Documentary and tree-ring evidence for a long-term interval without ice impoundments from Glaciar Perito Moreno, Patagonia, Argentina

Claudia M Guerrido,[1,2] Ricardo Villalba[2] and Facundo Rojas[2]

Abstract
Glaciar Perito Moreno (hereafter GPM; 50°30′S and 72°50′W) is a major outlet glacier from the South Patagonia Icefield. In contrast to most Patagonian glaciers, glaciological studies indicate that GPM has been advancing or remained stable during the 20th century. The advances periodically block Canal de los Témpanos creating an ice dam that impounds Brazo Sur–Rico arms of Lago Argentino, raising their elevations, until the water is released in a major outburst flood. Documentary evidence indicates that GPM reached the coast of Península de Magallanes for the first time in 1917. However, the first major damming and rupture event occurred in 1936, when the flooding of the shorelines of Brazo Sur–Rico killed thousands of *Nothofagus* trees, some still standing dead today. Naturalists who visited the area before 1936 described dense forests extending downslope to the shoreline, confirming the evidence of photographs from 1899 to 1928 displaying no standing dead trees by the shores. Estimates of the water level in Brazo Sur–Rico during each glacier damming vary but indicate values of 10–12 m for the 1936–1948 events and maxima of 23.5 m for the 1954–1956 ice dams. There is evidence for 21 ice dams between 1936 and 2013 with an average interval of *c.* four years from 1936 to 1988 and *c.* two years between 2004 and 2012. However, ring counts from standing *Nothofagus* dead trees along the flooded shorelines indicate that the oldest trees killed by drowning were at least 250 years old providing evidence of no major damming and rupture events from *c.* 1650 to 1936. These data indicate that damming and outburst events by GPM, world-renowned processes, did not occur for a long-term period before 1936. Unlike most glaciers in Patagonia, GPM was less extensive in the 1700s and 1800s than it is today.

Introduction

Glaciar Perito Moreno (GPM) is the most studied glacier on the Argentinean side of the South Patagonian Icefield (hereafter SPI; Rott et al., 1988; Skvarca, 2002; Skvarca et al., 2004; Skvarca and Naruse, 1997, 2005; Stuefer et al., 2007). Unlike most outlet glaciers from the SPI, GPM has been advancing or remained stable since the early 20th century (Heim, 1951; Raffo et al., 1953; Skvarca, 2002). Successive advances of the glacier across the Canal de los Témpanos form a natural ice dam, blocking the flow of water from the Brazo Sur–Rico arms to Lago Argentino. The water accumulating upstream from the dam eventually discharges violently, breaking through the front of the glacier in events locally known as 'ruptures'. These impressive, semi-periodical ruptures of the glacier front have occurred a number of times over at least the last 80 years, but their early history is poorly defined.

The easy access to the spectacular 50–70 m tall and 3-km-wide glacier front, and the opportunity to view frequent calvings and occasional ice dam ruptures has resulted in an impressive flow of tourists to this region. Annual visitation has increased from *c.* 50,000 in 1992 to 80,000 in 2001 and approximately 400,000 in 2013 (National Park Administration data). The exceptional nature of this particular glacier and its surroundings has been internationally acknowledged in the 1981 UNESCO recognition of Parque Nacional Los Glaciares as World Heritage Site (http://whc.unesco.org/en/list/145).

Given the high tourist and scientific interest of this site, this paper reconstructs the occurrence of GPM natural dams, shoreline floods, and rupture events using historical and tree-ring records. The recent history and timing of these events has been extensively discussed elsewhere (Chinni and Warren, 2004; Skvarca and Naruse, 2005; Stuefer et al., 2007; Warren, 1994), but little is known about their earlier history and when these events began. We therefore use charts, drawings, and descriptions of the area by naturalists, scientists, and travelers to develop a chronology of natural dams and rupture events during the first

[1]Universidad de la Patagonia Austral, Argentina
[2]CCT Mendoza – CONICET, Argentina

Corresponding author:
Claudia M Guerrido, Universidad de la Patagonia Austral, Unidad Académica Río Turbio (UNPA UART), Av. Los Mineros 1260, CP 9407, Río Turbio, Santa Cruz, Argentina.
Email: claudiaguerrido@gmail.com

half of the 20th century. The earliest documented photographs of GPM date from 1899 to 1900 (Gallois, 1901; Hauthal, 1904; Prichard, 1902) and provide direct evidence of the characteristics of the shoreline around the Brazo Sur–Rico at that time. These images are used as indirect measures of damming events since trees along the shorelines are killed during flood events and become visible after the drainage of the ice-dammed lakes. In addition, we used conventional dendrochronological methods to determine the ages of these trees killed by flooding along the shorelines and provide evidence of a long-term period without ice damming by GPM prior to the 1930s.

