 2020). Degassing of this sequestered CO_2 caused by changes in the vertical circulation of the deep North Pacific could have had large impacts on global climate (Feely et al., 2001; Rae et al., 2014; de La Fuente et al., 2015; Alves et al., 2018). Variations in overturning circulation in the North Pacific could also have affected climate by changing the global pattern of oceanic heat transport (SI Section 1.1.6). Like Atlantic Meridional Overturning does today, vigorous deepwater formation in the North Pacific would have drawn warm, surface waters to high latitudes (Rae et al., 2020). For these reasons, understanding the prehistoric dynamics of overturning circulation in the North Pacific has been a topic of intense interest and continuing controversy.

The production of North Pacific Intermediate Water (NPIW)

probably increased during the Last Glacial Maximum when sea ice was more extensive (Keigwin, 1998; Horikawa et al., 2010; Okazaki et al., 2010; Gong et al., 2019; Rae et al., 2020). Formation of sea ice releases salt into surface waters, which causes a decrease in buoyancy, which can then facilitate downwelling (Ferrari et al., 2014). Additional influences on overturning circulation in the North Pacific have been proposed, including the opening / closing of Bering Strait (Davies-Walczak et al., 2014), changes in the vigor of the South Asian Monsoon system (Lembke-Jene et al., 2017), and fluctuating amounts of exchange between the subtropical and subpolar gyres (Rae et al., 2020). During the coldest intervals of the last ice age, origination of NPIW may have expanded from the Sea of Okhotsk into the southern Bering Sea (Zhong et al., 2023).

Overturning circulation in the North Pacific may not always have been limited to the production of North Pacific Intermediate Water (NPIW) (Matsumoto et al., 2002; Cook et al., 2016; Max et al., 2017). One view is that overturning circulation intensified in the subarctic Pacific during the Last Glacial Maximum (LGM), to the extent of causing significant amounts of tropical heat to be carried to high, northern latitudes (Matsumoto et al., 2002; Okazaki et al., 2010; Rae et al., 2014; Maier et al., 2018; Rae et al., 2020). Based on a combination of computer modelling and multi-proxy data from multiple marine cores located mostly in the western North Pacific, Okazaki et al. (2010) interpreted a reduction in the ^{14}C age differences between benthic and planktic foraminifers (B-P ages) during Heinrich Event 1 (HE 1) as indicating a significant increase and deepening of overturning circulation. Consistent with this interpretation, Maier et al. (2018) inferred that the advection of subtropical water into the subarctic Pacific increased during coldest periods of the LGM.

Okazaki et al. (2010) proposed that the following sequence of events occurred during the global cooling that accompanied Heinrich Event 1. 1) Meltwater from retreating glaciers around the North Atlantic made surface waters there less dense, which caused Atlantic Meridional Overturning Circulation (AMOC) to stop. 2) This caused the entire Northern Hemisphere to cool. 3) In response, the Intertropical Convergence Zone shifted southwards, which caused 4), a reduction in Atlantic to Pacific moisture transport, which led to 5), an increase in the salinity of surface waters in the North Pacific. The closed state of Bering Strait facilitated the buildup of salinity in the surface waters of the subarctic Pacific. 6) Saltier, denser surface waters weakened the halocline, which then triggered 7), meridional overturning circulation to depths of ~2500 m. 8) This enhanced circulation drew more salty, subtropical water into the North Pacific, which further enhanced overturning circulation, possibly to depths of 3000 m (Okazaki et al., 2010). Building on Okazaki et al.'s (2010) conclusions, Menviel et al. (2012) used an Earth system model to suggest that deep-overturning circulation in the subarctic Pacific may have created a bipolar seesaw in sea surface temperature between the North Pacific and Southern Ocean. Assuming Okazaki et al. (2010) were correct about Atlantic Meridional Overturning Circulation being shut down by the cooling of the North Atlantic, the onset of deep overturning circulation in the subarctic Pacific would also have generated a North Pacific / North Atlantic SST seesaw (Menviel et al., 2012).

Max et al. (2014) arrived at different conclusions about overturning circulation in the North Pacific during cold intervals of the last deglaciation. They reconstructed changes in ocean ventilation based on multiple cores from the northwestern North Pacific, including from the Sea of Okhotsk and western Bering Sea. Their results suggested that the formation of North Pacific Intermediate Water (NPIW) increased and ventilation was enhanced at depths shallower than 2100 m during both Heinrich Event 1 (HE 1) and the Younger Dryas (YD) chronozone when Atlantic Meridional Overturning Circulation was reduced. In other words, NPIW formation did increase, but in contrast to the Okazaki et al. (2010) scenario, deep-water formation never occurred. In fact, Max et al. (2014) inferred that North Pacific deepwater actually became more isolated from the ocean surface during HE 1 than today. Reconstructions

of sea surface temperature (SST) and sea ice coverage during HE 1 and the YD (Max et al., 2012) failed to detect the warming expected if overturning circulation had in fact triggered positive feedbacks capable of destabilizing the subarctic North Pacific's halocline in the ways Okazaki et al. (2010) suggested. Instead of deep, overturning circulation of regional extent, Max et al. (2014) and later Rippert et al. (2017) inferred that only a modest revving-up of NPIW formation occurred during the coldest intervals of the last 20 kyr. Because North Pacific deepwater was more isolated from exchange with the atmosphere, Max et al. (2014) suggested that enhanced NPIW production in the high latitude North Pacific actually increased CO₂ sequestration in the deep North Pacific during the coldest times of Marine Isotope Stage 2.

Rae et al. (2014) interpreted the history of overturning circulation in the high-latitude North Pacific in a somewhat similar way as Max et al. (2014). In a core from the Patton Sea Mount in the southwestern Gulf of Alaska, Rae et al. (2014) found a marked decline in the ¹⁴C age differences between benthic and planktic foraminifers (B-P ages) during Heinrich Event 1, which they attributed to the mixing of older, deep-water (> 2000 m) with younger, shallower water masses. They suggested this resulted from warming sea surface temperatures and increasing surface salinity caused by reduced freshwater input from the Asian Summer Monsoon.

In a subsequent study, Rae et al. (2020) compiled proxy data describing ventilation, primary productivity, temperature, and salinity across the ice-age North Pacific and then modelled their regional and global impacts. Their conclusion was that deepwater (below 2000 m) was poorly ventilated during the Last Glacial Maximum (LGM), much as it is today. In contrast, waters above ca. 2000 m were relatively well-ventilated, suggesting more vigorous and widespread formation of North Pacific Intermediate Water (NPIW) during the LGM, which they estimate could have reached 8 Sv yr⁻¹. This is approximately 4× what it is today, but still significantly less than Atlantic Meridional Overturning Circulation, even at the latter's minima during the LGM (Rae et al., 2020). These authors note that most of the sites where salinity and sea surface temperature increased and where the ¹⁴C age differences between benthic and planktic foraminifers (B-P ages) declined during the LGM are located in the subarctic Pacific. Rae et al. (2020) follow Okazaki et al.'s (2010) reasoning that enhanced NPIW formation was driven by a weakened, regional hydrological cycle caused by cooler global temperatures.

A major focus of the Rae et al. (2020) study was the impact of changes in North Pacific overturning circulation on atmospheric CO₂. Today, widespread upwelling of nutrient- and CO₂-rich subsurface waters occurs in the subarctic Pacific, and CO₂ outgasses from this

upwelling water (Fig. 38). During the Last Glacial Maximum (LGM), in contrast, Rae et al. (2020) inferred that limited vertical mixing caused CO₂-rich water to be trapped below ~2000 m, which is consistent with the conclusions of Max et al. (2014) and also with time series of ¹⁴C age differences between benthic and planktic foraminifers (B-P ages) compiled by Praetorius et al. (2020) that show the ¹⁴C ages of near-surface and abyssal (< 2000-m depth) waters diverged markedly between ca. 20 and 17 ka and again during the Younger Dryas chronozone. Rae et al. (2020) suggested that the release of this long-sequestered CO₂ between ca. 15 and 10 ka acted as an important driver of global climate changes in the course of the modern circulation regime becoming established in the North Pacific (Gray et al., 2018).

In contrast to the conclusions of Okazaki et al. (2010, 2014) and Rae et al. (2020) that North Pacific overturning circulation intensified between 20 and 10 ka, Davies-Walczak et al. (2014) inferred that overturning circulation at intermediate depths near the glaciated, northeastern margin of the Gulf of Alaska was similar to or only slightly greater during the Last Glacial Maximum (LGM) than during the Holocene. Prior to ca. 14.5 ka, they found no evidence for a ¹⁴C-depleted ("old"), intermediate-depth water mass indicating enhanced intermediate water formation. In the northeastern Gulf of Alaska, deep- and intermediate-level waters were most ventilated during the Bølling-Allerød (14.8–12.9 ka) and early Holocene, which parallels ventilation history in the North Atlantic and negates a seesaw relationship between the North Pacific and North Atlantic (Praetorius et al., 2020).

