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RETREAT OF THE CORDILLERA DARWIN ICEFIELD DURING TERMINATION I

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ABSTRACT. *During the last glaciation, the Cordillera Darwin icefield expanded northward toward the Straits of Magellan, eastward across Isla Grande de Tierra del Fuego and through Canal Beagle, and south and west across the numerous islands of southernmost Chile. Deglaciation commenced at ~18 ka during Termination I. Alpine glaciers in the Fuegian Andes also likely retreated at that time. Radiocarbon ages from the interior regions of Cordillera Darwin suggest ice in at least some locations had retreated close to its present-day limit as early as ~16.5 ka. The most likely cause for such rapid ice retreat was rising atmospheric temperatures at the start of Termination I.*

Retroceso de los campos de hielo de la Cordillera Darwin durante el periodo Termination I

RESUMEN. *Durante la última glaciación, el campo de hielo de la Cordillera Darwin se expandió hacia el norte en dirección al Estrecho de Magallanes; hacia el este, a través de la Isla Grande de Tierra del Fuego y del Canal Beagle; y hacia el sur y oeste, a través de las numerosas islas del sur de Chile. La deglaciación comenzó hace ~ 18 ka, durante el Termination I. Los glaciares alpinos en los Andes Fueguinos probablemente también se retiraron en ese momento. Las edades de radiocarbono de las regiones interiores de la Cordillera Darwin sugieren que el hielo en algunas localidades se había retirado cerca de su límite actual ya hacia ~ 16.5 ka. La causa más probable de este rápido retroceso del hielo fue el aumento de las temperaturas atmosféricas al inicio del periodo Termination I.*

Key words: Cordillera Darwin, Termination I, radiocarbon, deglaciation, Tierra del Fuego.

Palabras clave: Cordillera Darwin, Termination I, radiocarbono, deglaciación, Tierra del Fuego.

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1. Introduction

Cordillera Darwin (~54ºS; Fig. 1A) is the southernmost temperate icefield on earth, with glaciers that respond sensitively to changes in temperature (Sagredo *et al*., 2014). Thus, a history of its fluctuations affords important clues for reconstructing temperature history, as well as the behavior of and mechanisms within the Southern Hemisphere climate system. Moreover, the region lies in a zone of strong climate gradients from the Patagonian icefields to the north (~37-45ºS) to the Antarctic Peninsula to the south (67-70ºS) and thus is well-situated to aid in understanding the transition in climate between the polar high-southern latitudes and the more temperate mid-latitude regions.

We focus here on the behavior of glaciers in Tierra del Fuego, southernmost South America, during the termination of the last ice age, ~18-14.5 ka. This time period, known as Heinrich Stadial 1 (HS-1) in the North Atlantic basin, coincides with the last termination in the Southern Hemisphere. Understanding the far-field effects of HS-1 and its possible role in Southern Hemisphere climate may be key for unravelling the cause of Termination I. For example, Denton *et al*. (2010) proposed that cold northern conditions during HS-1 led to southward movement of the Intertropical Convergence Zone and, in turn, of the southern westerly wind belts and oceanic fronts in the vicinity of Tierra del Fuego. This movement of both atmospheric and oceanic boundaries has been documented in southern South America during both glacial and interglacial times (e.g., Lamy *et al*., 2004, Kaiser *et al*., 2005; Björck *et al*., 2012; Moreno *et al*., 2012; Kohfeld *et al*., 2013; Vanneste *et al.,* 2015). Anderson *et al*. (2009) proposed that shifting of the westerly winds over the latitude of the Drake Passage during HS-1 caused increased upwelling, which was instrumental in breaking down Southern Ocean stratification and releasing carbon dioxide to the atmosphere during the last termination.

In this paper, we begin by reviewing evidence for the extent of the Cordillera Darwin ice field at the last glacial maximum (LGM: 19-23 ka, Mix *et al*., 2001) and then present the current understanding of the timing and causes of deglaciation of this region during Termination I. The goal is to begin to develop an understanding of the process that set in motion the complex changes in ice extent, sea level, and landscape evolution in this region at the end of the last ice age.

Tables 1 and 2 present chronologic information used in this paper. For radiocarbon data, ages quoted in the text are in calendar years obtained from the INTCAL13 dataset and CALIB 7.0 or (in one case) the Marine13 dataset with a delta R of 140 years (Reimer *et al*., 2013). Original radiocarbon dates are in Table 1. Beryllium-10 surface exposure ages (Table 2) are all calculated using the Lago Argentino production rate (Kaplan *et al*., 2011) and the Lal (1991)/Stone (2000) scaling scheme.

Table 1. Compilation of radiocarbon ages of basal organic remains in bog cores. Radiocarbon ages were converted to calendar years using CALIB 7 and the INTCAL13 and MARINE13 datasets (Reimer et al.*, 2013). Dates presented here are calculated as the midpoints of the ranges given by CALIB. Calibrations with a probability <10% are not included. Calibrated ages may differ from those presented in the original papers due to changes in calibration datasets. Superscripts after the calibrated ages are keyed to Figure 3.*

Location	Core or Depth	Lab #	Material	^{14}C yr B.P.	1σ	Cal yr B.P.	2σ
			Bahía Inútil/Northern Isla Dawson				
E. Esmerelda II[g]	300-312 cm	A-6793	Bulk carbon	14 260	350	17 240[1]	930
E. Cameron II[f]	420 cm	AA-42413	Plant remains	13 980	120	16 960[2]	410
E. Esmerelda II[h]	312 cm	SRR-5143	Bulk carbon	13 890	50	16 810[3]	230
E. Esmerelda II[g]	300-312 cm	A-6814	Bulk carbon	13 650	310	16 520[4]	900
E. California[f]	341 cm	AA-42414	Plant remains	13 614	86	16440[5]	300
E. Esmerelda I[g]	390-400 cm	A-6807	Bulk carbon	13 425	310	16 160[6]	910
P. Cameron[g]	No information	A-6791	Bulk carbon	13 030	260	15 520[7]	860
Paso Garibaldi[j]	284 cm	A-4882	Bulk peat	10 730	180	12 570[8]	450
			Northern Cordillera Darwin				
P. Marinelli[e]	MARPT-07-02_10.34-10.35m	OS-64095	Peat macro.	13 950	55	16 900[9]	250
P. Marinelli[e]	MARPT-07-02_10.34-10.35m	OS-61545	Gyttja	14 050	70	17 080[10]	290
P. Marinelli[e]	MARPT-07-02_10.35-10.36m	OS-64068	Peat macro.	13 250	85	15 930[11]	260
P. Marinelli[e]	MARPT-07-02_10.36m	OS-61606	Sedge	13 400	85	16 110[12]	270
P. Marinelli[e]	MARPT-07-02_10.36-10.38m	OS-63929	Seeds	13 250	55	15 930[13]	200
P. Marinelli[e]	MARPT-07-02_10.36-10.38m	OS-64070	Peat macro.	13 650	90	16 490[14]	310
P. Esperanza[e]	PE-07-01_8.74-8.77m	OS-61551	Gyttja	13 350	65	16 050[15]	220
S. Almirantazgo[d]	NBP0505 JPC77_0.78m	No data	Marine carbonate*	13 650	70	15 690[16]	320
			Eastern Canal Beagle				
Harberton[a]	Harberton_10.4m	QL-4279	unknown	14 640	260	17 790[17]	650
Harberton[j]	998 cm	A-4817	*Drepanocladus*	13 360	280	16 080[18]	830
Harberton[i]	HAR12-PB01A/727	GdA-2882	Brown moss	13 335	59	16 040[19]	210
Caleta Róbalo[b]	Caleta Róbalo_9.1m	QL-1685	unknown	12 730	90	15 120[20]	360
Ushuaia[c]	Ushuaia 2_8.2m	Beta 55681	Bulk org.	12 430	80	14 480[21]	510
Ushuaia[c]	Ushuaia 3_5.1m	QL-4162	Bulk org.	12 100	50	13 950[22]	160
Ushuaia[c]	Ushuaia 1_6.7m	QL-4436	Bulk org.	12 060	60	13 920[23]	160
Lapataia[c]	Lapataia_5.1m	RL-2001	Bulk org.	10 080	250	11 820[24]	740
			Southern Cordillera Darwin				
V. Holanda[e]	H-07-01_3.95m	OS-61638	Peat macro.	12 550	60	14 780[25]	360
Bahía Pía[e]	BL-07-16B_4.56m	OS-64237	Peat macro.	12 350	120	14 500[26]	490
Caleta Olla[e]	CO-07-02_5.3m	OS-61542	Peat macro.	10 300	50	12 090 (80%)[27] 12 320 (15%)	160 60
Bahía Pía[e]	BL-07-15_1.50m	OS-61603	Grass,sedge	9310	65	10 490[28]	190