Figure 1. Location of the study site showing Glaciar Perito Moreno (GPM) and the southern sector of Lago Argentino, Parque Nacional Los Glaciares, Argentina. Sampling sites for standing dead trees are indicated by red dots (see Table 1 for site codes). NASA Astronaut photograph ISS030-E-91253, acquired on 21 February 2012, at the time of the last GPM ice dam. The last rupture of GPM ice dam occurred in March 2012, few days after this image was taken. Note differences in water color between Lago Argentino and Brazo Sur–Rico arms during the impoundment event.

Materials and methods

Study site

GPM is located in southwestern Argentina in Parque Nacional Los Glaciares nearby the Península de Magallanes Provincial Reserve (50°30′S, 72°50′W). The glacier is one of the main eastern outlets of the SPI and terminates on a grounded calving front, which drains into Lago Argentino. The southern arm of Lago Argentino comprises the Canal de Los Témpanos (Iceberg Channel) and the Brazo Rico and Brazo Sur arms (Figure 1).

Methods and data

We used a combination of historical documents (Metcalfe et al., 2002; Prieto and Herrera, 2009) and tree-ring records (Fritts, 1976; Hughes et al., 2011) to reconstruct the history of damming events at GPM. The sources examined included reports of naturalists, explorers, and travelers, scientific publications, books, newspapers, and magazines. The archives consulted are listed in Supplementary Online Material (SOM) Table 1 (available online). We determined several variables from the analysis of documents, namely, (1) changes in the position of GPM's front, (2) rupture events of GPM ice dams, and (3) changes in water level in the Brazo Sur–Rico arms of Lago Argentino. Relevant indicators were (1) the distance between GPM and the Península de Magallanes, (2) date and length of dammed periods, (3) rupture event dates, and (4) measurements of water height in the impounded lake arms.

Historical photographs were sorted by date (SOM 1, available online) and, whenever possible, retaken from their original viewing points. Three photographs taken by members of the German Scientific Society in 1914 and by the Salesian priest Alberto de Agostini in 1928 were replicated following the methods proposed by Zumbühl and Holzhauser (1988). For these three photographs, (1) the date of the images was known, (2) the glacier and its surroundings were clearly depicted, and (3) the position of the photographer in the early photographs could be identified in the field.

Increment cores or partial cross sections were collected from standing dead trees in previously flooded areas along the Brazo Sur–Rico shorelines. Most samples were taken at breast height. However, given the difficulty of obtaining cross sections from large trees, the sampling height varied according to safety regulations for the use of the chainsaw. Collections were conducted at eight shoreline sites (Figure 1; Table 1). The number of samples taken per site ranges from 10 to 40, totalizing 92 samples. We avoid sampling trees with intense decay or erosion in the external sectors of the stem. Small portions of the bark were identified in some standing dead trees, suggesting none or minor erosion of the wood. The elevation of the base of each tree was determined in relation to the regular or reference lake level (i.e. the water level of Lago Argentino concurrent with that at Brazo Sur–Rico arms without ice dammings). Lago Argentino is an exoreic lake that drains into the South Atlantic Ocean through
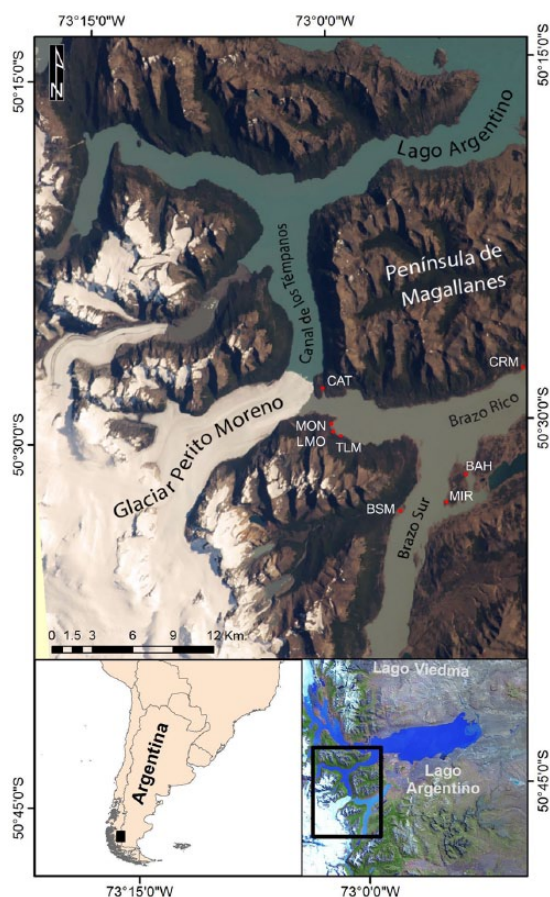
Table 1. Sampling sites of dead standings *Nothofagus* trees.

