

Little Ice Age and recent glacier advances in the Cordillera Darwin, Tierra del Fuego, Chile

Pequeña Edad de Hielo y los avances recientes en los glaciares de la Cordillera Darwin, Tierra del Fuego, Chile

Johannes Koch¹

Abstract

Preliminary fieldwork provides evidence for glacier advances in the Cordillera Darwin during the 'classic' Little Ice Age as well as in the late 20th and the early 21st centuries. Little Ice Age advances have been reported at nearby sites in the Patagonian Andes, but previous research claimed that glaciers of the Cordillera Darwin did not advance during 'classic' Little Ice Age time, but earlier. The present study indicates that glaciers in the Cordillera Darwin likely followed a similar Little Ice Age chronology as most glaciers in the Patagonian Andes. The recent glacier advances of over 1.5 km are supported by previous work. The reason for these advances remains unclear, especially as clear warming trends are observed in southern South America in the 20th and early 21st centuries. However, similarly to glaciers in Norway and New Zealand that also advanced late in the 20th century, the strength of westerly atmospheric circulation has increased in Patagonia, which led to an increase in precipitation likely offsetting the increase in temperature.

Keywords:

Little Ice Age, recent glacier advances, Cordillera Darwin, southernmost South America.

Resumen

Trabajo preliminar de terreno proporciona evidencia de avances de glaciares en la Cordillera Darwin durante la clásica Pequeña Edad de Hielo, así como a finales del siglo 20 e inicios del 21. Los avances de la Pequeña Edad de Hielo han sido informados en sitios cercanos en los Andes Patagónicos, pero

investigaciones previas postulan que los glaciares de la Cordillera Darwin no avanzaron durante la "clásica" Pequeña Edad del Hielo, sino que lo hicieron antes de ésta. El presente estudio indica que los glaciares en la Cordillera Darwin probablemente siguieron una cronología Pequeña Edad de Hielo similar a la mayoría de los glaciares en los Andes Patagónicos. Avances recientes de glaciares de sobre 1.5 km son respaldados por trabajos previos. Las razones para estos avances permanecen sin clarificar, especialmente ante las claras tendencias al calentamiento en el sur de Sud América en los siglos 20 e inicios del 21. Sin embargo, en forma similar a glaciares en Noruega y Nueva Zelanda que también avanzaron a finales del siglo 20, la intensidad de la circulación atmosférica del oeste ha aumentado en la Patagonia, lo que lleva a un incremento en precipitación muy probablemente compensando el aumento en temperatura.

Palabras clave:

Pequeña Edad de Hielo, avances glaciares recientes, Cordillera Darwin, extremo sur de Sud América.

INTRODUCTION

The Little Ice Age, which spans much of the past millennium, was a period of variable, but

¹ Department of Geography, Kwantlen Polytechnic University, Surrey, British Columbia V3W 2M8, Canada. Joe.Koch@kpu.ca ✉