[a]Heusser (1989a);[b]Heusser (1989b);[c]Heusser (1998); [d]Boyd *et al*. (2008); [e]Hall *et al*. (2013); [f]McCulloch *et al*. (2005b); [g]Clapperton *et al*. (1995); [h]McCulloch and Bentley (1998); [i]Vanneste *et al*., 2015; [j]Markgraf and Huber, 2010
*A delta R of 140 years was applied to this sample, following the original authors.

Table 2. Surface-exposure age data relating to the innermost LGM moraine belt (Belt "D" of McCulloch et al.*, 2005b) at Bahía Inútil and deglaciation in the Fuegian Andes. Calculations are based on the Lago Argentino production rate and the time-dependent Lal (1991)/Stone (2000) scaling scheme ("Lm"). Ages for the Bahía Inútil region were recalculated from the original papers by Kaplan* et al. *(2011). Ages are quoted with 1-sigma internal error. Superscripts after the ages are keyed to Figure 3.*

Sample	Latitude	Longitude	Elev. (m)	Thickness (cm)	Shielding	^{10}Be atoms	Error (1σ)	Standard	Age (yr BP)
Ages for the "D" moraines									
BI:C1[a]	-53.5781	-69.4844	52	4.0	1.0	96 455	6752	S555	18 500 ± 1300[29]
BI:C2[a]	-53.5808	-69.4872	48	4.0	1.0	98 849	14 234	S555	19 000 ± 2800[30]
BI:C3[a]	-53.5881	-69.4889	54	4.0	1.0	100 012	9800	S555	19 100 ± 1900[31]
SM-02-21[b]	-53.5783	-69.4852	60	0.6	1.0	107 975	31 430	S555	20 100 ± 5900[32]
SM-02-23[b]	-53.5798	-69.4781	56	2.9	1.0	92 397	8565	S555	17 500 ± 1600[33]
Ages of striated bedrock in front of cirque glaciers									
11-19F[c]	-54.6632	-68.3321	641	5.2	0.98	128 100	6000	07KNSTD	16 670 ± 790[34]
11-21A[c]	-54.6613	-68.3313	650	6.6	0.98	136 500	6000	07KNSTD	17 830 ± 790[35]

[a]McCulloch *et al*., 2005b
[b]Kaplan *et al*., 2008a
[c]Menounos *et al*., 2013

2. Regional Setting and Physiography

Hundreds of islands from the Straits of Magellan to Cape Horn make up Tierra del Fuego (Fig. 1A, B). Cordillera Darwin, an east-west trending crystalline mountain range with peaks that surpass 2000 m elevation, dominates the central portion of region and forms the western peninsula of Isla Grande de Tierra del Fuego (hereafter "Isla Grande"). The mountains stretch nearly from the Pacific to the Atlantic Ocean and are bordered to the northwest by Canals Cockburn, Magdalena, and Gabriel, as well as to the north by Seno Almirantazgo and to the south by the Canals Beagle and Ballenero. The highest peaks lie near the center of the range and decrease in elevation both east and west.

Much of Tierra del Fuego lies under a wet, maritime climate strongly affected by the Southern Westerlies. Average mean annual temperature is ~5ºC (Rabassa *et al*., 2000). Precipitation is several meters per year near the Pacific coast and declines to less than 0.5 m/yr in drier areas of eastern Tierra del Fuego (Lliljequist, 1970; Tuhkanen, 1992; C. Porter, unpublished data, 2007; Fontana and Bennett, 2012). This precipitation gradient has an effect both on modern snowline elevations, which rise from west to east, and on vegetation.

Cordillera Darwin, as well as the islands to the south, display a rugged landscape (Fig. 2) characterized by extensive tracts of areally scoured bedrock and dissected by fjords (~200-400 m water depth). In contrast, eastern Isla Grande has a more rolling topography, and the landscape is dominated by LGM-aged and older moraines and glaciofluvial sediments. Relatively few constructional glacial landforms occur between the LGM moraine belt and Holocene/Late Glacial moraines located in the interior of the mountains near present-day glaciers.

3. Last Glacial Maximum Position

Although well-documented in some locations, the LGM extent of the Cordillera Darwin ice field remains uncertain along most of its perimeter (Fig. 1A). Caldenius (1932) produced the earliest comprehensive map showing proposed LGM ice extent and, in many locations, this map still remains the only resource. During the LGM, ice spread from the high peaks of central Cordillera Darwin and flowed northward to the Straits of Magellan, eastward through Seno Almirantazgo to Lago Fagnano, southeastward through Canal Beagle to the junction with the Atlantic Ocean, and south and westward across the numerous islands of southern and western Tierra del Fuego to end on the continental shelf (Caldenius, 1932; Coronato *et al.*, 1999, 2009; Rabassa *et al.*, 2000, 2011).