| Site	ID	Latitude S	Longitude W	No. of trees
BAHIA Brazo Sur	BAH	50°31′59.1	72°52′10.9	10
MIRADOR Brazo Sur	MIR	50°32′36.1	72°53′23.8	17
BRAZO SUR Brazo Sur	BSM	50°34′21.1	72°57′27.1	9
CATALANA Brazo Rico	CAT	50°28′39.6	73°01′27.0	14
CAMPING RIO MITRE Brazo Rico	CRM	50°26′47.4	72°46′17.1	3
LAS MONEDAS Transect I Brazo Rico	MON	50°29′53.1	73°00′58.1	10
LAS MONEDAS Transect II Brazo Rico	LMO	50°30′06.0	73°00′57.5	14
LAS MONEDAS Transect III Brazo Rico	TLM	50°30′31.4	72°59′50.7	15
TOTAL				92
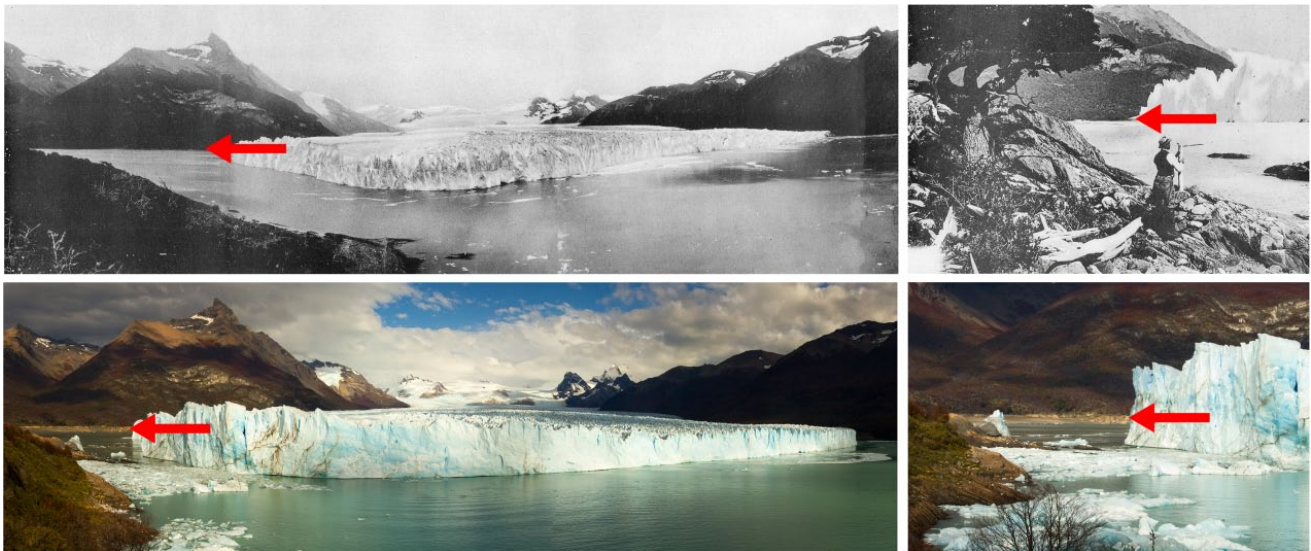
Figure 2. Comparison between paired early 20th-century and contemporary photographs of Glaciar Perito Moreno. Note the dense forest extending downslope to the shoreline and the barren (i.e. treeless) shoreline in the Brazo Rico arm on the upper and lower photographs, respectively. The upper photographs were taken in 1914 by the German Scientific Society Expedition (Kölliker et al., 1917) and the lower photographs in 19 April 2013 by Claudia Guerrido.

the Santa Cruz River. Changes in the level of Lago Argentino should be considered negligible in relation to those recorded in Brazo Sur–Rico arms due to GPM impoundments. Indeed, except for the Brazo Sur–Rico arms, not standing dead trees have been reported on Lago Argentino shorelines, suggesting that the level of Lago Argentino has remained almost constant during historical times.

Wood samples were dated using standard dendrochronological methods (Stokes and Smiley, 1968) and ring-width variations measured with a precision of 0.01 mm. Increment cores and cross sections from dead standing trees were cross-dated (Holmes, 1983) against local chronologies from living trees of the same species (Masiokas and Villalba, 2004; Srur et al., 2009; Villalba et al., 2003) to determine the dates of the innermost and outermost rings in each sample.

Changes in front positions and rupture events of GPM

Historical documents

In comparison to most glaciers in the SPI, the frontal fluctuations of GPM during the early 20th century received much attention and were often mentioned by scientific expeditions (Hauthal, 1904; Reichert, 1917; Liss, 1970; Raffo et al., 1953; Stuefer et al., 2007). Rudolf Hauthal (1904) made the first record of the front position of GPM in 1899. He estimated that the glacier front was 750 m from Península de Magallanes. Hauthal re-visited the area a year later and noted that the front of the glacier had advanced several meters closer to Península de Magallanes (Hauthal, 1904). Two photographs from 1901 published by Gallois (1901) and in the Argentinean Exposition Report on the border dispute with Chile (Argentinian Government, 1902) show GPM front in approximately the same position as in the Compton drawing printed in Hauthal (1904).