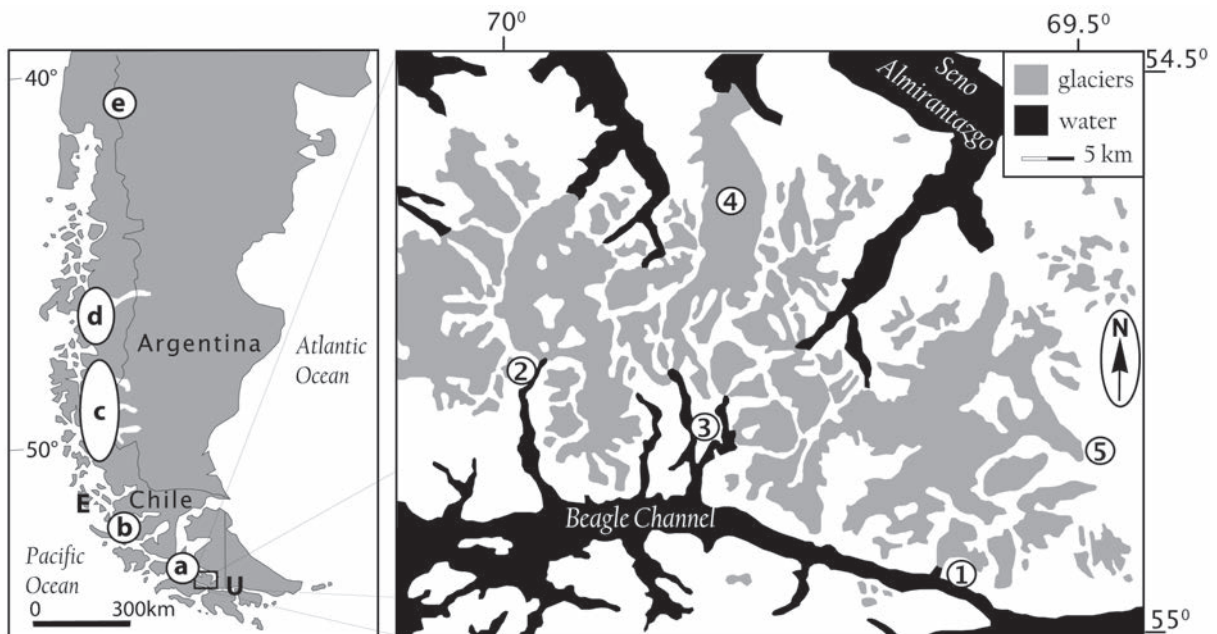


Fig. 1. Location map of Cordillera Darwin with location names mentioned in the text. 1, Glaciér Italia; 2, Seno Garibaldi with Ventisquero Garibaldi at the head of the fjord; 3, Bahía Pía with Glaciér Pía just east of the 3; 4, Ventisquero Marinelli; 5, Glaciér Stoppani. Inset map shows the location of Cordillera Darwin and other study and weather station sites mentioned in the text. a, Monte Sarmiento; b, Gran Campo Nevado; c, Hielo Patagónico Sur; d, Hielo Patagónico Norte; e, Monte Tronador, northern Patagonia; U, Ushuaia; E, Evangelistas.

generally cool climate when glaciers were more extensive than at other times in the Holocene (Grove, 1988). Evidence for this event is widespread and has been recorded in all glacierized mountains of the world (e.g., Luckman & Villalba, 2001; Holzhauser *et al.* 2005; Koch *et al.* 2007). The Little Ice Age comprises early advances between AD 1100 and 1300 and a series of late advances from 1700 to 1900 (Grove, 1988). The latter were generally more extensive and commonly obliterated older deposits. In extratropical South America some glacier advances were more extensive during the 17th century than during later advances (Villalba *et al.* 1990; Koch & Kilian, 2005; Strelin *et al.* 2008; Masiokas *et al.* 2009b), but more data is needed to fully evaluate this situation. Available data suggest synchronous glacier behaviour during the Little Ice Age on a centennial timescale from Tierra del Fuego to Alaska (Luckman & Villalba, 2001), but many glaciers have not been studied, and well-dated records of Little Ice Age glacier fluctuations are still needed (Luckman & Villalba, 2001; Masiokas *et al.* 2009b). Very little previous research in Patagonia has concentrated on Little

Ice Age glacier fluctuations (Villalba *et al.* 1990; Winchester *et al.* 2001; Koch & Kilian, 2005; Aravena, 2007; Masiokas *et al.* 2009a, b, 2010), even though the Patagonian Andes, with glaciers reaching well below treeline, show great promise for high quality data (Hall *et al.* 2011; Maurer *et al.* 2012).