Northern ice flow from Cordillera Darwin is characterized best along a flowline through Canal Whiteside to Bahia Inútil, where numerous, low-relief moraines enclose

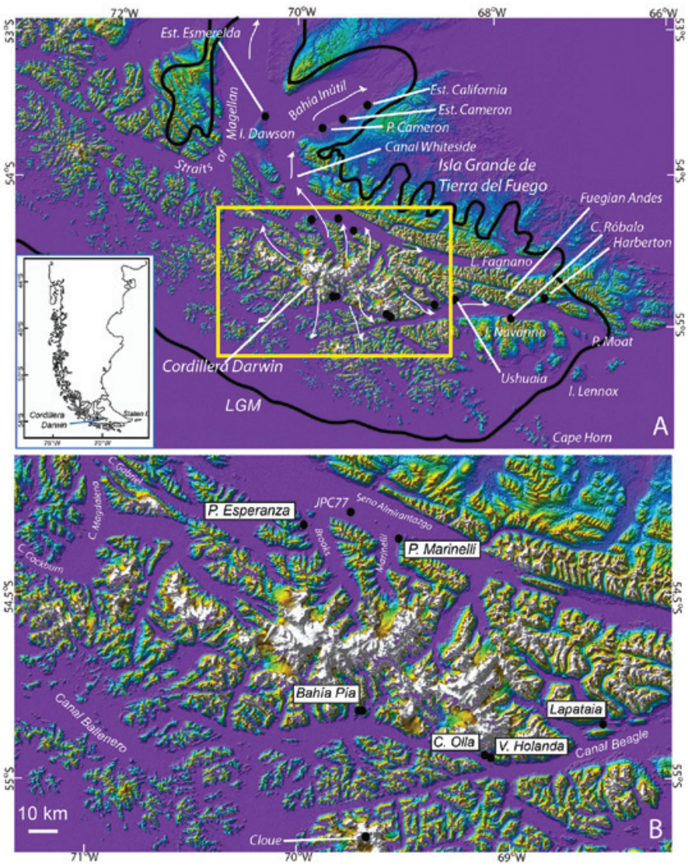

Figure 1. Index map of Cordillera Darwin, showing locations mentioned in the text. Base image is a digital elevation model constructed from Shuttle Radar Topography Mission (SRTM) data. Modified after Hall et al. *(2013).*

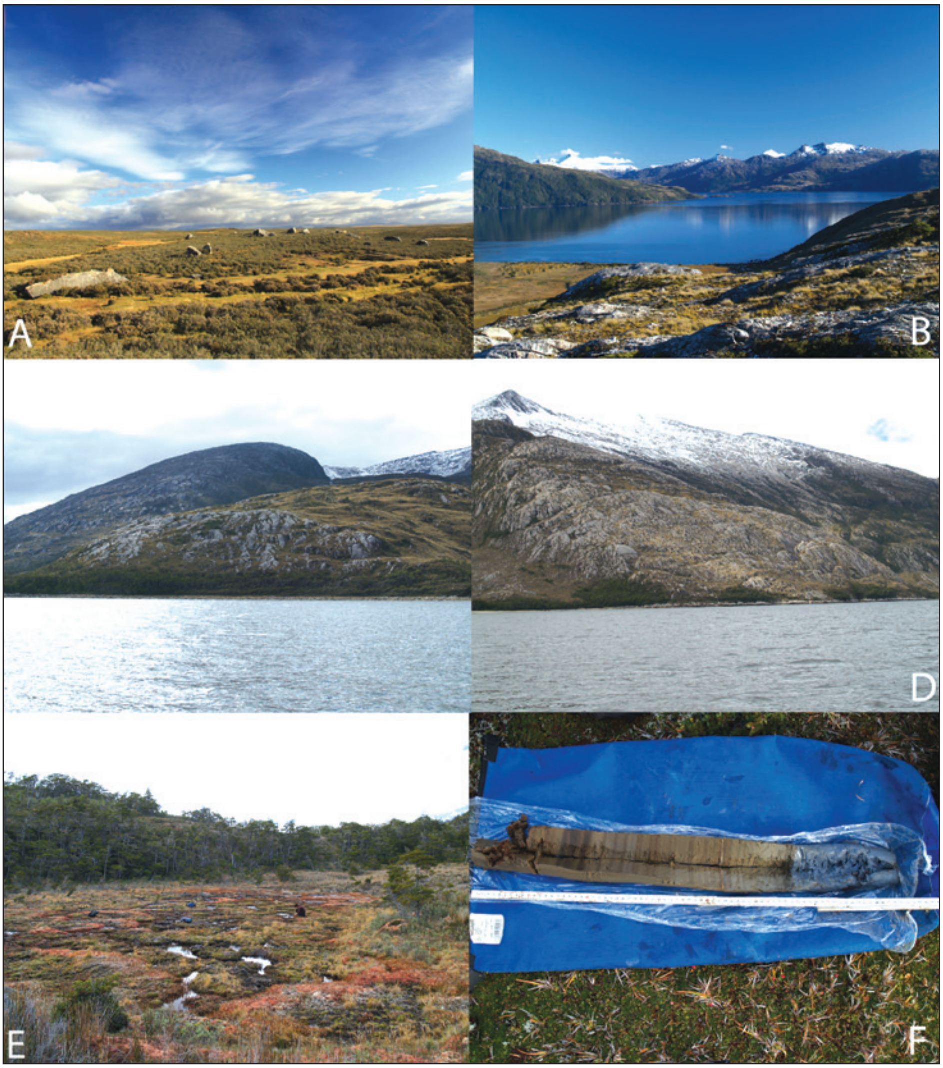

Figure 2. Glacial features in Tierra del Fuego. A. "Darwin's Boulders" along the right-lateral moraines adjacent to Bahía Inútil; B. Topography adjacent to Canal Beagle, near Bahía Pía; C. and D. Areally scoured terrain in the interior of Cordillera Darwin along Canal Beagle; E. Punta Marinelli bog; F. Lower meter of the MARPT-07-02 core, showing organic sediment (left) overlying blue-gray glacial lacustrine clay (right). Scale marks are in centimeters.

the eastern end of the bay (Caldenius, 1932; Meglioli, 1992; Clapperton *et al.,* 1995; Bentley *et al*., 2005; McCulloch *et al*., 2005a, 2005b; Evenson *et al*., 2009; Darvill *et al*., 2014). The moraines can be traced southeastward across Isla Grande, where they are thought to correlate with those enclosing the eastern end of Lago Fagnano (Coronato *et al*., 2009). One distinguishing feature of the right lateral moraines at Bahía Inútil is the presence of a train of large boulders of Beagle granite (Fig. 2A). Known as Darwin's

Boulders (Evenson *et al.*, 2009), these erratics mark a former ice flowline from central Cordillera Darwin that, based on lithology, must have originated at the head of Marinelli and/or Brooks fjords (Fig. 1B).

The age of many of the Bahía Inútil moraines is uncertain. The traditional paradigm is that the inner belts of moraines closest to the bay (B, C, and D of Bentley *et al.*, 2005) date to the LGM and that the outer moraines (A and older), particularly those along the Atlantic coast, relate to much older glaciations (Meglioli, 1992; McCulloch *et al.*, 2005; Evenson *et al.*, 2009). In this context, boulders in the older moraine belts that yield what seem to be anomalously "young" ages have been interpreted as having loss of cosmogenic nuclides from significant erosion (e.g., Kaplan *et al.*, 2007; Evenson *et al.*, 2009). However, Darvill *et al.* (2015), noting that Darwin's Boulders all appear to be from a single flowline and show similar degrees of weathering, opened the possibility that many of the outer moraines are younger than previously thought and may be from the last glaciation.

The LGM moraine belt trends southeastward from Bahía Inútil to Lago Fagnano, where it extends around the eastern end of the lake. The Lago Fagnano ice lobe was fed by an outlet glacier that streamed southeastward through Seno Almirantazgo, as well as by input from local alpine glaciers (Coronato *et al.*, 2009). Radiocarbon ages of peat layers within deltaic deposits below till suggest that ice advance to the LGM position occurred after ~36 ka (Bujalesky *et al.*, 1997; Coronato *et al.*, 2009), although it is uncertain if the radiocarbon ages are truly finite.