Percy D Quensel visited the area in 1908 and part of his chronicle was included in the publication of the Swedish Expedition to the Patagonian Andes (Skottsberg, 1911; SOM 2, available online). Quensel measured the opening of the channel in front of the glacier and reported that it was 350 m wide. Federico Reichert (1917) published a figure showing glacier front positions based on observations by Hauthal (1899–1900), Quensel (1908), and his

own measurements in March 1914 (SOM 2, available online). Figure 2 compares the 1914 photographs taken by Reichert (1917) with a recent, 2013 photograph. In 1914, the glacier front was located about 100 m from Península de Magallanes, and the first known closure of Canal de los Témpanos by GPM actually happened in the summer of 1917 (de Agostini, 1945).

The Italian priest Alberto de Agostini visited the glacier during the summer of 1928, almost 10 years after the first reported GPM closure event, and took a photograph which shows an open channel of approximately 150–200 m wide (de Agostini, 1945; Feruglio, 1944). In Figure 3, we compare this image with another from the same author taken in 1943 and a recent (2013) photograph from the same viewpoint.

In 1932, the front of GPM was separated from Península de Magallanes by a narrower channel than in 1928 but still wide enough to pass through it with a boat (Feruglio, 1944). Heim (1951) stated that GPM advanced from the position registered by de Agostini in 1928 reached Península de Magallanes during the summers of 1934 and 1935 and blocked the channel (Feruglio, 1944; Heim, 1951; Nichols and Miller, 1952). Later, in the summer of 1936, a photograph taken by de Agostini shows a large block of dead ice on the shore of Península de Magallanes (de Agostini, 1937; Feruglio, 1944; Heim, 1951). Based on the size of the dead ice block shown in de Agostini's photograph (Figure 4), we assumed that the first significant natural dam occurred between the winter of 1935 and the summer of 1936. The frontal fluctuations of GPM during the first half of the 20th century are summarized in Figure 5, and SOM Tables 2 and 3 (available online) list the documented frontal fluctuations and rupture events.

Naturalists' and botanists' observations

The floods caused by GPM killed thousands of trees along the shores of Brazo Sur–Rico, and observations of the forest by naturalists and travelers provide additional information on ice dam dynamics during the first half of the 20th century. Prichard (1902) refers to the difficulties he encountered traveling along the shore of Brazo Rico in the summer of 1900 (SOM 2, available online). This contrasts markedly with the current situation (Figure 6), where it is extremely easy to travel along Brazo Rico's shoreline
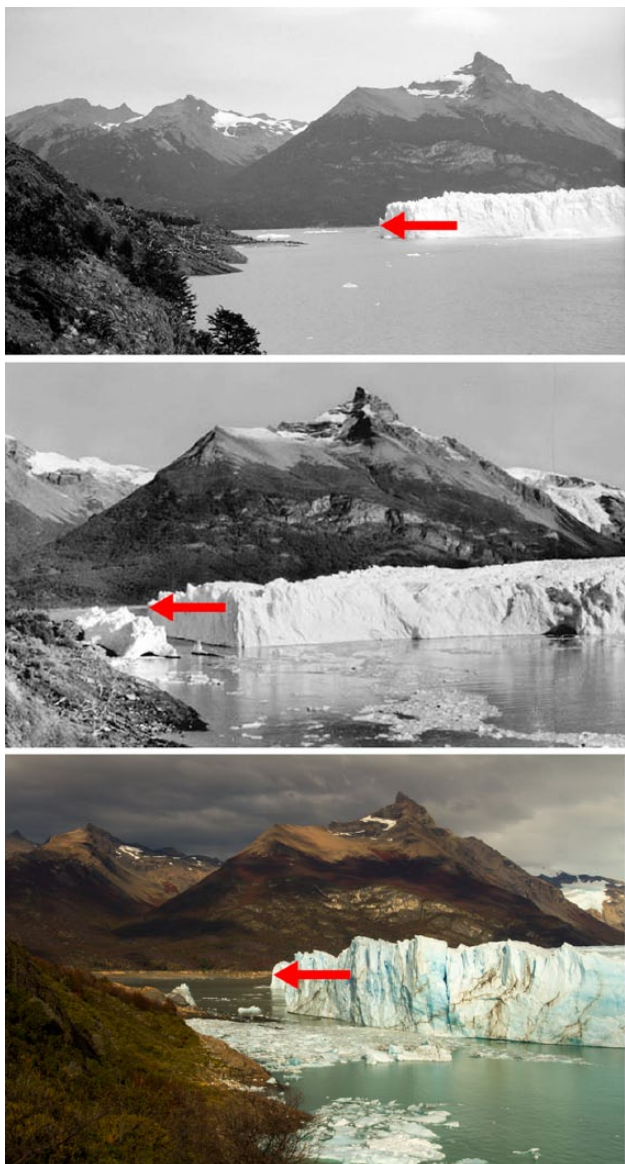
Figure 3. Photographic comparison of Canal de los Témpanos and Brazo Rico showing the forested shoreline on Brazo Rico in 1928 (de Agostini, 2010) and the barren shoreline in 1943 (de Agostini, 2010) and 19 April 2013 (Claudia Guerrido). The area affected by impoundments is more reduced in the photograph of 1943 than in 2013, consistent with low water levels during the earliest GPM ice dams in comparison with those recorded in the 1950s.