Glacier fluctuations during the 20th century have been documented from photographic and historical evidence, and detailed reconstructions are available for many glaciers around the world, most of which generally receded during the 20th century (Dyurgerov & Meier, 2000; Oerleman, 2005), as did most in Patagonia (Warren & Sugden, 1993; Warren, 1994; Holmlund & Fuenzalida, 1995; Aniya, 1999; Rignot *et al.* 2003; Möller *et al.* 2007). Retreat dominated between the 1870s and about 1920. Stillstands and readvances occurred between 1920 and the 1960s, particularly in the 1930s and 1940s. Most glaciers in Patagonia have retreated since the 1960s, some at extraordinary rates. Exceptions to this general pattern include Perito Moreno Glacier, an eastern outlet glacier of the Southern Patagonian Icefield, which remains

near its Neoglacial maximum (Warren, 1994; Minowa *et al.* 2015), and Glaciar Pio XI, a western outlet glacier of the Southern Patagonian Icefield that advanced over 11 km since 1944 and reached its maximum Holocene extent (Rivera *et al.* 1997) before it started to retreat sometime during the past decade (Koch, pers. obs in March 2006).

Glaciers in the Cordillera Darwin on Tierra del Fuego, southernmost Chile, have been studied in the past (Liboutry, 1956; Holmlund & Fuenzalida, 1995; Kuylenskierna *et al.* 1996; Porter & Santana, 2003). Holmlund and Fuenzalida (1995) describe an asymmetric response of glaciers in the 20th century between glaciers with accumulation areas facing south and west and the ones facing north and east; the latter showed retreat while the former advanced or had stable fronts. Kuylenskierna *et al.* (1996) documented late Holocene glacier fluctuations of the Bahía Pía area along the Beagle Channel (55° S; Fig. 1) and their data indicate that the glacier system reached maxima sometime prior to 3060 BP, before 940 BP, and between 940 and 675 BP, and that there was no 'classic' Little Ice Age (17th to 19th centuries) advance for this area.

The objectives of this paper are to a) provide preliminary evidence of 'classic' Little Ice Age as well as late 20th and early 21st centuries glacier advances in the Cordillera Darwin along the Beagle Channel; b) reconcile the findings of this study with Kuylenskierna *et al.* (1996); and c) explain the recent glacier activity.

STUDY AREA AND METHODS

The Cordillera Darwin (ca. 54.5° S, 68.5–71.5° W), in the southwestern part of Tierra del Fuego, is the continuation of the Andes, which here trend west to east. The highest peak reaches nearly 2500 m, and nearly 50% of the mountain range is glacierized (Holmlund & Fuenzalida, 1995). In the southern part of the Cordillera, along the Beagle Channel, deep fiords dominate the landscape, and glaciers reach tidewater and calve (Fig. 1). Climate is humid and cool, with average annual temperature around 5° C and little annual variation (Núñez, 1994). Climate is dominated by strong westerlies and is highly oceanic on the west and south sides of the Cordillera but becomes increasingly conti-

nental towards the north and east. Precipitation is fairly equally distributed throughout the year, but decreases from about 7200 mm along the main divide of the Andes at Gran Campo Nevado (Schneider *et al.* 2003) to 500 mm at Ushuaia (Núñez, 1994). Vegetation is dominated by Magellanic Moorland and Magellanic Rainforest, which is dominated by *Nothofagus betuloides* and *Nothofagus antarctica*.

Preliminary fieldwork was conducted during a short visit to Glaciar Italia (Figs. 1, 2) and by observing eight more glaciers from a vessel in March 2006. At Glaciar Italia ten trees were cored to provide dating control. Furthermore, a tree recently killed by a glacier advance was also cored. Due to lack of time at the glacier, and the rather dense forest cover on the outermost moraine it is likely that the oldest trees were not cored and thus ages provide a minimum estimate for moraine formation. Ecesis (the time from surface stabilization to seedling germination; Sigafos and Hendricks, 1969; McCarthy & Luckman, 1993; Koch, 2009), and the time for trees to grow to coring height (McCarthy *et al.* 1991; Koch, 2009) have not been investigated in this study, and thus values from other locations in Patagonia (Koch & Kilian, 2005; Koch, 2009) are taken into account to provide better dating control on the moraine. Two cores from each tree were processed and analyzed following standard dendrochronological procedures (Stokes & Smiley, 1996). A master chronology was developed for all samples to be able to crossdate the floating chronology of the killed tree and thus provide a calendar date of the most recent advance.