On the south side of the former Darwin ice field, the only flow line known with some confidence is one that extended eastward along Canal Beagle, terminating at Punta Moat, where it formed moraines near the junction with the Atlantic Ocean (Rabassa *et al.*, 1990, 2000). The LGM ice position along the southern and western margins of the icefield remains uncertain, as there are no documented terminal moraines and the ice likely terminated offshore. Caldenius (1932) placed the ice margin near the shelf edge, whereas Coronato *et al.* (1999) drew it closer to the present-day coast and showed extensive subaerial outwash plains on what is now the continental shelf.

The timing of the youngest LGM moraine –the age of which affords a close maximum limit on the timing of deglaciation– is known only near Bahía Inútil. Here, ^{10}Be cosmogenic surface-exposure ages of boulders on moraine crests suggest an age of ~18.4 ± 1.7 ka for the innermost moraines along the south shore of the bay (error-weighted mean of five ages published in McCulloch *et al.* (2005b) and Kaplan *et al.* (2008a), recalculated in Kaplan *et al.* (2011); see Fig. 3A and Table 2).

4. Timing of Recession

Information on the timing of ice recession comes primarily from radiocarbon dates of the lowest organic materials found in bogs that lie proximal to the LGM moraine belt. Such dates afford minimum-limiting radiocarbon ages for deglaciation. In humid areas, such as Cordillera Darwin, re-vegetation following deglaciation appears to have occurred quickly. Observation today suggests a lag time there of less than a decade for vegetation growth following ice retreat in Cordillera Darwin (C. Porter, unpublished data). The delay in revegetation may be more substantial in drier areas of Isla Grande (Coronato *et al*., 1999).

Radiocarbon dates of basal organic materials in bogs adjacent to Bahía Inútil and on northern Isla Dawson afford minimum ages for initial deglaciation from the D moraines (Table 1). McCulloch *et al*. (2005b) obtained ages as old as ~17 ka from bogs inboard of the D moraines on the south shore of the bay at Estancias Cameron and California (Figs. 1A, 3A). The northern tip of Isla Dawson may have been deglaciated by about the same time (Clapperton *et al*., 1995; McCulloch and Bentley, 1998; McCulloch *et al*., 2005b).

More recently, Hall *et al*. (2013) cored bogs in the interior of Cordillera Darwin along the same ice flow lines that fed the Bahía Inútil lobe. Ice emanating from Brooks fjord flowed north through Canal Whiteside to feed the Bahía Inútil lobe at the LGM. The flow direction of ice discharging from Marinelli fjord is less clear. Although it is likely that ice from this fjord also augmented the Bahía Inútil lobe, the possibility cannot be discounted that it may have contributed to ice that ultimately fed the Lago Fagnano lobe. In either case, dates of basal organic materials in bogs from these sites afford minimum ages for the retreat of the former Darwin icefield back into the heart of the mountains. At Brooks fjord, a radiocarbon date of organic material within a core at Punta Esperanza yielded a minimum age for deglaciation of ~16.1 ka (Hall *et al*., 2013; Table 1; Fig. 3B). This date is not thought to afford a close-limiting age, because the core did not penetrate to the glacial clay, and thus it is not known if the lowest organic materials were sampled. To the east at the mouth of Marinelli fjord, six samples of plant remains within four centimeters of the top of the glacial lacustrine clay yielded a weighted mean of 16.3 ± 0.5 ka (Hall *et al*., 2013; Fig. 2F, Table 1). The location of this bog indicates that ice must have retreated to within seven kilometers of the position it occupied in the 20th century by that time. Additional confirmation for the basal ages in both the Marinelli and Brooks bogs comes from the presence of the Reclus tephra (~15 ka; Stern, 2008) at higher levels in the cores at both sites (Hall *et al*., 2013). Moreover, a core from the adjacent sound produced an age of ~15.7 ka for the lowest recovered marine carbonate, consistent with deglaciation prior to that time (Boyd *et al*., 2008). Thus, it seems likely that the Darwin icefield had receded back into the mountains on the north side of the Cordillera by at least ~16.3 ka.

There are also ages for basal organic materials in several bogs on the south side of Cordillera Darwin. Along eastern Canal Beagle ~50 km inboard of the Moat moraines, Heusser (1989a) obtained an age of ~17.8 ka for the lowest organic materials within a bog at Harberton. This age affords evidence that deglaciation from the LGM position was already underway at that time. Other dates from bogs located along eastern Canal Beagle have been interpreted as showing a pattern of gradual ice retreat towards the center of Cordillera Darwin (Fig. 3A, B; Heusser, 1998; Rabassa *et al.,* 2000). Organic material in a bog at Caleta Róbalo on Isla Navarino produced an age of ~15.1 ka. Another bog near Ushuaia gave an age of ~14.5 ka, whereas one farther west at Lapataia yielded a date of ~11.8 ka. However, recent data from the center of Cordillera Darwin conflicts with this pattern of slow retreat. From dates of bogs near Bahía Pía, Hall *et al*. (2013) concluded that ice had retreated far into the interior of Cordillera Darwin prior to 14.5 ka (Table 1; Fig. 3B). Support for this minimum-limiting age comes from a core near Ventisquero

Holanda, only 800 m from the late Holocene moraine complex. Plant remains overlying basal gravel there produced an age of 14.8 ka. This date is not thought to be a close-minimum age, because it came from hillside peat rather than from a bog. However, the date shows that ice retreat had progressed to nearly modern positions by at least ~15 ka.

A cosmogenic surface exposure age dataset from the Fuegian Andes along eastern Canal Beagle further constrains the timing of ice retreat in Tierra del Fuego. Although focused primarily on the Holocene record, Menounos *et al*. (2013) obtained two dates of bedrock just distal to the Late-Glacial (Antarctic Cold Reversal) moraine. Similar to the date from Harberton, these ages indicate that alpine ice in the eastern part of Tierra del Fuego had already begun to retreat by ~17.8 ka and had receded to at least its Late-Glacial position by ~16.7 ka (Table 2; Fig. 3A).