In summary, overturning circulation during the Last Glacial Maximum and Heinrich Event 1 (HE 1) in the North Pacific probably never approached the scale of Atlantic Meridional Overturning Circulation in terms of water volume, heat transport, and dissolved-carbon transfer. Overturning circulation probably never penetrated to depths below 2000 m; however, overturning circulation did increase during particularly cold periods like HE 1 and the Younger Dryas chronozone, which caused an increase in the production of North Pacific Intermediate Water (NPIW) in response to the combination of an expansion of sea ice, colder sea surface temperatures, and increased exchange between the subtropical and subpolar gyres. The expansion and invigoration of NPIW was most pronounced in the northwestern North Pacific where winter cooling was greatest bordering the Eurasian landmass. NPIW formation seems to have never expanded into the northeastern Gulf of Alaska where freshwater runoff from the coastal mountains and the Cordilleran Glacier Complex probably maintained a strong halocline. Despite never developing into deep, overturning circulation, changes in the vigor of NPIW probably did modulate the outgassing of CO₂ from the deepwater below it. In this way, it may have played an

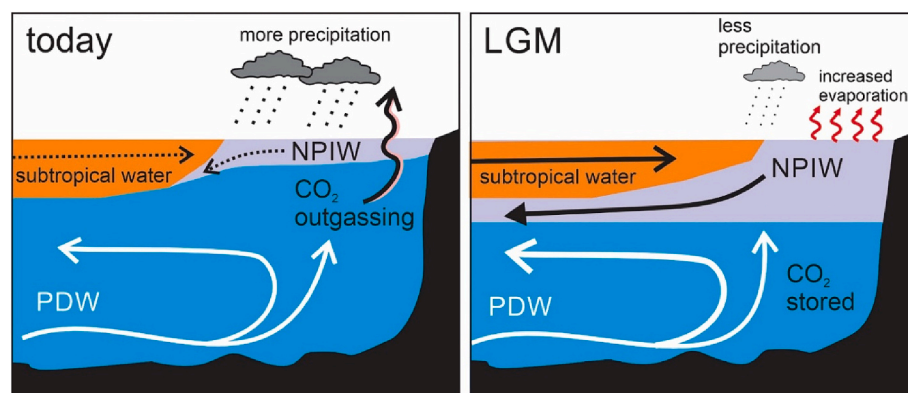


Fig. 38. Differences in ocean circulation in the North Pacific between the Last Glacial Maximum (LGM) and today. Rae et al. (2020) inferred that during the LGM surface waters in the subarctic Pacific were saltier and warmer than during the Holocene because of a combination of increased inflow of subtropical water, increased evaporation, and reduced precipitation. In response, the production of North Pacific Intermediate Water (NPIW) increased, which enhanced ventilation above ~2000 m but simultaneously isolated deeper water, causing large amounts of ¹⁴C-depleted carbon to be sequestered there. This reconstruction does not hold for coastal waters in the Gulf of Alaska where a persistent halocline created by runoff from the coastal mountains probably suppressed overturning circulation throughout the LGM and during deglacial times. Redrawn from Rae et al. (2020). "PDW" = Pacific Deep Water.

important, though still poorly understood role in modulating global climate during the last deglaciation.

4.1.9. Did outburst floods into the North Pacific trigger regional and global climate changes?

4.1.9.1. Floods from the Columbia River Basin. Today, the freshness of the North Pacific's surface waters influences the production of North Pacific Intermediate Water (NPIW) and the extent of sea ice (SI Section 1.1.3). Episodically during deglaciation, glacial outburst floods dumped large amounts of freshwater suddenly into the Northeast Pacific (Praetorius et al., 2020). Between ~ 19.3 and 14.9 ka, multiple floods occurred from lakes impounded behind glacial dams in the headwaters of the Columbia River (Atwater, 1986, 1987; Blais-Stevens et al., 2003; Lopes and Mix, 2009; Gombiner et al., 2016; Balbas et al., 2017). The largest of these floods occurred at 18.2 ± 1.2 ka (Balbas et al., 2017), around the time an even larger flood issued from pluvial Lake Bonneville when a sill leading into the Columbia River drainage collapsed (Oviatt, 2015). The largest of these Columbia Basin floods released as much as 17 Sv of freshwater into the North Pacific via the Columbia River over the span of days to weeks (O'Connor and Costa, 2004; Hendy, 2009; Lopes and Mix, 2009; Davies et al., 2011; Praetorius et al., 2020).

To detect the impacts of Columbia River outburst floods on the ocean / atmosphere system of the North Pacific, Praetorius et al. (2020) compiled records of sea surface temperature (SST), surface salinity, and ^{14}C -age offsets between near-surface and deepwater foraminifera between 20 and 10 ka. As did Maier et al. (2018) in an earlier study, Praetorius et al. (2020) found evidence for multiple episodes of cooling and freshening in the North Pacific accompanied by reductions in deep circulation that were probably related to megafloods (Fig. 39). The most significant episodes of freshening occurred in the intervals 19.5–18 ka and 13.4–11.8 ka. The earlier episode preceded Heinrich Event 1, though how closely depends on what limiting ages are assigned to that event. The latter freshening episode occurred during the Younger Dryas chronozone.

Given their large volumes, where they entered the North Pacific, and the subarctic Pacific's sensitivity to changes in its halocline, outburst floods from the Columbia River undoubtedly influenced climate along the Northwest Coast during Marine Isotope Stage 2. Computer modeling suggests that floodwaters released from the Columbia River would have circulated northward via the Alaska Coastal Current and reached the Gulf of Alaska and the eastern Bering Sea within five years (Praetorius et al., 2020). Another plume of freshwater probably spread westward to Japan within ten years. The effects of these floods on the climate and oceanography of the North Pacific could have been transmitted to the

entire northern hemisphere (Maier et al., 2018). General circulation models suggest that the cooling / freshening of the high latitude North Pacific resulting from Columbia River megafloods initiated cooling throughout the northern hemisphere, possibly enough cooling to tip the North Atlantic region into stadial conditions, which then might have triggered Heinrich Event 1 (Praetorius et al., 2020).

Uncertainties in when outburst floods actually issued from the Columbia River Basin make it difficult to test whether these floods actually triggered regional and global climate changes (Fig. 39). For instance, one of the largest floods occurred at 18.2 ka, but this date has a reported error of ± 1.5 kyr (Balbas et al. (2017)). Similarly, the Lake Bonneville flood is only broadly constrained between 17.1 and 18.4 (Oviatt, 2015), which means that it could have occurred after the beginning of Heinrich Event 1 (HE 1) and thus after the cooling of the subarctic Atlantic that preceded HE 1 (Max et al., 2022). Adding to the chronological challenges is the fact that the oceanographic time series used by Praetorius et al. (2023) has dating uncertainties caused by unknowns surrounding marine-reservoir ages (Section 4.1.10). The Columbia River flood-climate correlation is most convincing for the Younger Dryas (YD) chronozone; however, if it did trigger or contribute to the global YD (12.9–11.7 ka) through its effect on Atlantic Meridional Overturning Circulation, it did so via an atmospheric teleconnection (Peteet et al., 1997) rather than an oceanic one because the Bering Strait was still closed or oceanographically insignificant at 12.9 ka (Section 4.1.6).

4.1.9.2. Alaskan outburst floods. The Columbia River Basin was not the only source of megafloods entering the North Pacific during Marine Isotope Stage 2. Large outburst floods also occurred from glacier-dammed lakes in southern Alaska, and while the timing of these floods remains obscure, their impacts on the oceanography and atmosphere of the North Pacific could have been significant because of where they entered the sea.

Of particular interest is Glacial Lake Atna in the Copper River Basin (Williams et al., 1989; Reger et al., 2008a; Wiedmer et al., 2010; Smith, 2019) (Fig. 40). The Glacial Lake Atna-Susitna system episodically covered >9000 km² (Ferrians et al., 1989). Multiple outburst floods occurred through different outlets when local ice dams were breached (Smith, 2019). Floods through Mentasta Pass traveled down the Tanana and Yukon Rivers into the Bering Sea (Reger et al., 2008a; Smith, 2019). At least one flood entered upper Cook Inlet and the Gulf of Alaska via Tahneta Pass (Fig. 40) (Wiedmer et al., 2010) (though see Reger et al. (2011)). Because it drains the lowest part of the entire basin, the Copper River potentially carried the largest floods directly into the Gulf of Alaska (Nichols and Yehle, 1969).

Wiedmer et al. (2010) estimated that some floods from Glacial Lake Atna were of similar size as megafloods from Glacial Lake Missoula in the Columbia River Basin (Zuffa et al., 2000; Lopes and Mix, 2009). Some of the Lake Atna floods may have carried up to 2600 km³ of freshwater into either the Bering Sea (via Mentasta Pass) or the Gulf of Alaska (via the other three outlets) at rates as high as 11 Sv (Wiedmer et al., 2010). For comparison, an outburst flood from Glacial Lake Agassiz that reached the Arctic Ocean via the MacKenzie River valley around the time of the Younger Dryas had a larger total volume (23,000 km³), but may have occurred more slowly (1.8 to 2.5 Sv) (Norris et al., 2021).