Ventisquero Garibaldi was advancing into forest and a tributary glacier during visits in 2004, 2006, and 2008. Masiokas *et al.* (2009b: Fig. 9) report this advance and mapped extents for 2000, 2001, 2002, 2003, and 2007. Frontal extents from 2000, 2001, 2004, 2006, 2008, and 2013 were mapped on an airphoto by comparing distinctive features close to the glacier margins and along the fiord coastline that could be identified on the air and ground photographs from each of these years. Differences in photo scale, contrast, lighting, and photographic distortion result in possible errors of up to 20 m in the mapped margins, but allow a general reconstruction of the amount and rate of this advance over time.

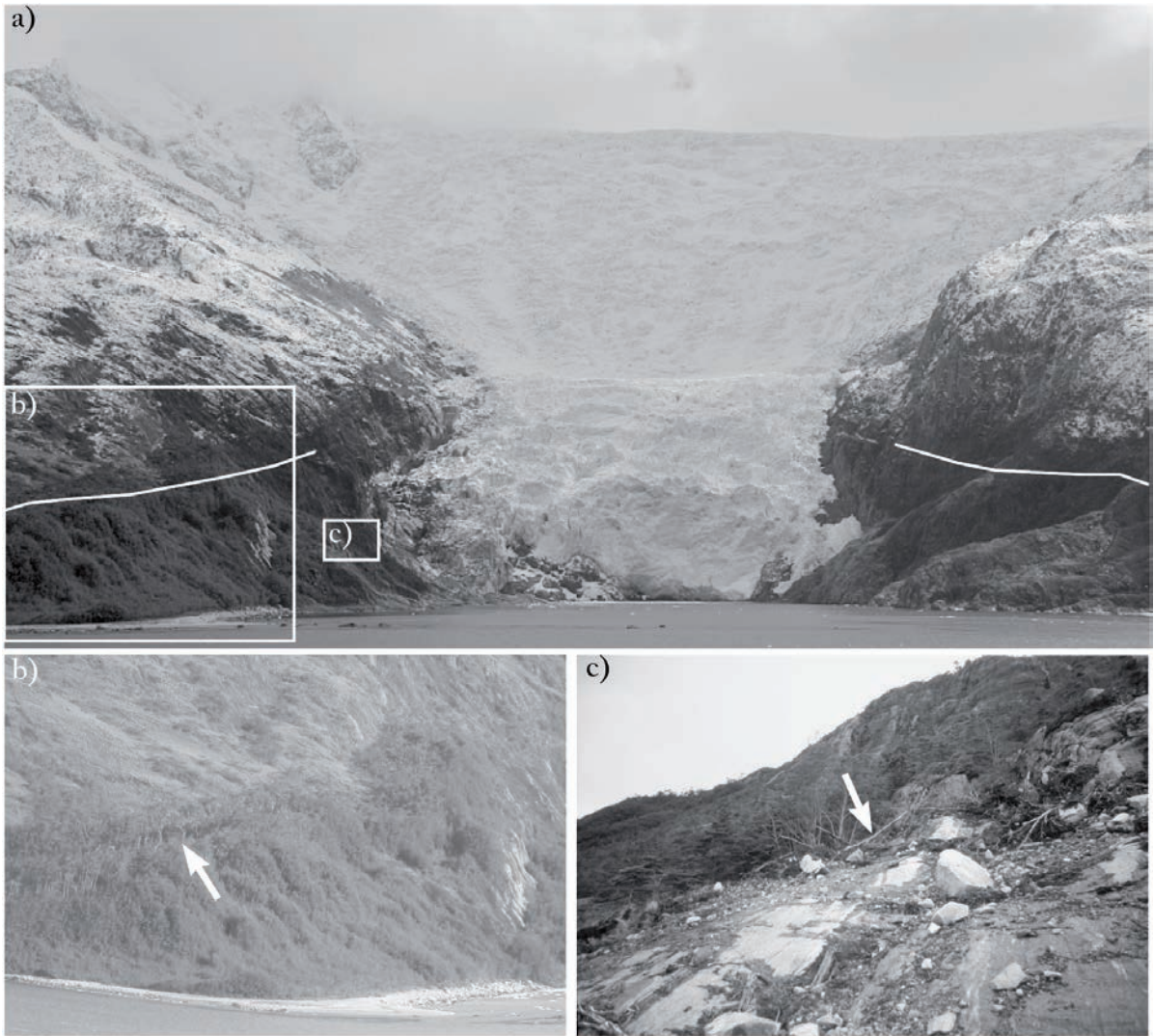


Fig. 2. (a) Photo of Glaciar Italia from the Beagle Channel looking north in December 2008. White lines are approximate extent of Little Ice Age advance indicated by a distinct break in vegetation. Locations of (b) and (c) are also indicated. (b) Distinct break in vegetation indicated by arrow. Similar vegetation breaks were observed at all other glaciers from the ground and on satellite photos. (c) Glaciar Italia advanced recently into forest killing and damaging trees as well as scraping off soil. Arrow indicates the tree that was sampled for dating.

RESULTS

Several glaciers on the southflank of Cordillera Darwin, along the Beagle Channel, were observed and a short amount of time was spent on shore at Glaciar Italia (Figs. 1, 2). Two distinct breaks in the forest vegetation are interpreted to represent an area not affected by glacier activity in the past few centuries and therefore outside the glacier forefield, a forest in a younger successional

stage indicating ice cover within the past couple centuries, and an area that is still free of trees (Fig. 2a, b). No moraines were visible outside the glacier forefield, but subdued moraines are observed at the vegetation break from older to younger forest. The outermost and most distinct of these moraines can be traced across the mouth of the little embayment that separates it from the Beagle Channel. Two cores each were taken from eight trees growing on this moraine, which represents the maximum Little