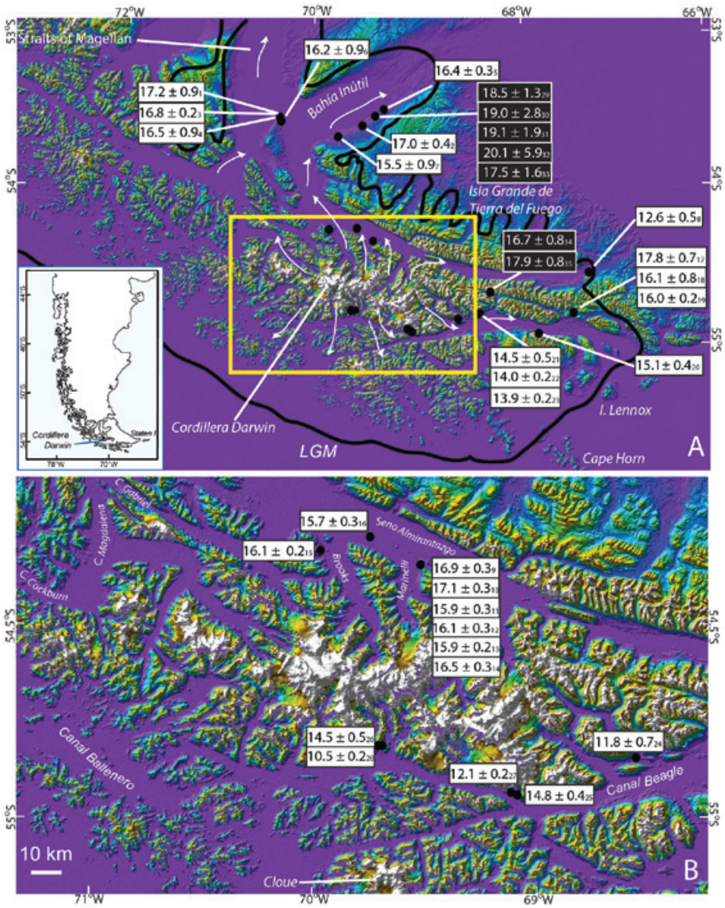

Figure 3. Chronologic constraints on the timing of ice recession in Tierra del Fuego during the last termination. Dates on black background are ^{10}Be surface exposure ages and afford actual ages of moraines and erratics that record former ice position (Table 2). Dates on white background are minimum-limiting radiocarbon ages for deglaciation (Table 1).

Available evidence from Cordillera Darwin suggests only modest ice advance during the subsequent Antarctic Cold Reversal. Although early reports suggested a major ACR advance to the vicinity of Isla Dawson on the north side of Cordillera Darwin (McCulloch *et al*., 2005a), sediment cores from Puntas Esperanza and Marinelli are at odds with that interpretation, as they lack any evidence for a readvance following initial deglaciation. The Punta Esperanza bog core, in particular, would have been covered by any ice that advanced north from Cordillera Darwin through Canal Whiteside to Isla Dawson. Therefore, we conclude that the deposits attributed to the ACR must date to an earlier time period. The only confirmed ACR-age moraines are from cirque glaciers in the Fuegian Andes, where the ice margins lay only 0.85-2.5 km beyond their present positions (Menounos *et al*., 2013). Moraines similar in appearance and position relative to the modern glaciers occur in central Cordillera Darwin; work is under way to determine their age (Hall *et al*., in prep.).

In summary, available data on both sides of Cordillera Darwin, as well as in the Fuegian Andes, suggest rapid ice recession shortly after the start of Termination I (~18 ka), with retreat into the interior fjords no later than ~16.5 ka on the north side and at >~14.8 ka on the south flank of the mountain range. The icefield at that time appear to have retreated at least to its Late-Glacial position, if not behind the fronts of present-day glaciers. To put this recession in context, such a retreat resulted in a loss of >85% of the Brooks flowline in <~2000 years. Such a rapid recession is remarkably similar to that in earlier modelling studies by Hulton *et al*. (2002), who suggested that 80% of the icefield may have disappeared within 2000 years of the start of Termination I, based on application of a rapid 6ºC temperature warming in the model.

5. Mechanisms

What caused rapid recession of the Darwin icefield shortly after 18 ka? Although several factors can cause glaciers to retreat (rising air temperatures, decreased precipitation, rapid calving in a marine environment), available information favors a significant air-temperature increase, which caused a rapid rise in regional equilibrium-line altitudes (ELA). Numerous studies have shown the temperature-sensitivity of mountain glaciers (i.e., Oerlemans, 2005; Zemp *et al*., 2015), but the most pertinent here is an in-depth latitudinal study of Andean glaciers, including those in Cordillera Darwin. Using a surface energy-balance model, Sagredo *et al*. (2014) found that ELA is relatively insensitive to precipitation changes in humid, cloudy environments, such as Cordillera Darwin, because of the link between surface energy balance and atmospheric emissivity. They further calculated that a precipitation increase of ~75% (in an area already very wet) would be required to offset a 1ºC temperature rise in Cordillera Darwin (Sagredo *et al*., 2014). We thus feel comfortable with concluding that rapid ice recession in Cordillera Darwin during Termination I was due primarily to rising air temperatures and not to precipitation deficits. This interpretation is consistent not only with new Antarctic ice-core temperature records (e.g., WAIS Divide, Buizert *et al*., 2015; Fig. 4), but also with the marine record offshore of southwestern Chile, which shows a warming ocean at the same time (Lamy *et al*., 2004; Kaiser *et al*., 2005;

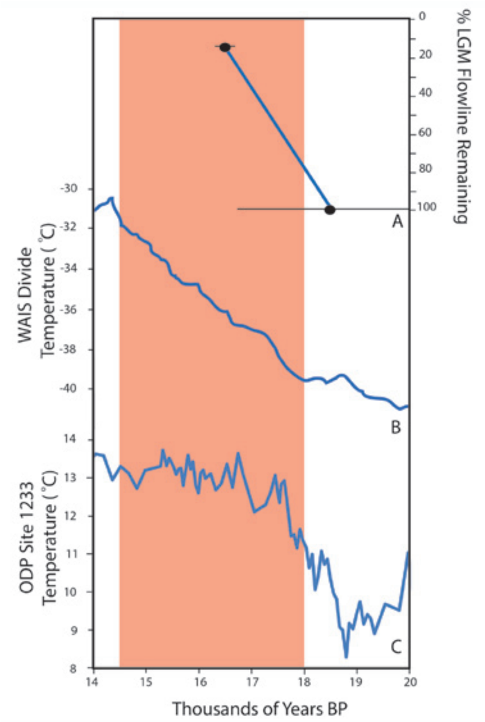

Figure 4. Retreat of the Cordillera Darwin icefield compared to marine sea-surface and atmospheric temperatures during the termination of the last ice age. A) Percent of the LGM flowline remaining, based on distance from the head of Brooks fjord to the Bahía Inútil "D" moraines. B) Air temperatures from the WAIS Divide ice core in West Antarctica, based on δD measurements calibrated against borehole temperatures (Buizert et al.*, 2015). C) Alkenone-based sea-surface temperatures for waters off Chile at site ODP 1233 (41°S; Lamy* et al.*, 2007). Red bar shows approximate timing of HS-1 in the North Atlantic region.*

Caniupán *et al.*, 2011; Saavedra-Pellitero *et al.*, 2011). Although the warm marine water did not directly impact much of the Cordillera Darwin icefield through melting at the grounding line during initial deglaciation [the sea did not flood the Straits of Magellan and Canal Beagle until later (e.g., Bujalesky *et al.*, 1997), and much of the glaciated continental shelf was above sea level], ocean and atmospheric temperatures are commonly linked in this region (e.g., McKinnon *et al.*, 2013). Thus, the rapid recession of the Cordillera Darwin icefield at ~18 ka likely was a symptom of rapidly warming climate during Termination I.

6. Summary

The major pulse of deglaciation of Tierra del Fuego commenced at ~18 ka, with recession of the Cordillera Darwin icefield documented from both Bahía Inútil in the north and Canal Beagle in the south. Alpine glaciers in the Fuegian Andes also likely retreated at that time. Radiocarbon ages from the interior regions of Cordillera Darwin suggest ice in at least some locations had retreated close to its present-day limit as early as ~16.5 ka. The most likely cause for such rapid ice retreat was rising atmospheric temperatures at the start of Termination I.