where there are only standing dead trunks. This provides a strong indication that in 1900, the forest came right up to the lakeshore.

In the same year, Lieutenant Iglesias from the Argentinean Navy conducted a hydrological survey of Río Santa Cruz, named GPM, and mapped the entire route from the South Atlantic coast to Lago Argentino. In his report, Iglesias (1901) precisely described woods that 'circumscribe the Laguna Rica (Rico arm)' without referring to standing dead trees along the shore, a fact that should have not gone unnoticed, considering the level of detail on forest coverage with which he portrayed the nearby mountain slopes (SOM 2, available online).

In 1914, Hicken clearly describes what might have happened if the GPM had dammed the lake and flooded Brazo Sur and Rico (SOM 2, available online). He suggested that if the ice dam did not collapse, the water would have discharged south into the Lago Frias, located at the southern tip of the Brazo Sur arm. It seems reasonable to assume that if the floods in the coastal areas of Brazo Sur–Rico had happened before 1914, Hicken would have mentioned its occurrence (Hicken, 1915).

Water levels in relation to ice dams

There is no information on the level reached by waters in Brazo Sur–Rico arms during the 1936 ice dam event. In the winter of 1939, prior to the second rupture of GPM's front on 17 February 1940, Volpi and Grandi (1940) reported an elevation difference of 4 m between the water levels on both sides of the ice dam (in Brazo Sur–Rico vs in the Canal de los Témpanos). For the same event, Heim (1951) stated, based on data provided by Parque Nacional Los Glaciares, a difference in the water levels of 9 m for 25 October 1939. He added that over 40 km^2 of land in the eastern sector of Brazo Rico had already been flooded (Heim, 1951). Finally, based on a comparison with the 1952 and 1953 ice dams, Raffo et al. (1953) estimated that the level of the water on Brazo Sur–Rico in 1939–1940 was 11.5 m higher than in Canal de los Témpanos.

The third rupture of GPM occurred on 20 March 1942 (Nichols and Miller, 1952; Raffo et al., 1953). According to Raffo et al. (1953), the water level in Brazo Sur–Rico rose 8.41 m during the first few months of 1942. Heim (1951) stated that the difference in level was 13.44 m, whereas Liss (1970) reported a difference of 14.9 m. For March 1942, Nichols and Miller (1952) reported an increase of 17 m.

Raffo et al. (1953) reported the occurrence of a new ice dam in November 1947. This closure caused a relatively short flood and the difference in water levels between the two sides of the glacier only reached 2.61 m. The same value was reported by Liss (1970).
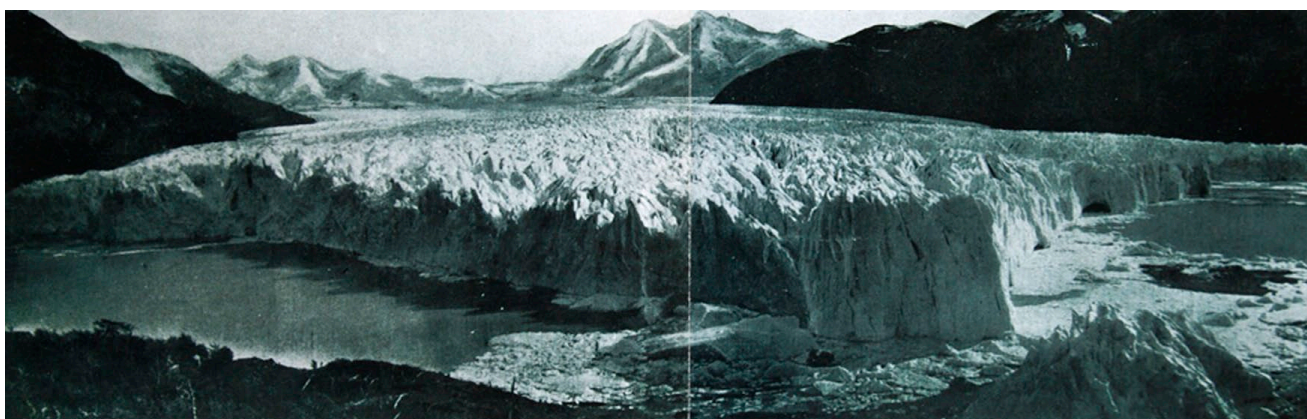