The timings of megafloods from Glacial Lake Atna remain poorly constrained, but multiple floods are known to have occurred after 16 ka in the course of regional deglaciation (Reger et al., 2008a; Wiedmer et al., 2010; Smith, 2019). If the megaflood over Tahneta Pass (Wiedmer et al., 2010) did indeed occur, limiting dates on glacier retreat from the Matanuska valley (Williams et al., 1989; Kocczynski et al., 2017; R.D. Reger, pers. comm. 2021) suggest it took place after 16.4 ka. Some of the outburst floods happened after the earliest human occupation of the Copper River basin ca. 13 ka (Kari, 2019; White et al., 2022). The final

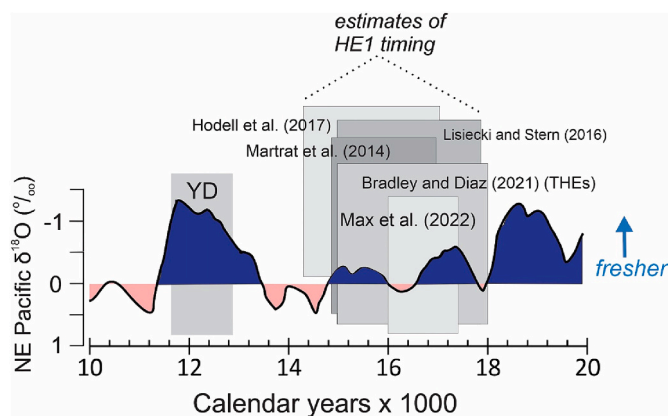


Fig. 39. Changes in the relative freshness (blue) of surface water in the Northeast Pacific (redrawn from Praetorius et al., 2020). Differently shaded boxes show various authors' age estimates for the timing of Heinrich Event 1 (HE 1). "YD" = Younger Dryas. "THEs" = tropical hydrological events.

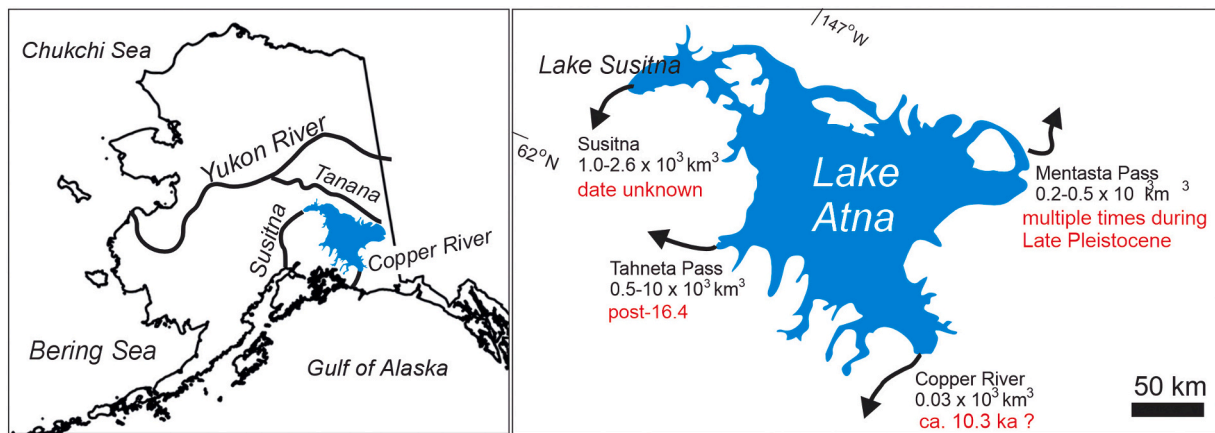


Fig. 40. The largest glacier-dammed lake in Alaska during Marine Isotope Stage 2 was Glacial Lake Atna in the Copper River Basin. Multiple outburst floods from Lake Atna reached the Gulf of Alaska and the Bering Sea; however, the timings and magnitudes of these floods are still poorly known. Estimates of total flood volumes are from Wiedmer et al. (2010).

drainage of Glacial Lake Atna may have occurred down the Copper River shortly before 10.3 ka (Muhs et al., 2013; Smith, 2019). Because of their direct inputs into the Gulf of Alaska and Bering Sea, outburst floods from Glacial Lake Atna could have had significant impacts on regional oceanography and climate.

4.1.10. Was the subarctic Pacific as a trigger point for global climate?

4.1.10.1. The Walczak Hypothesis. The North Pacific-centric hypothesis of Walczak et al. (2020) asserts that events in the ocean / atmosphere / cryosphere of the Gulf of Alaska preceded and triggered Heinrich Events in the North Atlantic region, which then had global effects. If true, this turns Atlantic-centric paleoclimatology on its head and generates a number of new questions. Here we consider the Walczak Hypothesis in the case of Heinrich Event 1 because it is the most recent and hence the best documented Heinrich Event.

The scenario described by the Walczak hypothesis for Heinrich Event 1 (HE 1) begins in the tropics with the gradual strengthening of the Asian

Summer Monsoon (ASM) ca. 23 ka (Fig. 41). This strengthening of the ASM may have been in response to a northward shift in the Intertropical Convergence Zone (ITCZ) caused by an increase in summer insolation received at 10° north (Fig. 32). Based on how the ITCZ responded to similar latitudinal shifts during the Holocene (Deininger et al., 2020), a northern shift in June insolation near the Equator would have pushed the ITCZ further into the northern hemisphere, which, based on the monsoon's recent behavior (Wang et al., 2013; Walker et al., 2015), would have strengthened the ASM. A stronger and more extensive summer monsoon would then have increased the amounts of freshwater and latent heat transported into the North Pacific (Section 7.1.2.1). In response, sea surface temperature (SSTs), air temperature, and precipitation probably increased along the Northwest Coast, triggering rapid responses from the glaciers comprising the seaward flank of the Cordilleran Ice Sheet. At 20 ka, glaciers covered approximately $500 \times 10^3 \text{ km}^2$ of the continental shelf bordering the Northwest Coast. Many of these glaciers fed ice streams grounded below their contemporary sea level, some located as far south as 50° N. These calving-susceptible glaciers had been in extended positions for at least several millennia and so had reached isostatic equilibrium with the region's relatively thin lithosphere. The situation was primed for rapid, iceberg-calving retreats at a time when eustatic sea level was beginning to rise.

Continuing with the scenario described by the Walczak et al. (2020), the invigorated Asian Summer Monsoon freshened and warmed the surface waters of the subarctic Pacific, which steepened the halocline / thermocline there (Haug et al., 2005; Davies et al., 2011). This triggered widespread calving ablation of marine-based glaciers (Benn et al., 2007; Motyka et al., 2011) through the “Marcott Mechanism” (Fig. 43). The meltwater and icebergs from these retreating glaciers caused the expansion of sea ice in winter over some $3 \times 10^6 \text{ km}^2$ of the high-latitude North Pacific that today are perennially ice-free. The presence of this winter sea ice displaced the Aleutian Low southwards and oriented it more zonally (Section 4.1.7). In response, winter temperatures and precipitation decreased across the northern sectors of the Northwest Coast and winter precipitation increased in the western USA.

This idea that strengthening Asian Summer Monsoon (ASM) caused freshening of the subarctic Pacific is supported by Walczak et al.'s (2020) reconstruction of ocean circulation based on temporal patterns in the differences between the ^{14}C ages of benthic versus planktonic foraminifera (B-P) ages in a core located on the continental slope 75 km offshore of the Bering Glacier in the Gulf of Alaska (Fig. 35). Beginning ca. 18–19 ka, (B-P) ages diverged markedly, indicating a reduction in vertical mixing consistent with increased freshening of surface water. The rapid calving retreat of marine-based glaciers bordering the Gulf of Alaska is recorded by widespread deposition of ice-rafted debris (IRD)

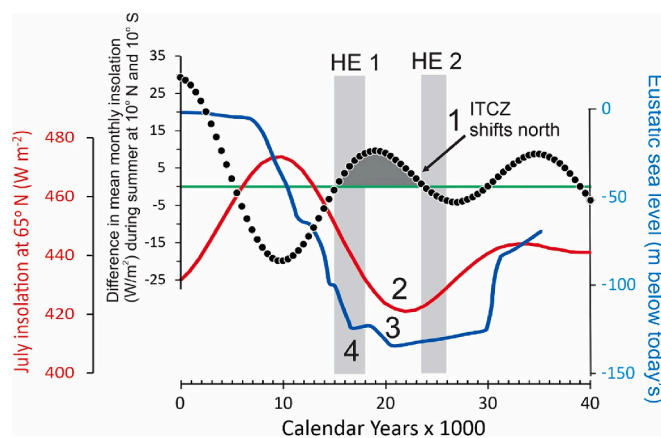


Fig. 41. Setting the stage for Heinrich Event 1 (HE 1). (1) Beginning ca. 23 ka, Milankovitch orbital variations caused summer insolation to increase in the northern hemisphere tropics. In response, the Intertropical Convergence Zone (ITCZ) shifted northward, strengthening the Asian Summer Monsoon, which then transported more moisture and heat into the high-latitude North Pacific. (2) Ca. 22 ka, July insolation at 65° N began to increase and then ca. 21 ka, eustatic sea level started to rise (3) in response to ice-sheet melt. These phenomena combined to destabilize the marine-based glaciers fringing the Northwest Coast. According to the Walczak Hypothesis, meltwater and icebergs from these glaciers cooled the Gulf of Alaska and triggered Heinrich Event 1 (4).