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References

Anderson, R.F., Ali, S., Bradtmiller, L., Nielsen, S.H.H., Fleisher, M.Q., Anderson, B.E., Burckle, L.H. 2009. Wind-driven upwelling in the Southern Ocean and the deglacial rise in atmospheric CO_2. *Science* 323 (5920), 1443-1448. http://doi.org/10.1126/science.1167441.

Balco, G., Stone, J.O., Lifton, N.A., Dunai, T.J. 2008. A complete and easily accessible means of calculating surface exposure ages or erosion rates from ^{10}Be and ^{26}Al measurements. *Quaternary Geochronology* 3 (3), 174-195. http://doi.org/10.1016/j.quageo.2007.12.001.

Bentley, M.J., Sugden, D., Hulton, N.R.J., McCulloch, R.D. 2005. The landforms and pattern of deglaciation in the Strait of Magellan and Bahía Inútil, southernmost South America. *Geografiska Annaler* 87A (2), 313-333. http://doi.org/10.1111/j.0435-3676.2005.00261.x.

Björck, S., Rundgren, M., Ljung, K., Unkel, I., Wallin, Å. 2012. Multi-proxy analyses of a peat bog on Isla de los Estados, easternmost Tierra del Fuego: a unique record of the variable Southern Hemisphere westerlies since the last deglaciation. *Quaternary Science Reviews* 42, 1-14. http://doi.org/10.1016/j.quascirev.2012.03.015.

Boyd, B.L., Anderson, J.B., Wellner, J.S., Fernandez, R.A. 2008. The sedimentary record of glacial retreat, Marinelli Fjord, Patagonia: Regional correlations and climate ties. *Marine Geology* 255 (3-4), 165-178. http://doi.org/10.1016/j.margeo.2008.09.001.

Broecker, W. 1998. Paleocean circulation during the last deglaciation: A bipolar seesaw? *Paleoceanography* 13 (2), 119-121. http://doi.org/10.1029/97PA03707.

Buizert, C., Cuffey, K.M., Severinghaus, J.P., Baggenstos, D., Fudge, T.J., Steig, E.J., Markle, B.R., Winstrup, M., Rhodes, R.H., Brook, E.J., Sowers, T.A., Clow, G.D., Cheng, H., Edwards, R.L., Sigl, M., McConnell, J.R., Taylor, K.C. 2015. The WAIS Divide deep ice core WD2014 chronology — Part 1: Methane synchronization (68-31 ka BP) and the gas age-ice age difference. *Climate of the Past* 11, 153-173. http://doi.org/10.5194/cp-11-153-2015.

Bujalesky, G. 2011. The flood of the Beagle Valley (11,000 yr BP), Tierra del Fuego. *Anales Instituto Patagonia* 39 (1), 5-21. http://doi.org/10.4067/S0718-686X2011000100001.

Bujalesky, G., Heusser, C., Coronato, A., Roig, C., Rabassa, J. 1997. Pleistocene glaciolacustrine sedimentation at Lago Fagnano, Andes of Tierra del Fuego, southernmost South America. *Quaternary Science Reviews* 16, 767-778. http://doi.org/10.1016/S0277-3791(97)00018-8.

Caldenius, C.C. 1932. Las glaciaciones Cuaternarias en la Patagonia y Tierra del Fuego. *Geografiska Annaler* 14, 1-164 (English summary, p. 144-157).

Caniupán, M., Lamy, F., Lange, C.B., Kaiser, J., Arz, H., Killian, R., Baeza, O. 2011. Millennial-scale sea-surface temperature and Patagonian Ice Sheet changes off southernmost Chile (53ºS) over the past ~60 kyr. *Paleoceanography* 26, PA3221. http://doi.org/10.1029/2010PA002049.

Clapperton, C., Sugden, D., Kaufman, D.S., McCulloch, R.D. 1995. The last glaciation in central Magellan Strait, southernmost Chile. *Quaternary Research* 44 (2), 133-148. http://doi.org/10.1016/qres.1995.1058.

Coronato, A., Salemme, M., Rabassa, J. 1999. Palaeoenvironmental conditions during the early peopling of Southernmost South America (Late Glacial-Early Holocene, 14-8 ka B.P.). *Quaternary International* 53/54, 77-92. http://doi.org/10.1016/S1040-6182(98)00009-3.

Coronato, A., Seppälä, M., Ponce, J.F., Rabassa, J. 2009. Glacial geomorphology of the Pleistocene Lake Fagnano ice lobe, Tierra del Fuego, southern South America. *Geomorphology* 112 (1-2), 67-81. http://doi.org/10.1016/j.geomorph.2009.05.005.

Darvill, C.M., Stokes, C.R., Bentley, M.J., Lovell, H. 2014. A glacial geomorphological map of the southernmost ice lobes of Patagonia: The Bahía Inútil – San Sebastían, Magellan, Otway, Skyring, and Río Gallegos lobes. *Journal of Maps* 10 (3), 500-520. http://doi.org/10.1080/17445647. 2014.890134.

Darvill, C.M., Bentley, M.J., Stokes, C.R. 2015. Geomorphology and weathering characteristics of erratic boulder trains on Tierra del Fuego, southernmost South America: Implications for dating of glacial deposits. *Geomorphology* 228, 382-397. http://doi.org/10.1016/j.geomorph.2014.09.017.

Denton, G., Anderson, R.F., Toggweiler, J.R., Edwards, R.L., Schaefer, J., Putnam, A. 2010. The last glacial termination. *Science* 326 (5986), 1652-1656. http://doi.org/10.1126/science.1184119.

Denton, G., Heusser, C., Lowell, T., Moreno, P., Andersen, B.G., Heusser, L.E., Schlüchter, C., Marchant, D. 1999a. Interhemispheric linkage of paleoclimate during the last glaciation. *Geografiska Annaler* 81A (2), 107-153. http://doi.org/10.1111/1468-0459.00055.

Denton, G., Lowell, T., Heusser, C., Schlüchter, C., Andersen, B.G., Heusser, L., Moreno, P., Marchant, D. 1999b. Geomorphology, stratigraphy, and radiocarbon chronology of Llanquihue drift in the area of the southern Lake District, Seno Reloncaví, and Isla Grande de Chiloé, Chile. *Geografiska Annaler* 81A (2), 167-229. http://doi.org/10.1111/1468-0459.00057.

Evenson, E., Burkhart, P., Gosse, J., Baker, G., Jackofsky, D., Meglioli, A., Dalziel, I., Kraus, S., Alley, R., Berti, C. 2009. Enigmatic boulder trains, supraglacial rock avalanches, and the origin of "Darwin's boulders," Tierra del Fuego. *GSA Today* 19, 4-10. http://doi.org/10.1130/GSATG72A.1.

Fontana, S.L., Bennett, K.D. 2012. Postglacial vegetation dynamics of western Tierra del Fuego. *The Holocene* 22, 1337-1350. http://doi.org/10.1177/0959683612444144.

Hall, B.L., Porter, C.T., Denton, G.H., Lowell, T.V., Bromley, G.R.M. 2013. Extensive recession of Cordillera Darwin glaciers in southernmost South America during Heinrich Stadial 1. *Quaternary Science Reviews* 62, 49-55. http://doi.org/10.1016/j.quascirev.2012.11.026.