Ice Age advance, as well as from two trees that are growing in the older forest and thus outside the area covered by ice during the maximum Little Ice Age advance. The samples outside the forefield are interpreted to provide a maximum age for the outermost moraine, as these trees were not impacted by but were growing during the maximum Little Ice Age advance. The samples from the trees on the outermost moraine provide a minimum age for the maximum Little Ice Age advance. Samples from the trees outside the forefield yielded 257 and 288 rings, while trees on the outermost moraine ranged from 113 to 152 rings. Adding 15 years for ecesis and 5 years for growth to coring height provides AD1698 and AD1834 for the area just outside the forefield and the outermost moraine respectively. The ecesis value seems reasonable as previous studies suggest less than 20 years for Bahia Pía in the Cordillera Darwin (Holmlund & Fuenzalida, 1995) and about 15 years for Glaciar Lengua at Gran Campo Nevado (Koch & Kilian, 2005). Rings near the pith of all cores obtained were relatively narrow and thus slow growth to coring height is assumed (Koch, 2009). Values at Gran Campo Nevado varied from 2 to 7 years to reach 50 cm coring height (Koch & Kilian, 2005), thus 5 years seems appropriate.

Glaciar Italia shows clear evidence for a recent advance into forest and over soil (Fig. 2c), which is supported by observations from other forefields in the Cordillera Darwin of advancing glaciers in the late 20th century (Holmlund & Fuenzalida, 1995; Porter & Santana, 2003). The advance bulldozed into forest and killed and damaged trees. Bedrock is exposed from this advance on a bedrock knoll on the westside of the embayment, and the little soil that supported tree growth prior to this advance on the bedrock knoll is pushed into a small ridge that stands about 20 cm above the exposed bedrock. Trees that were growing on this bedrock knoll have been pushed ahead of the ice and into living trees beyond the reach of the advance. These pushed trees are tilted, some are nearly horizontal, rest against the living trees, and most of them lack any remaining foliage. Both *Nothofagus* species growing here are evergreen, and thus trees devoid of foliage were interpreted to be dead, while pushed trees that retained partial foliage were considered still