Figure 4. Block of dead ice (lower right hand side) separated from Glaciar Perito Moreno after the first rupture of the glacier in the summer of 1936 (de Agostini, 1937).
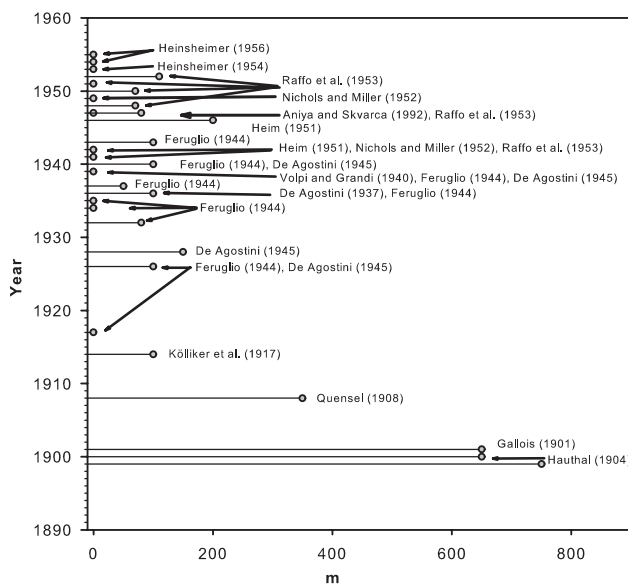
Figure 5. Estimated distances between the front of GPM and Península de Magallanes recorded in several historical documents (for sources, see SOM Table 2, available online).

However, according to Bertone (1972), at this time, waters in Brazo Rico rose 8 m above those in the Canal de Los Témpanos. At the end of 1948 and early in 1949, GPM advanced and closed Canal de los Témpanos again (Bertone, 1972; Nichols and Miller, 1952).

In response to a new ice dam in August 1951, the water level in Brazo Rico was rising at a rate of 3 cm and 7.4 cm per day in spring and summer, respectively (Raffo et al., 1953). According to Raffo et al. (1953), the water level increased to 12.7 m at the time of the rupture event on 2 March 1952. Although Liss (1970) reported the same level increase, Heinsheimer (1959) reported 11.3 m for the same event. In August of the same year, the glacier again closed Canal de los Témpanos and the water reached 14.4 m (Raffo et al., 1953). However, Heinsheimer (1954, 1959) reported for the same event that the water reached 11 and 12.85 m above the regular level of the lakes in his publications of 1954 and 1959, respectively.

The highest water levels were reported for the 1956 ice dam event, when the water in Brazo Sur–Rico arms reached 23, 25.6, or 26 m according to Mercer (1967), Liss (1970), and Heinsheimer (1959), respectively. However, the last two values exceed the maximum estimates of 23.5 m recently reported by Stuefer (1999) based on the difference in elevation of the lower boundary

Figure 6. (a) Flooded shore with standing dead trees on the shore of Brazo Rico. (b) Sampling cross section from dead standing trees along Brazo Rico. For scale, note the person (circled) sampling at the base of the tree. Photographs taken on February 2012 at the time of the last GPM ice dam. The water level at the time of the photographs was 5.9 m above the regular level of Brazo Rico arm according to Parques Nacionales, El Calafate, Santa Cruz.

of the remaining dense vegetation (unaffected by the floods) with the water level in Canal de los Témpanos.

The large variations in reported levels for a particular damming event might be due to measurements being taken on different dates, with different equipment, and in different places. Variations in water level for the historical damming events are summarized in Figure 7, and more recent measurements are listed in SOM Table 3, available online.

Tree-ring records

Dates for establishment and death of standing dead trees located on the flooded coastal lands by GPM impoundments are shown in Figure 8. Fifty-five (60%) from 92 cross sections from dead

standing trees were cross-dated. Dates of tree death are reported as years of the outermost ring without correcting for possible ring erosion. Cross sections from standing dead trees that dies between the 1930s and 1950s show bark remains or incipient erosion of the outer rings. In consequence, the true dates of death are probably no more than 1 or 2 years later. When dates of tree death for all eight sampling sites are combining two periods of abundant tree mortality, centered in 1936 and 1953, are evident. For these two periods, the percentages of samples with bark are 27% and 36%, respectively, assuring a precise dating of these mortality events.