Heusser, C. 1989a. Climate and chronology of Antarctica and adjacent South America over the past 30,000 yr. *Palaeogeography, Palaeoclimatology, Palaeoecology* 76 (1-2), 31-37. http://doi.org/10.1016/0031-0182(89)90101-6.

Heusser, C. 1989b. Late Quaternary vegetation and climate of southern Tierra del Fuego. *Quaternary Research* 31, 396-406. http://doi.org/10.1016/0033-5894(89)90047-1.

Heusser, C. 1998. Deglacial palaeoclimate of the American sector of the Southern Ocean. Late Glacial-Holocene records from the latitude of Canal Beagle (55ºS), Argentine Tierra del Fuego. *Palaeogeography, Palaeoclimatology, Palaeoecology* 141 (3-4), 277-301. http://doi.org/10.1016/S0031-0182(98)00053-4.

Heusser, C. 2003. Ice Age Southern Andes: A chronicle of palaeoecological events. Volume 3.Elsevier, Netherlands.

Holmlund, P., Fuenzalida, H. 1995. Anomalous glacier responses to 20th century climatic changes in Darwin Cordillera, southern Chile. *Journal of Glaciology* 41 (139), 465-473. http://doi.org/10.3198/1995JoG41-139-465-473.

Hulton, N.R.J., Purves, R.S., McCulloch, R.D., Sugden, D.E., Bentley, M.J. 2002. The Last Glacial Maximum and deglaciation in southern South America. *Quaternary Science Reviews* 21: 233-241. http://doi.org/10.1016/S0277-3791(01)00103-2.

Huybers, P., Denton, G. 2008. Antarctic temperature at orbital timescales controlled by local summer duration. *Nature Geoscience* 1, 787-792. http://doi.org/10.1038/ngeo311.

Kaiser, J., Lamy, F., Hebbeln, D. 2005. A 70-kyr sea surface temperature record off southern Chile (Ocean Drilling Program Site 1233). *Paleoceanography* 20, PA4009. http://doi.org/10.1029/2005PA001146.

Kaplan, M.R., Coronato, A., Hulton, N.R.J., Rabassa, J.O., Kubik, P.W., Freeman, S.P.H.T. 2007. Cosmogenic nuclide measurements in southernmost South America and implications for landscape change. *Geomorphology* 87, 284-301. http://doi.org/10.1016/j.geomorph.2006.10.005

Kaplan, M., Fogwill, C., Sugden, D., Hulton, N.R.J., Kubik, P., Freeman, S.P.H.T. 2008a. Southern Patagonian glacial chronology for the last glacial period and implications for Southern Ocean climate. *Quaternary Science Reviews* 27 (3-4), 284-294. http://doi.org/10.1016/j.quascirev.2007.09.013.

Kaplan, M., Moreno, P.I., Rojas, M. 2008b. Glacial dynamics in southernmost South America during Marine Isotope Stage 5e to the Younger Dryas chron: a brief review with a focus on cosmogenic nuclide measurements. *Journal of Quaternary Science* 23 (6-7), 649-658. http://doi.org/10.1002/jqs.1209.

Kaplan, M., Strelin, J., Schaefer, J., Denton, G., Finkel, R., Schwartz, R., Putnam, M., Vandergoes, M., Goehring, B., Travis, S. 2011. In-situ cosmogenic ^{10}Be production rate at Lago Argentino, Patagonia: Implications for late-glacial climate chronology. *Earth and Planetary Science Letters* 309 (1-2), 21-32. http://doi.org/10.1016/j.epsl.2011.06.018.

Kohfeld, K.E., Graham, R.M., de Boer, A.M., Sime, L.C., Wolff, E.W.,Le Quére, C., Bopp, L. 2013. Southern Hemisphere westerly wind changes during the Last Glacial Maximum: paleo-data synthesis. *Quaternary Science Reviews* 68, 76-95. http://doi.org/10.1016/j.quascirev.2013.01.017.

Lal, D. 1991. Cosmic ray labeling of erosion surfaces: *in situ* nuclide production rates and erosion models. *Earth and Planetary Science Letters* 104 (2-4), 424-439. http://doi.org/10.1016/0012-821X(91)90220-C.

Lamy, F., Kaiser, J., Ninnemann, U., Hebbeln, D., Arz, H., Stoner, J. 2004. Antarctic timing of surface water changes off Chile and Patagonian Ice Sheet response. *Science* 304 (5679), 1959-1962. http://doi.org/10.1126/science.1097863.

Lamy, F., Kaiser, J., Arz, H.W., Hebbeln, D., Ninnemann, U., Timm, O., Timmermann, A., Toggweiler, R. 2007. Modulation of the bipolar seesaw in the southeast Pacific during Termination I. *Earth and Planetary Science Letters* 259 (3-4), 400-413. http://doi.org/10.1016/j.epsl.2007.04.040.

Lliljequist, G. 1970. Klimatologie: Stockholm, Generalstabens Litografiska Anstalt.

Markgraf, V., Huber, U. 2010. Late and postglacial vegetation and fire history in southern Patagonia and Tierra del Fuego. *Palaeogeography, Palaeoclimatology, Palaeoecology* 297, 351-366. http://doi.org/10.1016/j.palaeo.2010.08.013.

McCulloch, R.D., Bentley, M.J. 1998. Late-glacial ice advances in the Strait of Magellan, southern Chile. *Quaternary Science Reviews* 17, 775-787. http://doi.org/10.1016/S0277-3791(97)00074-7.

McCulloch, R.D., Bentley, M.J., Tipping, R.M., Clapperton, C. 2005a. Evidence for late-glacial ice dammed lakes in the central Strait of Magellan and Bahía Inútil, southernmost South America. *Geografiska Annaler* 87A (2), 335-362. http://doi.org/j.0435-3676.2005.00262.x.

McCulloch, R.D., Fogwill, C., Sugden, D., Bentley, M.J., Kubik, P. 2005b. Chronology of the last glaciation in the central Strait of Magellan and Bahía Inútil, southernmost South America. *Geografiska Annaler* 87A (2), 289-312. http://doi.org/j.0435-3676.2005.00260.x.

McKinnon, K.A., Stine, A., Huybers, P. 2013. The spatial structure of the annual cycle in surface temperature: amplitude, phase, and Lagrangian history. *Journal of Climate* 26, 7852-7862. http://doi.org/10.1175/JCLI-D-13-00021.1.

McManus, J., Francois, R., Gherardi, J.M., Keigwin, L., Brown-Leger, S. 2004. Collapse and rapid resumption of Atlantic meridional circulation linked to deglacial climate changes. *Nature* 428, 834-837. http://doi.org/10.1038/nature02494.

Meglioli, A. 1992. *Glacial geology of southernmost Patagonia, the Strait of Magellan and northern Tierra del Fuego*. Ph.D. Dissertation, Lehigh University, Bethlehem, PA.

Menounos, B., Clague, J.J., Osborn, G., Thompson Davis, P., Ponce, F., Goehring, B., Maurer, M., Rabassa, R., Coronato, A., Marr, R. 2013. Latest Pleistocene and Holocene glacier fluctuations in southernmost Tierra del Fuego, Argentina. *Quaternary Science Reviews* 77, 70-79. http://doi.org/10.1016/j.quascirev.2013.07.008.