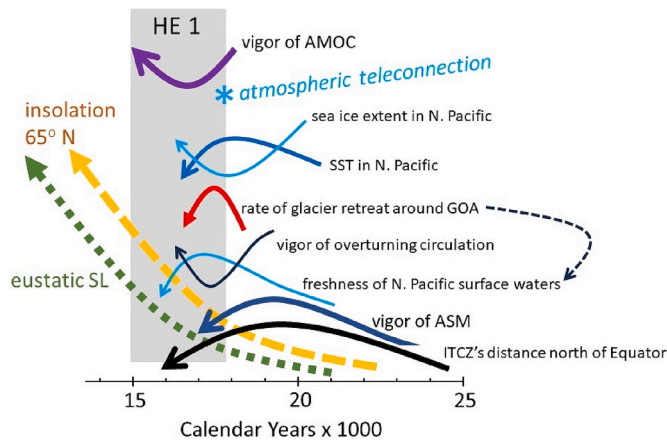


Fig. 42. Heinrich Event 1 (HE 1) may have ultimately been triggered by changes in the tropical Pacific and the Gulf of Alaska. Strengthening of the Asian Summer Monsoon (ASM) beginning ca. 23 ka caused freshening of North Pacific surface waters, which reduced overturning circulation in the Gulf of Alaska (GOA). This triggered the rapid calving retreat of marine-based glaciers, which then added more freshwater, causing additional cooling and freshening accompanied by the spread of sea ice in winter. Cooling of the high latitude North Pacific was then communicated to the North Atlantic by an unidentified atmospheric teleconnection (though see [Peteet et al., 1997](#)), which cooled sea surface temperatures (SSTs) there and slowed Atlantic Meridional Overturning Circulation (AMOC). “SL” = sea level.

between ca. 19 and 16 ka, with a peak of deposition ca. 17.5 ka ([Fig. 6](#)) ([Walczak et al., 2020](#)). These calving retreats were probably augmented by the gradual increase in solar insolation at high latitudes that began ca. 22 ka, and they were undoubtedly augmented by the progressive rise of eustatic sea level beginning ca. 21 ka ([Fig. 41,42](#)) ([Section 2.2.2](#)). The release of large amounts of meltwater from retreating, marine-based glaciers would have further accentuated the Marcott Mechanism ([Fig. 43](#)) and have contributed to enhanced sea ice cover across the subarctic Pacific in winter ([Section 4.1.7](#)), which would have contributed another positive feedback to the reduction of vertical mixing in winter and accentuation of glacier retreat ([Chiang and Bitz, 2005](#)).

4.1.10.2. Testing the Walczak Hypothesis

“...because of the limitations of age-model constraints in the North Pacific (related to poor knowledge of palaeo-reservoir ages), it is difficult to access the lead-lag relationship of North Pacific meltwater events with changes in the AMOC using proxy data.” [Maier et al. \(2018\)](#).

Dating accuracy is essential for testing the hypothesis that ocean/

atm changes in the Gulf of Alaska led the North Atlantic and triggered the global effects of Heinrich Event 1. Unfortunately, limited understanding of prehistoric marine reservoir ages makes it difficult to assess lead-lag relationships between Atlantic Meridional Overturning Circulation, Heinrich Events, and meltwater events in the North Pacific ([Maier et al., 2018](#)).

A reservoir effect occurs when ^{14}C is depleted through radioactive decay while not being replaced by younger carbon ([Stuiver and Braziunas, 1993](#)). Reservoir effects are often accentuated in the ocean because deepwater has only limited exchange with the new ^{14}C being formed in the upper atmosphere ([Skinner et al., 2019](#)). Water bodies differ in how isolated they are from the atmosphere ([Matsumoto, 2007](#)), and so they vary in how depleted their ^{14}C contents are relative to the atmosphere ([Alves et al., 2018](#)). Today, marine-reservoir ages (MRAs) range from several centuries in low-latitude seas, to as much as several millennia in some polar seas ([Butzin et al., 2017](#); [Skinner et al., 2019](#)). The larger the MRA is, the larger is ΔR , which is the difference between the local MRA and the modeled, global average MRA ([Reimer, 2012](#)) ([Fig. 44](#)).

Anything that interferes with the vertical mixing of water between the ocean surface and the deep ocean can accentuate the reservoir effect ([Alves et al., 2018](#)). For example, a decline in how much C is fixed by photosynthesis in near-surface waters can increase the ΔR of the

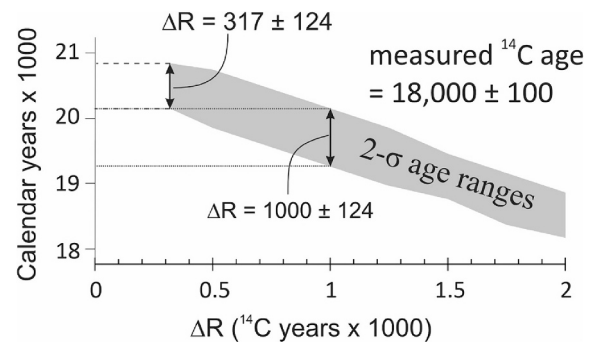


Fig. 44. Marine-reservoir effects change ΔR , the difference in the ^{14}C contents of the marine-derived organic matter being radiocarbon dated and the contemporaneous ocean where it originated. The calendar age of a ^{14}C date becomes younger as ΔR increases. Shown here are the calibrated (calendar) age ranges of a hypothetical sample of marine carbon dated by ^{14}C to $18,000 \pm 100$ years. In this example, ΔR values vary between 317 years (the ΔR specified in the Calib 8.2 program's Marine20 database for the Southeast Alaska region) and 1000 years. Today, values of ΔR of 1000 years occur in some high-latitude oceans affected by sea ice and glacial meltwater ([Stuiver et al., 1993](#); [Hutchinson et al., 2004](#); [Heaton et al., 2020](#)).

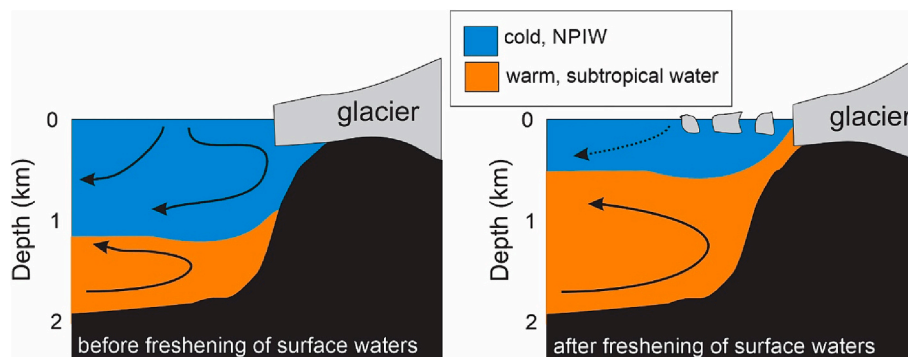


Fig. 43. The Marcott Mechanism. Reduction in overturning circulation can cause warmer ocean water to upwell along continental margins, where it can enhance the melting of marine-based glaciers. Once unseated from their terminal-moraine shoals, these glaciers may retreat rapidly through ice-berg calving without further stimulus from climate. Based on [Benn et al. \(2007\)](#), [Marcott et al. \(2011\)](#), [Alvarez-Solas et al. \(2013\)](#), [Bassiss et al. \(2017\)](#). “NPIW” = North Pacific Intermediate Water.

underlying water mass by reducing the amount of young, ^{14}C -rich organic matter being “pumped” downwards into deeper water in the form of dead organisms settling to the bottom. The shoaling or steepening of a halocline or thermocline can also increase the ΔR in deep-water by reducing overturning circulation. Covering the sea surface with sea ice is especially effective at increasing the ΔR of underlying water masses (Gordon and Harkness, 1992; Butzin et al., 2017; Heaton et al., 2020). Also, glacial meltwater containing ancient, terrestrial organic matter can introduce ^{14}C -depleted water into ocean surface waters (Hutchinson et al., 2004; Cosma and Hendy, 2008). All these phenomena are more frequent and widespread at high versus low latitudes, and, in the subarctic Pacific, all of them occurred more frequently during the ice age than during the Holocene (Hutchinson et al., 2004; Alves et al., 2018).

Marine-reservoir effects complicate the calibration of ^{14}C dates obtained on organic carbon fixed by organisms in the sea (Reimer and Reimer, 2017; Heaton et al., 2020). Two methods are typically used to estimate ΔR s and thereby correct for marine-reservoir effects. The first is by ^{14}C -dating marine samples of known age (e.g., museum collections of shells with precisely known dates of collection). The second is obtaining ^{14}C dates on paired terrestrial / marine samples found together at the same stratigraphic level (e.g., a pine needle and a bivalve shell within the same sedimentary unit) (Hutchinson et al., 2004; Alves et al., 2018; Hutchinson, 2020). Based on the paired-sample approach, Schmuck et al. (2021) found that ΔR along the Northwest Coast declined from 575 ± 165 years during the Bølling/Allerød to -55 ± 110 years during the Younger Dryas, before increasing slightly over the course of the Holocene. To our knowledge, there are no published paired-sample records of ΔR from anywhere in the subarctic Pacific that pre-date $\sim 12,000$ ^{14}C yr BP (Schmuck et al., 2021).