Establishment dates provide a minimum estimate of tree ages since most samples miss the center of the tree. Most tree stems have rotten centers, thus preventing accurate determinations of the establishment dates. Dates of tree establishment arranged
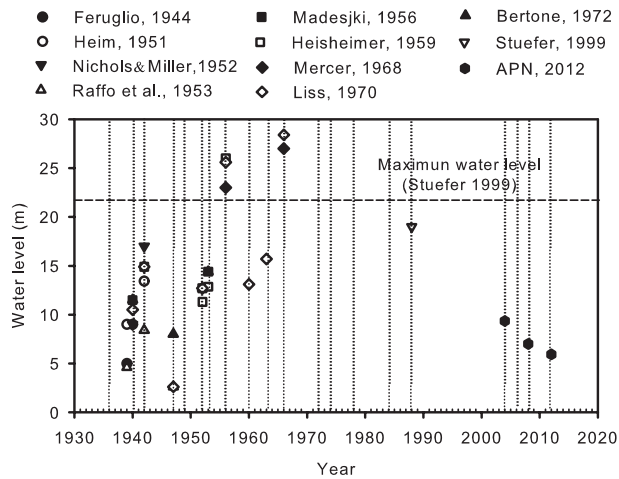
Figure 7. Estimates of the water levels of Brazo Rico during flooding events. Dotted lines correspond to rupture events, and zero water level corresponds to regular lake level.

according to elevations in relation to the regular water level in Brazo Sur–Rico are shown in Figure 9. The number of trees used for determining establishment ages per lake level is also included in Figure 9.

The innermost ring of a dead standing *Nothofagus pumilio* snag, which grew 8 m above the regular water level, is AD 1668, providing a conservative establishment date as the cross-section does not include the pith and comes from 1.5 m above the tree base. This indicates that there has been no flooding > 8 m elevation for at least 250 years before the 1936 event. Dating of dead standing trees located within 2 m of the regular water level yield establishment dates before 1760, indicating no flooding (and therefore no impoundments) associated with GPM for at least 170 years before the 1930s.

Discussion and conclusion

GPM is by far the most accessible, visited, and popular glacier in the southern Patagonian Andes. The frontal fluctuations and associated rupture events of this glacier have amazed visitors and attracted the attention of naturalists, explorers, and scientists for many decades. From 1936 to 1988, 17 damming and rupture events of GPM occurred every 2–4 years. After a period of 16 years without ice dams, ruptures occurred in 2004, 2006, 2008, and 2012. Detailed analysis of historical documents presented in this study indicates that the first closure of the GPM front happened during the summer of 1917; however, this first ice dam was brief without a significant increase in the water level of Brazo Sur–Rico arms.

The report and photograph by de Agostini (1937) of a large isolated block of dead ice standing on the shore of Península de Magallanes in the summer of 1936 represents the first historical evidence of a GPM rupture event (Figure 4). After each rupture event, large isolated blocks of dead ice severed from the front of GPM persist on Península de Magallanes for several months and, in some cases, for more than a year. No damming of the channel was reported in historical documents during the 37 years between Hauthal's visit in 1899 and 1936, even though GPM reached Península de Magallanes briefly in 1917.

Several early 20th-century documents and tree-ring records supported the date of the first historical ice damming event during the summer of 1936. When compared with contemporary photographs from the same locations, the older images indicate forest extending to the lake shoreline, whereas photographs taken after 1936 (e.g. de Agostini's photograph in 1943, Figure 3b) show a
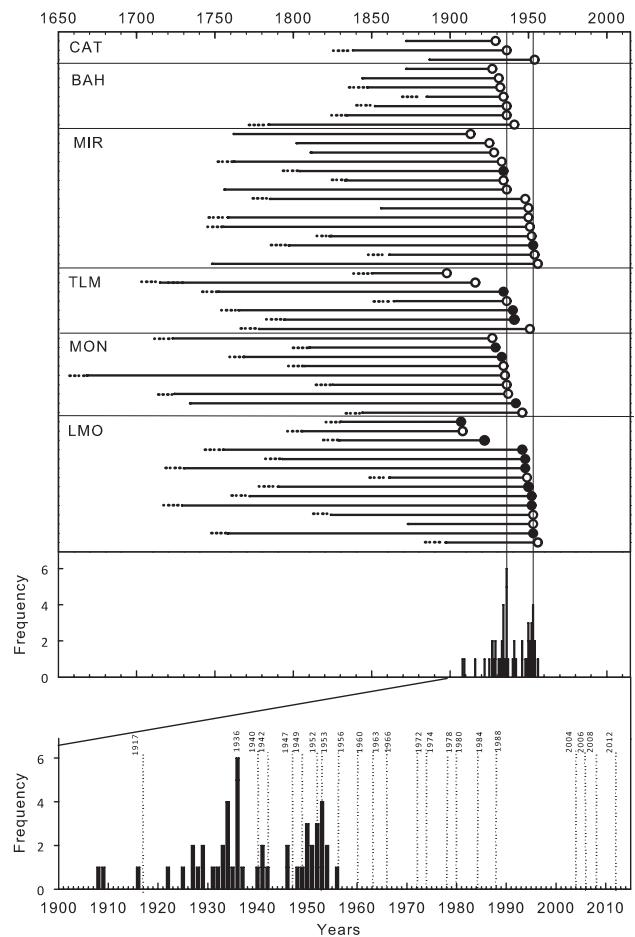