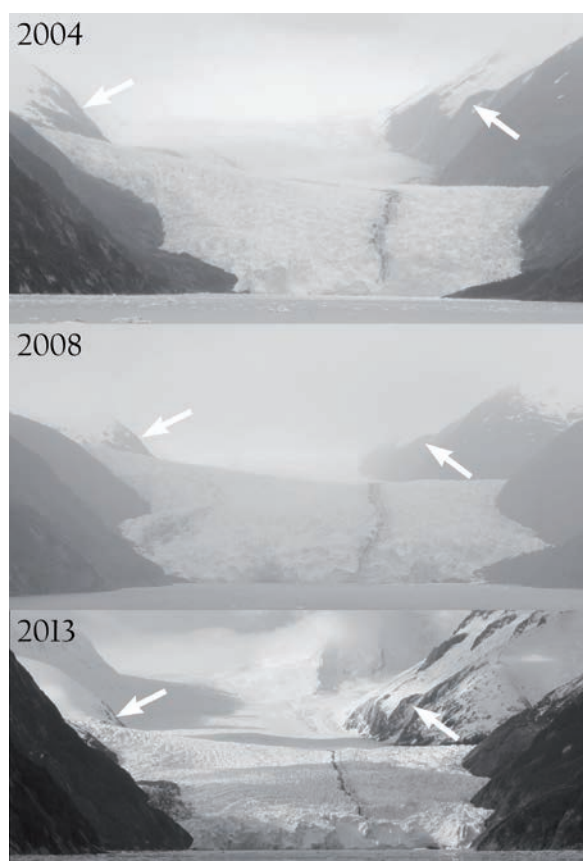


Fig. 3. Photo series documenting advance of Ventisquero Garibaldi between 2004 and 2013. Arrows point to the same locations in each photo.

alive. Two cores were taken from one of the trees with no foliage. The floating chronology, which spans 86 years, was crossdated with the living chronology ($r = 0.517$) and provides a kill date of 1999, indicating when this glacier advance ended. Since then Glaciar Italia has retreated by about 100 m and thinned by about 20 m and continues to retreat, as is the case for other glaciers on Tierra del Fuego (Holmlund & Fuenzalida, 1995; Strelin & Iturraspe, 2007). However, Ventisquero Garibaldi at the head of Seno Garibaldi (Figs. 1, 3) started its latest advance in 2001, which has continued at least until October 2013. Mapped extents in 2000, 2001, 2002, 2003, and 2007 (Masiokas *et al.* 2009b) are supplemented with extents in 2004, 2006, 2008, and 2013 (Fig. 3) to enable a reconstruction of the amount and rate of this advance (Table 1). Ventisquero Garibaldi, after retreating about 250 m between 2000 and

Table 1. Amounts and rates of frontal change of Ventisquero Garibaldi since 2000.

Period	Behaviour	Amount of change (m) ¹	Average rate of change (m/a)
2000-2001	retreat	~250	250
2001-2004 ²	advance	400	133
2004-2006	advance	500	250
2006-2008	advance	250	125
2008-2013	advance	580	116

¹ Values are rounded to the nearest 10 m.

² Glacier front behaviour between 2001 and 2004 was irregular with the western part of the tongue leading the advance in 2001-2002 and the eastern part catching up in 2002-2004.

2001, has advanced for over 1700 m between 2001 and 2013 at an average rate of 133 m/a (Table 1). Between 2004 and 2006 this rate nearly doubled to 250 m/a, possibly due to it starting to coalesce with a smaller tributary glacier from the west.