Lacking the paired terrestrial-marine samples necessary to specify changes in marine reservoir ages (MRAs) prior to ca. 12 ka, Walczak et al. (2020) estimated ΔR values based on ocean-mixing models calibrated using modern mixing rates measured along pre-bomb depth profiles of ^{14}C content in the subarctic Pacific. To assess the sensitivity of surface water ΔR s to changes in the MRA of pre-aged, deepwater entering the Gulf of Alaska as an underflow from the Southern Ocean, Walczak et al. (2020) varied the MRAs of this deepwater between 0 and 4000 yrs. and then calculated the effect on the reservoir age of both benthic and surface waters. When ^{14}C -depleted deepwater increased in abyssal waters, benthic ages became older relative to planktic ages. This increased the ^{14}C age of the water that was upwelling in the subpolar gyre and advecting across the ocean surface, which caused planktic foraminifera ages to also become older. Modelling results suggested that changes in (benthic - planktic) ^{14}C ages (B-P) ages) created surface reservoir ages 500 years older during the times in prehistory when the (B-P) age difference was largest, and 500 years younger when the age difference was least. Walczak et al. (2020) concluded that the planktic ΔR in the Gulf of Alaska has averaged 370 ± 350 years over the past 46 kyrs, which is within a decade of the last 200 years of surface-ocean ΔR in Southeast Alaska (Schmuck et al., 2021). Walczak et al. (2020) further concluded that the benthic ΔR in the Gulf of Alaska has averaged 1200 $\pm$ 600 over the past 46 kyrs.

Uncertainties in the marine-reservoir age (MRA) correction make it difficult to test the Walczak Hypothesis with the data at hand. Again, the oldest paired samples reported by Schmuck et al. (2021) date to only 12,000 ^{14}C yrs. In a companion study to the Walczak et al. (2020), Praetorius et al. (2020) attempted to validate the use of circa-modern values of ΔR by matching the timing of $\delta^{18}\text{O}$ records from foraminifera in the Gulf of Alaska with the calendar ages of the Bølling/Allerød and Younger Dryas. Both Walczak et al.'s (2020) modeling and Praetorius et al.'s (2020) wiggle-matching approaches for estimating paleo-MRAs and ΔR s assume stationarity in the pattern of vertical mixing in the North Pacific prior to ca. 14.7 ka, which is the onset of the Bølling-Allerød interstadial. Assuming stationarity in vertical mixing is problematic for several reasons. First, overturning circulation may have been

more vigorous and widespread during the Last Glacial Maximum (LGM) in the North Pacific than it is today (Okazaki et al., 2010; Max et al., 2014; Rae et al., 2014; Rippert et al., 2017; Maier et al., 2018; Rae et al., 2020). Increased production of North Pacific Intermediate Water (NPIW) during the LGM implies a fundamentally different pattern of overturning circulation than what occurred during deglaciation and during the Holocene. Other complicating factors are that the (B-P) ages that Walczak et al. (2020) used come from relatively shallow water (670 m) on the upper continental shelf only 75 km offshore of the Bering Glacier. Major changes in circulation probably occurred as this and other glaciers retreated and as relative sea level rose 120+ m, which doubled the distance between the core site and the coastline.

Another reason why the assumption of stationarity in vertical mixing may be invalid prior to ca. 14.7 ka in the northeastern Gulf of Alaska is the presence of ice on the sea (Section 2.3). Extensive sea ice was present seasonally at this location during the coldest intervals of Marine Isotope Stage 2. It was probably a mixture of actual sea ice and icebergs; regardless, the presence of ice of either sort would have affected vertical mixing. Suppression of deep circulation by ice and by fresh surface water coming from melting glaciers would have increased the marine reservoir ages of deepwater by reducing the exchange of ^{14}C across the sea surface and, possibly, by suppressing the biological pump.

Larger marine-reservoir ages (MRAs) mean that some parts of the chronology that the Walczak hypothesis is based upon may be too old by an undetermined amount. Based on the existing chronology, peak ice-rafter debris (IRD) deposition and minimum overturning circulation in the Gulf of Alaska led peak IRD deposition during Heinrich Event 1 (HE 1) in the North Atlantic by 1370 ± 550 years; however, some estimates of ice-age ΔR s in coastal waters of British Columbia and Washington range from 950 to 1200 yrs. (Hutchinson et al., 2004) and possibly higher (Kovanen and Easterbrook, 2002; Cosma and Hendy, 2008). This magnitude of ΔR could reduce or even remove entirely the lead time of the North Pacific over the North Atlantic (Fig. 44). Compounding the problem is the uncertainty in the age of the HE 1 in the North Atlantic (Fig. 39), which makes it a moving target for comparisons with IRD deposition in the Gulf of Alaska.

In summary, if correct, the Walczak hypothesis fundamentally changes our understanding of how the ice-age planet functioned. It focuses attention on the tropic-subarctic teleconnections at work in the North Pacific that influenced the buildup and break-down of, the marine margin of the Cordilleran Glacier Complex, followed by the disintegration of the other boreal ice sheets. Testing this hypothesis requires an improved understanding of paleo-marine reservoir ages in the Gulf of Alaska.

4.2. Synthesis: The atmosphere/ocean/cryosphere system of the Northwest Coast and Northeast Pacific during Marine Isotope Stage 2 and its global interconnections

4.2.1. Overview

Many key processes that shaped the paleoenvironments of the Northwest Coast during Marine Isotope Stage 2 (MIS 2) are missing or diminished today (SI Section). The Laurentide Ice Sheet and much of the Cordilleran Glacier Complex have vanished. Isostatic rebound is now mostly complete along the Northwest Coast (Section 2.2.1), leaving only localized responses to Little Ice Age deglaciation (Hu and Freymueller, 2019). Along with the ice sheets went the glacial outburst floods and the flotillas of ice bergs, with the result that Atlantic Meridional Overturning Circulation is now relatively stable. The position of the Intertropical Convergence Zone, which during the Last Glacial Maximum was geographically fickle (Section 4.1.10), is now relatively stable, as is the rhythm of ENSO. Offshore, the absence of sea ice in the North Pacific, other than in the Bering Sea and Sea of Okhotsk, has reduced the capacity for the production of Intermediate Water (Section 4.1.8), which has stabilized the overall circulation of the North Pacific. Compared with MIS 2, the Holocene has been impoverished in terms of climate

change. What was the sequence of events that brought the Northwest Coast out of its dynamic ice-age state into the more stable, Holocene one? What follows is a scenario of what might have happened from a global perspective, with a focus on the Northwest Coast.

4.2.2. The onset of Marine Isotope Stage 2 and the Last Glacial Maximum

Glacier cover increased in the northern hemisphere starting ca. 32 ka, probably in response to reduced summer insolation at both high and low, northern latitudes (Section 4.1.1). As ice sheets grew, eustatic sea levels fell, and blocking highs occurred more frequently over western Canada (Section 3.2). Once the Laurentide Ice Sheet had grown to its maximum extent between 24 and 21 ka, the polar jet tended to split north and south around it, which reduced the frequency of cyclonic storms reaching Southeast Alaska, Haida Gwaii, and the Pacific Northwest, causing a decline in snowfall there. This pattern of a blocking high over the western Cordillera accompanied by a deep low in the Northeast Pacific corresponds to today's negative phase of the Arctic Oscillation (Section 7.1.3) and to the positive phase of the Pacific-North American Pattern, which tends to accompany drier winters in the Pacific Northwest and snowier winters in western Alaska.

Between ca. 24 and 21 ka, the northern branch of the polar jet probably looped across the exposed continental shelf of the Bering Sea, while the southern branch followed a southward-diverted path similar to the one it follows today when Eastern Pacific Warm-El Niños coincide with positive phases of the Pacific Decadal Oscillation (PDO+) (SI Section 1.3.2). A major difference was that during Marine Isotope Stage 2, this southward displacement of the polar jet was probably a persistent feature lasting for millennia, rather than just for several years as it does today. The resulting increase in winter precipitation in the western USA, combined with cooling caused by proximity of the Cordilleran Glacier Complex and the Laurentide Ice Sheet, caused pluvial lakes to form (Section 3.5).

At the same time that chronic Eastern Pacific Warm-El Niño conditions (Section 4.1.5) caused a persistent positive phase of the Pacific Decadal Oscillation in the Northeast Pacific, the vigor of the Asian Summer Monsoon (ASM) declined (Section 4.1.3). The ASM experienced several major reductions, and these coincided with reduced overturning circulation in the Gulf of Alaska as revealed by minima in (Benthic-Planktic) ^{14}C ages (B-P) (Fig. 35). These (B-P) minima reflect weakening of the halocline in response to less freshwater being carried into the high-latitude North Pacific by the extratropical cyclonic storms usually fueled by the ASM (Section 4.1.2 and 8.1.2.2). This reduction of ASM-related moisture import, in conjunction with the diversion of storm tracks away from the eastern Gulf of Alaska, was probably why local Last Glacial Maxima along the Northwest Coast lagged most sectors of the Laurentide Ice Sheet (Section 2.1.5). This lag was most pronounced from Southeast Alaska southward, perhaps because colder temperatures further north in the Alaska Range compensated for drier conditions there and allowed glacier growth despite the reduced snowfall (Section 3.4).

Cooler sea surface temperatures (SSTs) in the Gulf of Alaska between 24 and 21 ka (Fig. 34) were accompanied by an expansion of sea ice north of $\sim 55^\circ\text{N}$ (Section 2.3). Sea ice was most widespread in the northwestern subarctic Pacific and the Bering Sea. Colder sea surfaces, reduced precipitation, and the presence of perennial sea ice would have augmented the production of North Pacific Intermediate Water (NPIW). This increase in overturning circulation, albeit always much less than Atlantic Meridional Overturning Circulation even during the latter's minima, probably drew significant amounts of subtropical water into the subarctic Pacific at intermediate depths (Section 4.1.8). This influx of heat was probably responsible for warming SSTs in the Gulf of Alaska between ca. 22 and 20 ka (Fig. 34) (Section 3.1).