Figure 8. Establishment and mortality of standing dead *Nothofagus* trees. Upper panel: horizontal bars correspond to the calendar times cover by the tree-ring series starting from the pith (solid lines) or missing the inner rings (dot lines). At the right ends, black circles correspond to trees with bark (no ring erosion). Middle panel: number of tree deaths, note two mayor events centered in 1936 and 1953. Lower panel: enlarged section showing GPM outburst events indicated by vertical dashed lines. GPM: Glaciar Perito Moreno.
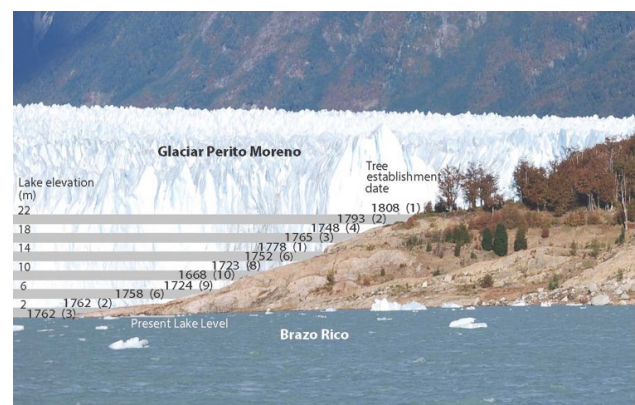

Figure 9. Minimum estimates for tree establishment dates from dead standing trees arranged by elevation above the regular lake level. The number of trees dated per lake level is included in parenthesis.

bare area along the coastline. Early historical accounts (e.g. Iglesias, 1901) also confirm that the forest extended down to the shores of Brazo Rico during the first decades of the 20th century. In contrast, most descriptions by naturalists after the ice dams in

the mid-20th century note thousands of standing and felled dead trees along the shores of Brazo Sur–Rico (Dimitri, 1972; Heinsheimer, 1954; Nichols and Miller, 1952).

Additional support to the proposed ice damming chronology is provided by the tree-ring dating of standing dead trees along the Brazo Sur–Rico shorelines. Mortality dates show two peaks in 1936 and 1953 associated with the first and largest flood events during the 20th century, respectively. These two mortality peaks are consistent with water elevations of Brazo Sur–Rico after each damming event. The 1943 photograph by de Agostini is consistent with estimates of approximately 10–12 m for flooding by the earliest major events associated with the 1936 mortality events. Maximum water levels of *c.* 22–26.5 m were estimated for the largest events in the 1950s and may be responsible for the second and extensive mortality event centered in 1953. On the other hand, the size of these *N. pumilio* and *N. betuloides* snags (diameters commonly over 1 m) indicates a considerable age which is confirmed by an innermost ring date of AD 1668 from a dead standing *N. pumilio* tree, located 8 m above regular lake level. This indicates that there were no ice-dammed lakes higher than this level for at least 250 years before the first historical event in the 1930s. Inner dates from before *c.* AD 1760 from trees close to the lake indicate no damming of the lake for at least 170 years prior to the 1930s. We assumed that the same date of establishment for trees located in levels 1 and 2 of Figure 9 (from lake reference level to 4 m) is merely coincidental. Indeed, none of the oldest trees in levels 1 and 2 has the pith, and all of them show rotten centers, suggesting that the year 1762 is a conservative estimate for tree establishment dates.

There have been many glaciological investigations into the unusual behavior of GPM, suggesting that the glacier front has remained relatively stable since the early 20th century (Aniya and Skvarca, 1992; Skvarca, 2002; Skvarca et al., 2004; Stuefer et al., 2007). In addition, attempts to establish links between GPM fluctuations and regional climate on a long-term perspective have not yet produced consistent results (Masiokas et al., 2009). GPM stands in contrast to the vast majority of glaciers in the SPI, which show fairly consistent patterns of retreat and thinning during recent decades in relation to regional warming during the 20th century (Masiokas et al., 2009; Rignot et al., 2003; Villalba et al., 2003). Our study does establish the earliest date of ice dam events of GPM in historical times. In doing that, our results add information on the anomalous GPM behavior suggesting that the glacier, in contrast to most glaciers of the SPI, was less extensive in the 1700s and 1800s than it is today. Our findings are consistent with previous glaciological work suggesting that GPM reached its maximum historical extend during the 20th century (Aniya and Skvarca, 1992; Mercer, 1968; Skvarca and Naruse, 1997; Stuefer, 1999). In addition, our contribution provides clear indications that major ice damming and flooding events were absent from at least 1650–1936. This study indicates that the particular history and dynamic of GPM have offered to our generations the great opportunity of enjoying the ice ruptures, one of the most spectacular natural processes on Earth.

Acknowledgements

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