DISCUSSION AND CONCLUSIONS

In this study evidence for ‘classic’ late Little Ice Age activity was observed at nine glaciers along the Beagle Channel on the southside of the Cordillera Darwin. Preliminary data from Glaciar Italia shows that its outermost moraine was deposited between AD1698 and AD1834, with the latter date considered a more accurate age. At each of the other observed glacier forefields similar evidence is visible in the form of distinct breaks in the forest cover, especially between the mature forest cover outside the moraines and the forest cover inside the glacier forefield. On air photos and satellite scenes of Cordillera Darwin similar landforms and vegetation breaks seem to be present for most glaciers including glaciers on the north, west, and east sides, indicating that glaciers of Cordillera Darwin advanced during the late Little Ice Age. Furthermore, evidence from Ventisquero Marinelli on the northside of Cordillera Darwin (Fig. 1) shows that glaciers overrode forests within the past 400 years (Hall *et al.* 2011), and a study of wood mats in the northeast lateral moraine of Glaciar Stoppani on the eastside of Cordillera Darwin (Fig. 1) provides clear evidence for its most extensive Holocene advance in the early 18th century (Maurer *et al.* 2012).

These findings are in disagreement with a

previous study in Bahia Pía on the Beagle Channel (Fig. 1) on the south flank of Cordillera Darwin (Kuylenstierna *et al.* 1996). The glacier system in Bahia Pía reached its maximum for the last time between 940 ± 75 ¹⁴C years BP (AD1020-1165) and 675 ± 70 ¹⁴C years BP (AD1270-1395), and by 250 ± 70 ¹⁴C years BP (AD1515-1805) the glacier system had retreated by more than 15 km (Kuylenstierna *et al.* 1996). Kuylenstierna *et al.* (1996) concluded that these data provide evidence that there was no glacial advance in Bahia Pía during the global Little Ice Age maximum (seventeenth to nineteenth centuries). This contrasts with the findings of more recent studies and needs explanation. Their evidence is based on radiocarbon dates obtained on peat and macrofossils from proximal and distal sites of a terminal moraine for the older dates and from wood on a peat-till interface for the 250 ± 70 ¹⁴C years BP date. The calibrated range of the 250 BP date is AD1515-1805 (1 sigma) or AD1460-1820 (2 sigma), and for both sigma ranges there is a very low possibility, 0.062 and 0.081 respectively, that the date could be as young as AD1950. The potential problem with young radiocarbon dates is well known (Porter, 1981). This means the site could have been icefree as early as the late 15th century, but it also could have been icefree only since the early 19th century. Nonetheless, Kuylenstierna *et al.* (1996) use this age as evidence that the glaciers in Bahia Pía were not much more extensive during the global Little Ice Age maximum than at present. However, the site of the 250 BP date is about 3.5 km from the present glacier snout. Even if the site was icefree at its earliest calibrated time, it is possible that the glacier reached well beyond the site, as the site is

80-100 m above sea level, and thus the glacier could have thickened and advanced but stayed below the site. In both possible scenarios, that the 250 BP site only became icefree in the early 19th century or that it was icefree earlier, but the glacier reached farther down the fiord below the 250 BP site, it seems reasonable to assume that the glacier in Bahía Pía was more extensive than at present during the global Little Ice Age maximum. Furthermore, distinct trimlines and several moraine ridges are visible on ground photos of Glaciar Pía on the east arm of Bahía Pía (Fig. 1), and two distinct partial moraine ridges protrude into Bahía Pía up to 7 km from the present glacier snout. The trimlines and moraines appear similar to the ones observed at Glaciar Italia, thus providing convincing evidence of glaciers in Bahía Pía advancing during Little Ice Age times.

Glaciers in Cordillera Darwin underwent late Little Ice Age advances, as did glaciers elsewhere in the Patagonian Andes, including Glaciar Ema at Monte Sarmiento, ca. 100 km to the west (Strelin *et al.* 2008), Glaciar Lengua at Gran Campo Nevado, ca. 300 km to the northwest (Koch & Kilian, 2005), glaciers of the South and North Patagonian Icefields and their surroundings, ca. 600-1000 km to the north (e.g., Mercer, 1968, 1970; Marden & Clapperton, 1995; Winchester *et al.* 2001; Masiokas *et al.* 2009a), and glaciers in northern Patagonia ca. 1600 km to the north (Villalba *et al.* 1990; Masiokas *et al.* 2010). The majority of these glaciers show rather synchronous behaviour with the culmination of Little Ice Age glacier advances occurring between AD 1600 and 1700 indicating a common forcing (Luckman & Villalba, 2001; Koch & Kilian, 2005). It seems likely that the Bahía Pía glacier system was more extensive early during the Little Ice Age (between 940 ± 75 ¹⁴C years BP [AD1020-1165] and 675 ± 70 ¹⁴C years BP [AD1270-1395]), than during the late Little Ice Age, which appears to be in agreement with other glaciers in the Patagonian Andes (Villalba *et al.* 1990; Koch & Kilian, 2005; Strelin *et al.* 2008).