The onset of the Last Glacial Maximum after 30 ka accompanied a steepening of the insolation gradient between the tropics and the Arctic during winter months (Section 4.1.1). Steepening of this gradient intensified the transport of oceanic heat and atmospheric moisture from the tropical North Pacific into the subarctic Pacific. The gradient was

steepest ca. 22–23 ka, which coincided with the maximum extent of the Laurentide Ice Sheet (LIS) (Fig. 16). After ca. 22 ka, the meridional gradient in winter insolation declined rapidly, reaching a minimum ca. 12 ka. As the winter insolation gradient declined, the meridional gradient in summer insolation steepened. Many glaciers in the Cordilleran Glacier Complex expanded to their maximum extents after the trajectories of these changing gradients crossed ca. 19 ka (Fig. 32). The ideal conditions for glacier growth around the Gulf of Alaska margin probably occurred ca. 19 ka when the insolation gradients between the tropics and the subarctic were steep during both winter and summer, which caused both abundant winter snowfall and persistent summer cloudiness. At the same time, the orographic effects of the LIS that diverted storm tracks away from the Northwest Coast were waning, and the Asian Summer Monsoon was experiencing a short-lived peak (Fig. 35).

4.2.3. Deglaciation begins

By 21 ka, the Northern Hemisphere ice sheets had undergone net growth for some 80 kyrs, and had accumulated most of the total eustatic drawdown (Denton et al., 2010). Sufficient time had passed for maximum isostatic depression to occur. Thus, a maximum amount of “excess ice” had accumulated (Raymo, 1997), and this ice was flowing seaward across isostatically depressed continental shelves to terminate along marine-based margins. In this situation, outlet glaciers and ice sheets were vulnerable to catastrophic calving retreats triggered by a combination of rising eustatic sea level and warming ocean temperatures. Meanwhile, starting ca. 21 ka, summer insolation began to increase at high northern latitudes, and the gradient between low- and high-latitude summer insolation steepened (Fig. 32). Strong baroclinicity implies vigorous cyclogenesis along the Subarctic Front in the North Pacific (Section 7.1.2.2), which entails large amounts of latent heat arriving at high latitudes within extratropical cyclones. At the intersection of these events, a grand ice-age termination was probably inevitable.

Deglaciation caused an influx of meltwater and ice bergs into the boreal oceans. In response, eustatic sea level rose and sea surface temperatures (SSTs) cooled in the subarctic Pacific and North Atlantic. This caused a major expansion of winter sea ice (Denton et al., 2010, 2022), even as waters at intermediate depths warmed and caused further retreat of marine-based glaciers (Fig. 43). Freshening surface waters and cooling SSTs suppressed overturning circulation, which declined in both boreal oceans. This change shows up in the Gulf of Alaska ca. 19–17 ka as an increase in (Benthic - Planktonic) ^{14}C ages (Fig. 35). Meanwhile in the Southern Ocean, the circum-Antarctic belt of winter sea ice shrank, and the Austral Westerlies strengthened (Denton et al., 2010), which enhanced the release of CO_2 from the ocean to the atmosphere (Fig. 45). From this point onward, the continued rise of CO_2 increasingly contributed to global deglaciation (Shakun et al., 2012).

4.2.4. Heinrich Event 1

The global, fine structure of Heinrich Event 1 (HE 1) provides a type example of ice-age modes of climate change and highlights the key processes involved. HE 1 lasted from ~ 18 to ~ 15 ka and interrupted the CO_2 -enhanced progression of global deglaciation. According to the canonical, Atlantic-centric interpretation, HE 1 began with a cooling of sea surface temperatures (SSTs) caused by the discharge of massive amounts of meltwater and icebergs into the North Atlantic in response to increasing summer solar insolation at high northern latitudes (Denton et al., 2005; Denton et al., 2010; Denton et al., 2022). Another possibility is that for reasons unknown, the cooling trend in the North Atlantic in which HE 1 was embedded began 10^2 – 10^3 yrs. prior to the onset of intense iceberg calving (Max et al., 2022). Whatever its proximate cause, cooling SSTs slowed Atlantic Meridional Overturning Circulation (AMOC) and initiated the Marcott Mechanism of ice-sheet retreat (Fig. 43). The retreat of marine-based glaciers was further enhanced by a combination of rising eustatic sea level, increasing summer insolation at

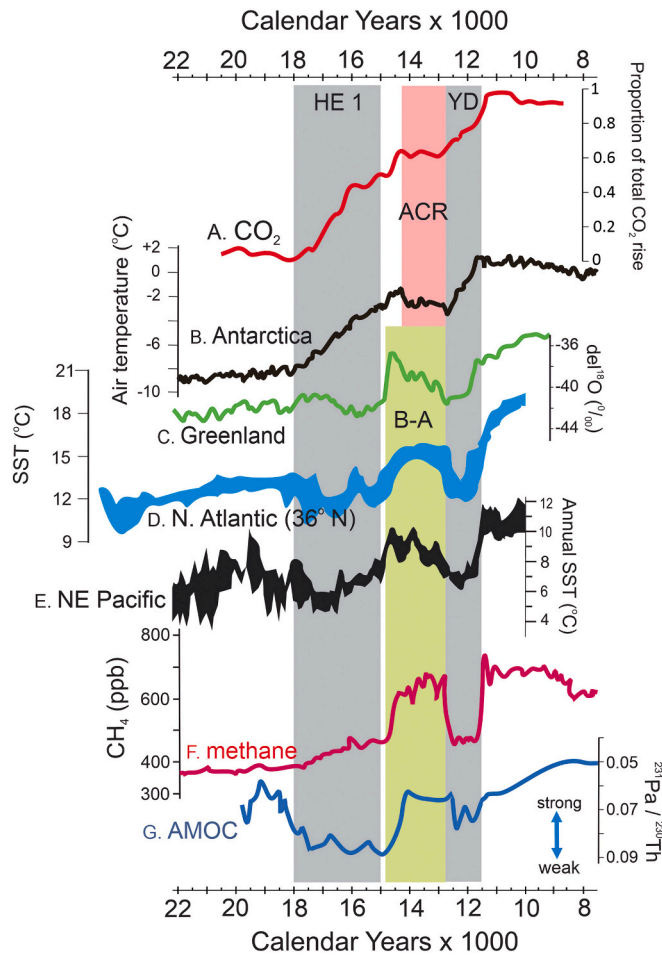


Fig. 45. Global events during the last deglaciation. A. Atmospheric CO₂ concentrations are from Marcott et al. (2014). B. Antarctic surface temperatures are from Parrenin et al. (2013) and Bereiter et al. (2018). C. Greenland surface temperatures are from the NGRIP Ice Core plotted on the GICC05 age scale (Svensson et al., 2008). D. North Atlantic sea surface temperatures (SSTs) at 36° N are from Martrat et al. (2014). E. Northeast Pacific SSTs are from Praetorius et al. (2023). F. Atmospheric methane (CH₄) data are from the WAIS Divide Ice Core (Rhodes et al., 2015; Bereiter et al., 2018). G. The record of Atlantic Meridional Overturning Circulation (AMOC) is from Bereiter et al. (2018). “HE 1” = Heinrich Event 1. “ACR” = Antarctic Cold Reversal. “YD” = Younger Dryas. “B-A” = Bølling-Allerød interstadial.

high northern latitudes, and enhanced heat transport in response to a steepening Equator to Subarctic gradient in summer insolation (Section 4.1.1). As the influx of icebergs and meltwater increased, SST cooled further in the North Atlantic and Gulf of Alaska.

If the alternate, Walczak hypothesis is correct, the ultimate cause for ocean cooling at high northern latitudes at the onset of Heinrich Event 1 clearly lay in the tropics, not at high latitudes (Section 4.1.10). Strengthening of the Asian Summer Monsoon (ASM) starting ca. 21 ka triggered glacial retreat along the Gulf of Alaska margin. An expansion of sea ice followed, which caused further sea-surface cooling and further glacier retreat, again through the Marcott Mechanism. This influx of freshwater into the Gulf of Alaska would have revved-up the Alaska Coastal Current (Royer and Finney, 2020), particularly between ca. 22 and 16.4 ka (Praetorius et al., 2023). Along the Northwest Coast, isostatic rebound accentuated the destabilizing effects that rising sea level had on marine-based glaciers by displacing meltwater seaward (Pan et al., 2021). Cooling in the subarctic Pacific was then teleconnected via the atmosphere (Peteet et al., 1997) to the North Atlantic, where it initiated the shutting down of Atlantic Meridional Overturning Circulation, which then triggered the full, global impacts of Heinrich

Event 1 (Fig. 46).

Regardless of whether the North Atlantic or the Northeast Pacific was the trigger point for Heinrich Event 1, meridional heat transport declined in the Northern Hemisphere as Atlantic Meridional Overturning Circulation (AMOC) slowed. In response, sea ice expanded across the North Atlantic in winter (Denton et al., 2005), and the Intertropical Convergence Zone shifted southward (Chiang and Bitz, 2005; Bradley and Diaz, 2021) (Fig. 46). Once AMOC had weakened significantly, the entire Northern Hemisphere cooled (Wu et al., 2008; Maier et al., 2018). The expansion of sea ice in winter was probably key in promulgating what started in the North Atlantic (alternatively, in the Gulf of Alaska) to the rest of the planet (Denton et al., 2005; Denton et al., 2010; Denton et al., 2022).