Mix, A.C, Bard, E., Schneider, R. 2001. Environmental processes of the last ice age: land, oceans, glaciers (EPILOG). *Quaternary Science Reviews* 20, 627-657. http://doi.org/10.1016/S0277-3791(00)00145-1.

Möller, P., Hjort, C., Björck, S., Rabassa, J., Ponce, J.F. 2010. Late Quaternary glaciation history of Isla de los Estados, southeasternmost South America. *Quaternary Research* 73, 521-534. http://doi.org/10.1016/j.yqres.2010.02.004.

Moreno, P.I., Kaplan, M., François, J.P., Villa-Martínez, R.P., Moy, C.M., Stern, C., Kubik, P. 2009. Renewed glacial activity during the Antarctic Cold Reversal and persistence of cold conditions until 11.5 ka in SW Patagonia. *Geology* 37 (4), 375-378. http://doi.org/10.1130/G25399A.1.

Moreno, P.I., Villa-Martínez, R., Cárdenas, M.L., Sagredo, E.A. 2012. Deglacial changes of the southern margin of the southern westerly winds revealed by terrestrial records from SW Patagonia (52ºS). *Quaternary Science Reviews* 41, 1-21. http://doi.org/10.1016/j.quascirev.2012.02.002.

Oerlemans, J. 2005. Extracting a Climate Signal from 169 Glacier Records. *Science* 308 (5722), 675-677. http://doi.org/10.1126/science.1107046.

Rabassa, J. 2008. Late Cenozoic glaciations in Patagonia and Tierra del Fuego. In: J. Rabassa (Ed.), *The Late Cenozoic of Patagonia and Tierra del Fuego*, *Developments in Quaternary Sciences* 11, 151-204. http://doi.org/10.1016/S1571-0866(07)10008-7.

Rabassa, J., Coronato, A., Bujalesky, C., Roig, F., Salemme, M., Meglioli, A., Heusser, C., Gordillo, S., Borromei, A., Quatrocchio, M.J. 2000. Quaternary of Tierra del Fuego, southernmost South America: an updated review. *Quaternary International* 68-71, 217-240. http://doi.org/10.1016/S1040-6182(00)00046-X.

Rabassa, J., Coronato, A., Martínez, O. 2011. Late Cenozoic glaciations in Patagonia and Tierra del Fuego: an updated review. *Biological Journal of the Linnean Society* 103, 316-335. http://doi.org/10.1111/j.1095-8312.2011.01681.x.

Rabassa, J., Heusser, C., Rutter, N. 1990. Late-glacial and Holocene of Argentine Tierra del Fuego. *Quaternary of South America and Subantarctic Islands* 7, 327-351.

Rabassa, J., Heusser, C., Rutter, N. 1989. Late Glacial and Holocene of Argentina, Tierra del Fuego. *Quaternary of South America & Antarctic Peninsula*, 7, 327-351, A.A. Balkema Publishers, Rotterdam.

Reimer, P., Bard, E., Bayliss, A., Beck, J.W., Blackwell, P.G., Bronk Ramsey, C., Buck, C.E., Cheng, H., Edwards, R.L., Friedrich, M., Grootes, P.M., Guilderson, T.P., Haflidason, H., Hajdas, I., Hatté, C., Heaton, T.J., Hoffmann, D.L., Hogg, A., Hughen, K.A., Kaiser, K.F., Kromer, B., Manning, S.W., Niu, M., Reimer, R.W., Richards, D.A., Scott, E.M., Southon, J.R., Staff, R.A., Turney, C.S.M., van der Plicht, J. 2013. IntCal13 and Marine13 Radiocarbon age calibration curves 0-50,000 years cal BP. *Radiocarbon* 55 (4), 1869-1887. http://doi.org/10.2458/azu_js_rc.55.16947.

Saavedra-Pellitero, M., Flores, J.A., Lamy, F., Sierro, F.J., Cortina, A. 2011. Coccolithophore estimates of paleotemperature and paleoproductivity changes in the southeast Pacific over the past ~27kyr. *Paleoceanography* 26 (1). http://doi.org/10.1029/2009PA001824.

Sagredo, E.A., Rupper, S., Lowell, T.V. 2014. Sensitivities of the equilibrium line altitude to temperature and precipitation changes along the Andes. *Quaternary Research* 81 (2), 355-366. http://doi.org/10.1016/j.yqres.2014.01.008.

Stern, C.R. 2008. Holocene tephrochronology record of large explosive eruptions in the southernmost Patagonian Andes. *Bulletin of Volcanology* 70 (4), 435-454. http://doi.org/10.1007/s00445-007-0148-z.

Stone, J.O. 2000. Air pressure and cosmogenic isotope production. *Journal of Geophysical Research* 105 (B10), 23753-23759. http://doi.org/10.1029/2000JB900181.

Strelin, J., Denton, G., Vandergoes, M., Ninnemann, U., Putnam, A. 2011. Radiocarbon chronology of the late-glacial Puerto Bandera moraines, Southern Patagonian Icefield, Argentina. *Quaternary Science Reviews* 30 (19-20), 2551-2569. http://doi.org/10.1016/j.quascirev.2011.05.004.

Toggweiler, J.R., Russell, J.L., Carson, S.R. 2006. Mid-latitude westerlies, atmospheric CO_2, and climate change during the ice ages. *Paleoceanography* 21, PA2005. http://doi.org/10.1029/2005PA001154.

Tuhkanen, S. 1992. The climate of Tierra del Fuego from a vegetation geographical point of view and its ecoclimatic counterparts elsewhere. *Acta Botánica Fennica* 125, 4-17.

Unkel, I., Björck, S., Wohlfarth, B. 2008. Deglacial environmental changes on Isla de los Estados (54.5 °S), southeastern Tierra del Fuego. *Quaternary Science Reviews* 27 (15-16), 1541-1554. http://doi.org/10.1016/j.quascirev.2008.05.004.

Vanneste, H., De Vleeschouwer, F., Martínez-Cortizas, A., von Scheffer, C., Piotrowska, N., Coronato, A., Le Roux, G. 2015. Late-glacial elevated dust deposition linked to westerly wind shifts in southern South America. *Nature Scientific Reports* 5, 11670. http://doi.org/10.1038/srep11670.

Zemp, M., Frey, H., Gärtner-Roer, I., Nussbaumer, S.U., Hoelzle, M., Paul, F., Haeberli, W., Denzinger, F., Ahlstrom, A.P., Anderson, B., Balracharya, S., Baroni, C., Braun, L.N., Cáceres, B.E., Casassa, G., Cobos, G., Dávila, L.R., Delgado Granados, H., Demuth, M.N., Espizua, L., Fischer, A., Fujita, K., Gadek, B., Ghazanfar, A., Hagen, J.O., Holmlund, P., Karimi, N., Li, Z., Pelto, M., Pitte, P., Popovnin, V.V., Portocarrero, C.A., Prinz, R., Sangewar, C.V., Severskiy, I., Sigurdsson, O., Soruco, A., Usubaliev, R., Vincent, C. 2015. Historically unprecedented global glacier decline in the early 21st century. *Journal of Glaciology* 61 (228), 745-761. http://doi.org/10.3189/2015JoG15J017.