Some glaciers in the Cordillera Darwin were advancing in the late 20th century (Holmlund & Fuenzalida, 1995), and Glaciar Italia moved into forest and over soil at that time. Ventisquero Garibaldi started to advance in 2001 until at least

October 2013 for over 1.7 km (Fig. 3, Table 1). Why glaciers on the west and south flanks of Cordillera Darwin were advancing in the late 20th century and some continue to do so, while glaciers on the north and east flanks have retreated significantly (Holmlund & Fuenzalida, 1995; Porter & Santana, 2003) is not fully understood. Instrumental temperature variations in southern Patagonia show clear warming trends in the 20th century (Holmlund & Fuenzalida, 1995; Rosenblüth *et al.* 1995, 1997; Villalba *et al.* 2003). Annual precipitation amounts decreased significantly in northwestern and central Patagonia (Rosenblüth *et al.* 1995; Aravena & Luckman, 2009), and no clear trends are discernable in southern Patagonia nor in Ushuaia, the nearest weather station (Fig. 1; Holmlund & Fuenzalida, 1995; Aravena & Luckman, 2009). However, at Evangelistas (Fig. 1), the weather station most exposed to the strong westerlies, precipitation has increased almost threefold in the last two decades of the 20th century (Aravena & Luckman, 2009). Some of the glaciers that have remained stable or advanced are calving glaciers, and thus some authors argue that they might not record climatic conditions (Warren, 1993). However, the different pattern between the south and west flanks and the north and east flanks held true for land terminating glaciers in the late 20th century, and thus it is more likely that the difference in glacier behaviour is driven by climatic changes (Holmlund & Fuenzalida, 1995). Holmlund & Fuenzalida (1995) show that glacier behaviour on the north and east flanks can be explained with observed changes in climate, but west and south facing glaciers should also show overall recession. They argue that increased wind activity could account for windward glaciers to advance due to increased orographic precipitation, and leeward glaciers to retreat significantly due to föhn winds, as observed at Ventisquero Marinelli (Fig. 1) between 1992 and 2000 (average retreat of ~800 m/a; Porter & Santana, 2003). A southward shift of subtropical anticyclones displaces the cyclones towards the south, but at the same time strengthens the pressure gradient between the Hadley and polar cells, leading to higher wind activity and speeds (Holmlund & Fuenzalida, 1995). Some glaciers in New Zealand and Norway also advanced at the end of the 20th century (Chinn

et al. 2005). In maritime Norway advances started as early as the mid-1960s, but were pronounced from the mid-1980s until around 2000. In New Zealand advances lasted from the mid-1980s to around 2000. Chinn *et al.* (2005) point out that what these two areas have in common is their location in maritime climates dominated by strong westerly airflow. They conclude that an increase in the strength of the westerly circulation and an associated increase in precipitation can explain the glacier advances in New Zealand and Norway. The Southern Annular Mode, a measure of zonal pressure gradient between 40° S and 60° S, showed a positive trend between the mid-1960s to 2000 (Marshall *et al.* 2004), which implies an increase in strength or frequency of westerly winds at the latitude of the Cordillera Darwin. It thus appears that similar to glaciers in Norway and New Zealand, an increase of westerly airflow and an associated significant increase in precipitation apply to some maritime glaciers of the Cordillera Darwin, and that those conditions can offset increases in temperature, which could explain glacier behaviour on the windward side.

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