In response to the southward shift of the Intertropical Convergence Zone (ITCZ) over the Equatorial Atlantic, trade winds intensified north of the Equator, which displaced the Pacific ITCZ southward and weakened both the Hadley Circulation (Chiang et al., 2014) and the Walker Circulation (Koutavas et al., 2002) (Fig. 46). This probably strengthened the already persistent Eastern Pacific Warm-El Niño phase of ENSO in the Equatorial Pacific (Section 4.1.5). It probably also weakened the Asian Summer Monsoon (ASM) (Section 4.1.3), which then reduced cyclogenesis, which in turn reduced heat and moisture export to the high-latitude North Pacific. Another effect of a reduced ASM would have been weakening of the Indian Ocean Subtropical High, which would have caused a decline in the Agulhas Leakage, which then further suppressed Atlantic Meridional Overturning Circulation by reducing the amount of salty, tropical water entering the North Atlantic from the Indian Ocean (Beck et al., 2018). Eventually, the poleward displacement of the subtropical gyres in the Southern Ocean caused the belt of Austral Westerlies to narrow and intensify. Once the Austral Westerlies shifted south of Aotearoa-New Zealand, a negative feedback (the “Zealandia Switch”) was activated (Denton et al., 2021), which then enhanced overturning circulation in the Southern Ocean, warmed sea surface temperatures there, and triggered the release of enormous amounts of CO₂ into the atmosphere (Fig. 45).

Floods issuing from the Columbia River basin and from the Copper River basin in southern Alaska entered the North Pacific intermittently during the deglacial period (Section 4.1.9). Some of these floods cooled the North Pacific, possibly to the extent of triggering responses in the North Atlantic via atmospheric teleconnections. However, direct effects of this Columbia basin freshwater on Atlantic Overturning Circulation were limited because flow through Bering Strait remained minor until sometime after 11 ka (Section 4.1.6).

4.2.5. Aftermath of Heinrich Event 1

Heinrich Event 1 (HE 1) ended as marine-based glaciers retreated onto land, reducing the supply of icebergs and meltwater, which reduced sea ice cover in winter, at the same time that increasing amounts of CO₂ and CH₄ were being released into the atmosphere (Fig. 45) and solar insolation was steadily increasing (Fig. 31, 41). As HE 1 ended, sea surface temperatures (SSTs) warmed across the North Atlantic and North Pacific, Atlantic Meridional Overturning Circulation revived (Fig. 45), and the production of North Pacific Intermediate Water declined (Section 4.1.8). Because the gradient in latitudinal insolation continued to steepen over the North Pacific (Fig. 32), more frequent cyclonic storms probably arrived over the Northwest Coast. Together with the reinvigoration of the Asian Summer Monsoon (Section 4.1.3), this increased the advection of moisture over the subarctic Pacific, which freshened the Gulf of Alaska and further strengthened the halocline there.

After Atlantic Meridional Overturning Circulation (AMOC) resumed abruptly ca. 14.7 ka at the outset of the Bølling-Allerød interstadial, CH₄ concentrations rose rapidly in the atmosphere (Fig. 45), probably mainly in response to the reinvigoration of the Asian Summer Monsoon, which tracked the rise of summer insolation and peaked ca. 10 ka (Fig. 33). The establishment of an ENSO regime similar to today’s saw a reduction in

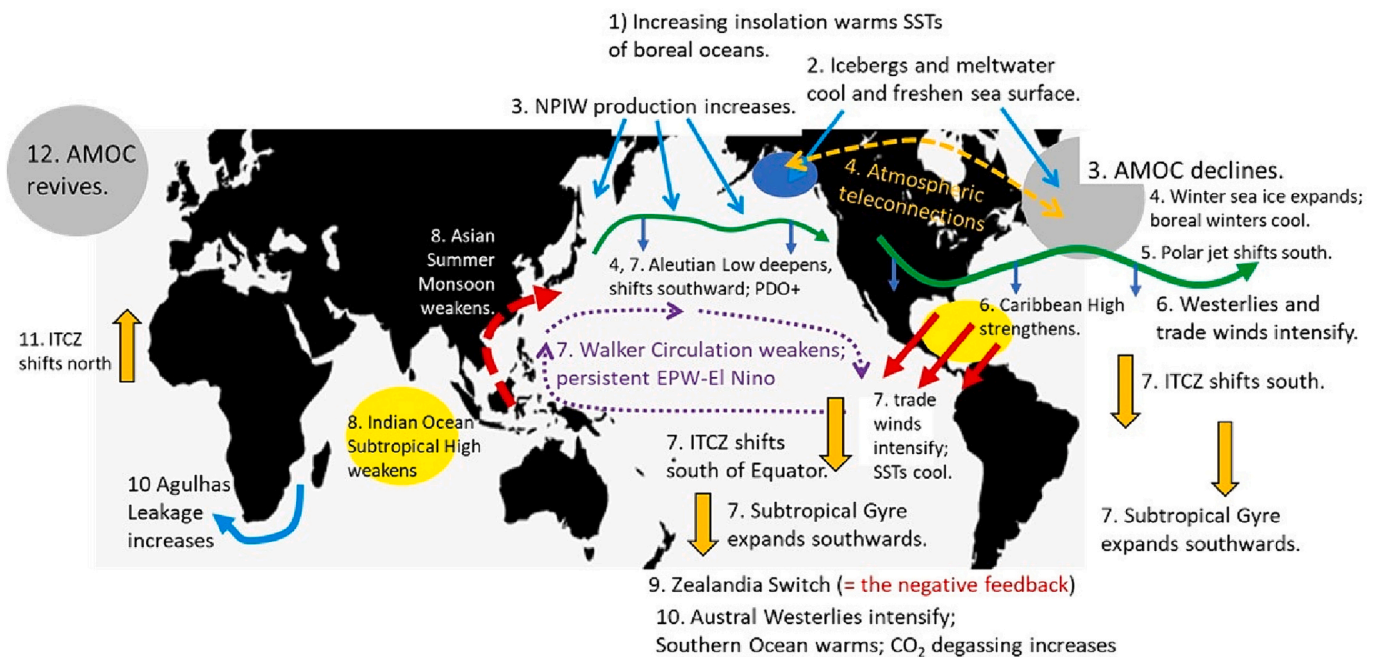


Fig. 46. A possible sequence of events during Heinrich Event 1. A similar, but less pronounced cycle of cryosphere-atmosphere-ocean interactions may have occurred during the Younger Dryas. This is the Atlantic-centric version of events; the Walczak Hypothesis asserts that the initial step was a strengthening of the Asian Summer Monsoon, which set off the retreat of glaciers along the Northwest Coast, which then caused the cooling of both boreal oceans. The key, negative feedback on global cooling triggered by the Zealandia Switch is described in detail by Denton et al. (2021). “AMOC” = Atlantic Meridional Overturning Circulation. “ITCZ” = Inter-tropical Convergence Zone. “SST” = sea surface temperature. “NPIW” = North Pacific Intermediate Water. “PDO+” = positive phase of Pacific Decadal Oscillation. “EPW-El Niño” = Eastern Pacific Warm-El Niño.

the occurrence of Eastern Pacific Warm-El Niños and removed the persistent dipole pattern of winter precipitation over the western USA. This caused pluvial lakes in the Southwest USA to dessicate.

Air temperatures rose dramatically throughout the Arctic as CO_2 levels progressively rose (Fig. 45). Holocene-like temperature were reached in the northern hemisphere between 14.6 and 12.9 ka at a time when the Southern Hemisphere was experiencing gradual cooling during the Antarctic Cold Reversal. Estimates of sea surface temperatures in the Gulf of Alaska suggest they peaked ca. 14 ka and then gradually cooled to near full-glacial conditions ca. 12 ka during the Younger Dryas chronozone.

It seems increasingly likely that the Younger Dryas (YD) was a winter phenomenon (Fig. 27). Cooler, drier winters during the YD in southern Alaska would explain the apparent lack of advances by coastal glaciers as well the subtlety and geographical variability of the paleobotanical signal (Section 3.3). Cooler, drier conditions in the Gulf of Alaska imply a southward-shifted Aleutian Low (AL), which is consistent with advances and standstills of alpine glaciers in the western USA during the YD (Marcott et al., 2019; Barth et al., 2022). Southward diversion of the AL is also consistent with the partial re-wetting of the western USA during the YD (Section 3.5) (Pigati and Springer, 2022).

5. Research needs

5.1. Testing the Extreme Winter Hypothesis

The Extreme Winter hypothesis (Fig. 27) was proposed by Denton et al. (2005, 2010, 2021, 2022) to resolve the Mercer Paradox, the observation that during Marine Isotope Stage 2, mountain glaciers in the two polar hemispheres fluctuated in synchrony, even though Milankovitch orbital forcing was asynchronous there. Extreme winters and mild, steadily ameliorating summers may explain the enigmatic records of climate during the Younger Dryas chronozone along the Northwest Coast (Section 3.3).

Testing the extreme winter hypothesis at sites along the Northwest

Coast requires proxy data that specify winter climate. Oceanographic proxies for sea surface temperature (Fig. 24) do not resolve summer conditions well, nor do the glacial geological records, nor do many climate-models. Possibilities for winter-climate proxies include pollen and plant macrofossil records from coastal tundra and high alpine sites where plants were strongly affected by winter winds and/or snow depth. Another possibility is reconstructing the growth rates of ice wedges during, before, and after the Younger Dryas (YD). Other possibilities include reconstructing the changing duration of ice-cover in lakes and ponds and constructing time series of ice-push ridges on lake shores (e. g., Berg et al., 2022). The ideal data set would be a record of sea ice cover in an embayment like Prince William Sound where winter cooling might have caused varying amounts of sea ice to form over the course of the YD.

5.2. North Pacific Sea Ice

The extent and timing of sea ice cover in the North Pacific during the Last Glacial Maximum and last deglaciation remain uncertain. This information is crucial for reconstructing oceanic and atmospheric circulations. Because sea ice can impact the dynamics of overturning circulation, these data are also needed to understand the time course of CO_2 release from North Pacific deepwater during deglaciation.

The main change in sea ice dynamics in the North Pacific involved seasonal (winter) ice. Given the relatively sensitive nature of the sub-arctic Pacific's halocline and thermocline today (SI Section 1.1.3), did changes in sea-ice cover affect overturning circulation? In the Southern Ocean today, the formation / melting of sea ice affects the surface buoyancy flux (Watson et al., 2015). Perennially ice-covered areas have a negative buoyancy flux conducive to overturning circulation, while areas covered by seasonal ice have a positive flux, which (other factors like wind-stirring being equal) tends to resist overturning circulation. What impacts, if any, did changing sea-ice coverage have on overturning circulation during Marine Isotope Stage 2 in the high-latitude North Pacific?

5.3. Testing the Walczak Hypothesis

It is a compelling idea that the 3500-km long, marine-based margin of the Cordilleran Glacier Complex served as the hair trigger for global deglaciation; however, the dating control upon which Walczak et al.'s (2020) hypothesis rests needs careful scrutiny. Specifically, we need to know how the marine-reservoir effect varied between 30 and 15 ka in the subarctic Pacific. One approach is to use chemically fingerprinted tephra layers (e.g., Austin et al. (1995)) that can be precisely ^{14}C -dated onshore using plant macrofossils and then be traced offshore, where they can serve as chronological markers in marine cores. Ideally, such paired dates would document marine reservoir ages over the entire span of Marine Isotope Stage 2 (MIS 2). This approach requires ice-free areas that accumulated tephras throughout MIS 2. Sites containing multiple tephras preserved in organic-rich pond sediment dating back to 17–18 ka exist at Low Cape on southwestern Kodiak Island (Mann and Peteet (1994) (Fig. 12), and possibly on Sanak Island (Misarti et al., 2012) (Fig. 14). Deglaciation probably occurred even earlier on Chirikof Island at the seaward end of the Shelikof Trough (Fig. 13).

5.4. Ice-free Areas; Glacial Refugia

Ice-free areas undoubtedly existed along the Northwest Coast during Marine Isotope Stage 2; however, ice-free does not equate to biological refugium. Changing glacier extent and fluctuating sea level meant that ice-free areas were often small, transient, and widely separated. Many were probably too small, too transient, and had too harsh a climate to support organisms. Evidence for the existence of small refugia that shifted their locations over time has proved elusive, even in Scandinavia where the topic of glacial refugia has been researched for more than a century (Kullman, 2004; Birks and Willis, 2008; Alsos et al., 2020). Even if organisms did survive in an ice-free area, species diversity was probably low and restricted to arctic-alpine taxa. This does not mean that refugia are uninteresting. Their chronologies constrain the timing of changes in relative sea level and glacier extent on the landscapes around them. The point here is that identifying them will require intensive, multidisciplinary research efforts. This challenge is made clear by the fact that despite decades of study, it is still uncertain if, when, and exactly where a biological refugium existed on Haida Gwaii during MIS 2 (Section 2.1.3.4).

The Alexander Archipelago is another area of the Northwest Coast where biological refugia have long been sought. Despite a much-improved understanding of the deglaciation chronology of Southeast Alaska (Lesnek et al., 2020; Baichtal et al., 2021; Walcott et al., 2022), it remains uncertain whether the outer coastline of the archipelago and adjacent continental shelf were totally covered by glacial ice during the local Last Glacial Maximum. The limited number geomorphic surfaces that have been dated, combined with the mountainous topography, makes it possible that some locations did in fact remain ice free and subaerial. The reconstructions of Carrara et al. (2007) and Lesnek et al. (2020) continue to seem reasonable in concept if not detail. Between the ice streams issuing from the major fjord systems, high coastal topography would have created “ice shadows” in their lee, particularly where a narrow shelf and/or deepwater prevented the accumulation of thick glacial ice (e.g., Vorren et al., 2015; Barrie et al., 2021) (Fig. 47). It seems likely that scattered ice-free areas flickered in and out of existence along the outer coast of the Alexander Archipelago and on the adjacent continental shelf. To test this idea, it will be necessary to reconstruct how relative sea levels and equilibrium-line altitudes changed along this coastline over the course of the Last Glacial Maximum and deglaciation. A high priority is exploring the possibility that an ice-free area / refugium existed on the Fairweather Grounds.

5.5. Reconstructing Paleo-Teleconnections

Today, tropical phenomena like ENSO strongly influence the climate

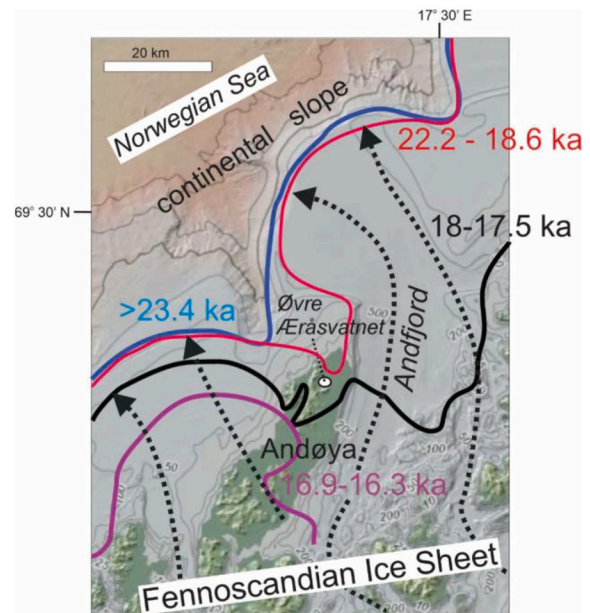


Fig. 47. An iconic outer coast refugium: Andøya in northwest Norway during Marine Isotope Stage 2 (Vorren et al., 2015). Areas with similar geography existed along the Northwest Coast and may have experienced similar glacial and refugial histories. The northern end of Andøya is located <10 km from the outer edge of the continental shelf. Calving of icebergs into the Norwegian Sea limited the buildup of grounded ice there, and low mountains partially shielded the northern end of Andøya from glaciers flowing from the interior. The area around Øvre Erårvatnet was possibly deglaciated as early as 26.7 ka (Alsos et al., 2020), and it probably served as a biological refugium through the remainder of the ice age (Birks et al., 2014). Glacial limits and their ages are from Vorren and Plassen (2002) and Vorren et al. (2015). The base map is from the National Centers for Environmental Information, Bathymetric Data Viewer, <https://www.ncei.noaa.gov/maps/bathymetry/>.

of the Northwest Coast (SI Section 1.3). Throughout this review, we have assumed that tropical teleconnections also operated along the Northwest Coast during the ice age, but how they functioned remains unclear because critical boundary conditions like sea ice extent and the topography of North American ice masses were fundamentally different. The Pacific Decadal Oscillation (PDO) (SI Section 1.3.2) is probably of most interest because of its importance today in the weather and climate of downwind North America and because of its teleconnections to Eastern Pacific Warm-El Niños (EPW- El Niños), which are thought to have been frequent during the coldest periods of Marine Isotope Stage 2 (Section 4.1.5). In conjunction with EPW-El Niños, the PDO probably spent long intervals in its positive phase; however, because of the expansion of winter sea ice in the Gulf of Alaska, the PDO's associated sea surface temperature and winter-precipitation patterns may have shifted southwards along the western coast of North America. Testing this hypothesis would involve reconstructing proxy records of winter storminess along the coastline between Washington and California. During recent centuries, the PDO has left a winter signature in the form of storm-damaged trees along the Northwest Coast (Gaglioti et al., 2019). Similar records of winter damage could be reconstructed from subfossil wood recovered from sites along the unglaciated, western coast of the USA. Varying amounts of winter precipitation caused by shifts in the location and vigor of the Aleutian Low (e.g., Gaglioti et al., 2017) under the influence of the PDO probably also left isotopic records in plant material deposited in lakes and bogs along the Northwest Coast (Anderson et al., 2016).

5.6. Global Impacts of CO₂ Degassing from the Abyssal North Pacific during Deglaciation

When and how much CO₂ was released from the North Pacific's

deepwater after ca. 20 ka? Answering these questions requires first resolving the ongoing controversy over the extent and timing of deep, overturning circulation in the subarctic Pacific during Marine Isotope Stage 2. To do this, more time series of (Benthic - Planktonic) foraminifera ^{14}C ages are needed in order to reconstruct the history of changes in deep, overturning circulation. As described in Section 6.3, obtaining age control for these time series requires paired, terrestrial-marine ^{14}C dates. To minimize complications arising from glacial meltwater and icebergs, the core sites need to be far offshore in places like the Patton Sea Mount.

Declaration of competing interest

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Data availability

Data will be made available on request.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at <https://doi.org/10.1016/j.earscirev.2024.104782>.

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