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Non-linear climatic response of Calving Glaciers: A case study of Pio XI Glacier, Chilean Patagonia

Respuesta climática no lineal de glaciares desprendentes: estudio del Glaciar Pio XI, Patagonia Chilena

CHARLES R. WARREN[1] y ANDRES RIVERA[2]

[1]Department of Geography, University of Edinburgh, Edinburgh EH8 9XP, Scotland, UK
[2]Department of Geography, University of Chile, Santiago, Chile

ABSTRACT

Pio XI (or Brüggen) Glacier is probably the only glacier in the world currently at its Neoglacial maximum. Its recent fluctuations provide a striking example of non-climatic glacier behaviour. A rapid 3 km advance in the 1920s was followed by retreat in the 1930s. Between 1945 and 1983 the glacier advanced 10 km at a mean rate of 263 m a^{-1}, since when it has oscillated around a quasi-stable position. In 1992 the terminus was advancing over large accumulations of proglacial sediment and the western margin was advancing into mature forest composed of southern beech (Nothofagus spp.) and Pilgerodendron uviferum. The proglacial delta has aggraded to sea level along two thirds of the front and the maximum water depth is 22 m, permitting only small-scale calving. The advance has blocked a tributary valley, forming a 240 km^2 ice-dammed lake into which large-scale, frequent calving is taking place. This pattern of behaviour cannot be explained with reference to climate alone. A simple descriptive model combining calving dynamics, sediment budget, fjord topography and climate explains the main features of recent behaviour. Many other Patagonian calving glaciers have also responded indirectly to climate this century. Since the established Late Glacial and Holocene chronology of Patagonian glacier oscillations is largely based on records from sites at calving glaciers, its validity and its uncritical use in inter-hemispheric comparative studies is questionable.

Key words: Historic Glacier fluctuations.

RESUMEN

El Glaciar Pío XI (o Brüggen) es probablemente el único glaciar en el mundo que está actualmente en su máximo Neoglacial. Sus fluctuaciones recientes constituyen un ejemplo notable de una respuesta glacial no climática. Un rápido avance de tres kilómetros en los años 1920, fue seguido de un retroceso en los años 1930. Entre 1945 y 1983, el glaciar avanzó 10 kms a una velocidad promedio de 23 $m.a^{-1}$. Desde entonces ha oscilado alrededor de una posición cuasi estable. En 1992, el extremo del glaciar estaba avanzando encima de grandes acumulaciones de sedimentos proglaciales, y el margen occidental estaba avanzando al interior de un bosque maduro de *Nothofagus* spp. y *Pilogerodendron uviferum*. El delta progracial ha acumulado sedimentos hasta el nivel del mar a lo largo de dos tercios del frente, donde la máxima profundidad del agua es de 22 mts, lo cual permite únicamente desprendimientos de pequeña escala. El avance ha bloqueado un valle tributario, formando un lago de 240 km^2 al interior del cual los desprendimientos de gran escala son frecuentes. Esta conducta no puede explicarse únicamente con referencia al clima. Un modelo descriptivo simple, combinando la dinámica del desprendimiento, el balance de sedimentos, la topografía del fiordo y el clima, contribuyen a explicar las principales características de su conducta reciente. Muchos otros glaciares desprendentes de la Patagonia también han respondido de manera indirecta al clima durante este siglo. Dado que la cronología tardiglacial y holocénica de la conducta de los graciares Patagónicos está basada en registros tomados en sitios de glaciares desprendentes, su validez y su utilización acrítica para estudios comparativos interhemisféricos es cuestionable.

Palabras Clave: Fluctuaciones históricas de glaciares.

CLIMATE AND CALVING GLACIERS

Ice sheets are an integral part of the Earth's climate system, modulating and amplifying change. Calving margins form an interface between the oceans, the atmosphere, and ice sheets and important information is therefore potentially available at such locations. However, our understanding of glacier- ocean- atmosphere interactions is limited by our poor knowledge of the complex physics of iceberg calving (Hughes 1992, Warren et al. 1994a). Consequently, the issue of iceberg calving is now viewed as one of the major unsolved problems in glaciology.

Calving glaciers have a fundamentally different relationship with climate from those ending on dry land. Calving introduces mechanical instability to the glacier system. As a result, the glacial response to climate is variably filtered through a range of environmental stability factors. These, working together, can partially decouple glaciers from climatic forcing such that they fluctuate cyclically in ways not directly reflecting climatic change (Trabant et al. 1991). Consequently, neither contemporary nor former fluctuations of calving glaciers can be used as reliable indicators of climatic change (Meier & Post 1987, Warren 1992).

The most important of these stability factors are water depth (Brown et al. 1982) and the topographic geometry of the fjord (Mercer 1961, Warren 1991). The water depth control is intimately linked with proglacial sedimentation dynamics which can themselves largely control frontal behaviour (Powell 1991, Alley 1991). Such decoupling has important implications for interpretations of the glacial geologic record, and also for predictions of the likely response of calving glaciers to projected global warming (Reeh 1994) with its associated implications for sea level rise (Warren et al. 1994b). Calving glacier behaviour is also of practical significance. It has engineering applications in the context of glaciers which calve into hydroelectric storage lakes (Hooke et al. 1989, Laumann & Wold 1992) and practical applications for the management of Chile's freshwater resources, which are predominantly glacial in origin (Pena and Escobar 1987, Escobar et al. 1992).

AIMS AND METHODS

This study is part of a wider investigation of the mechanisms which have controlled the response of Patagonian calving glaciers

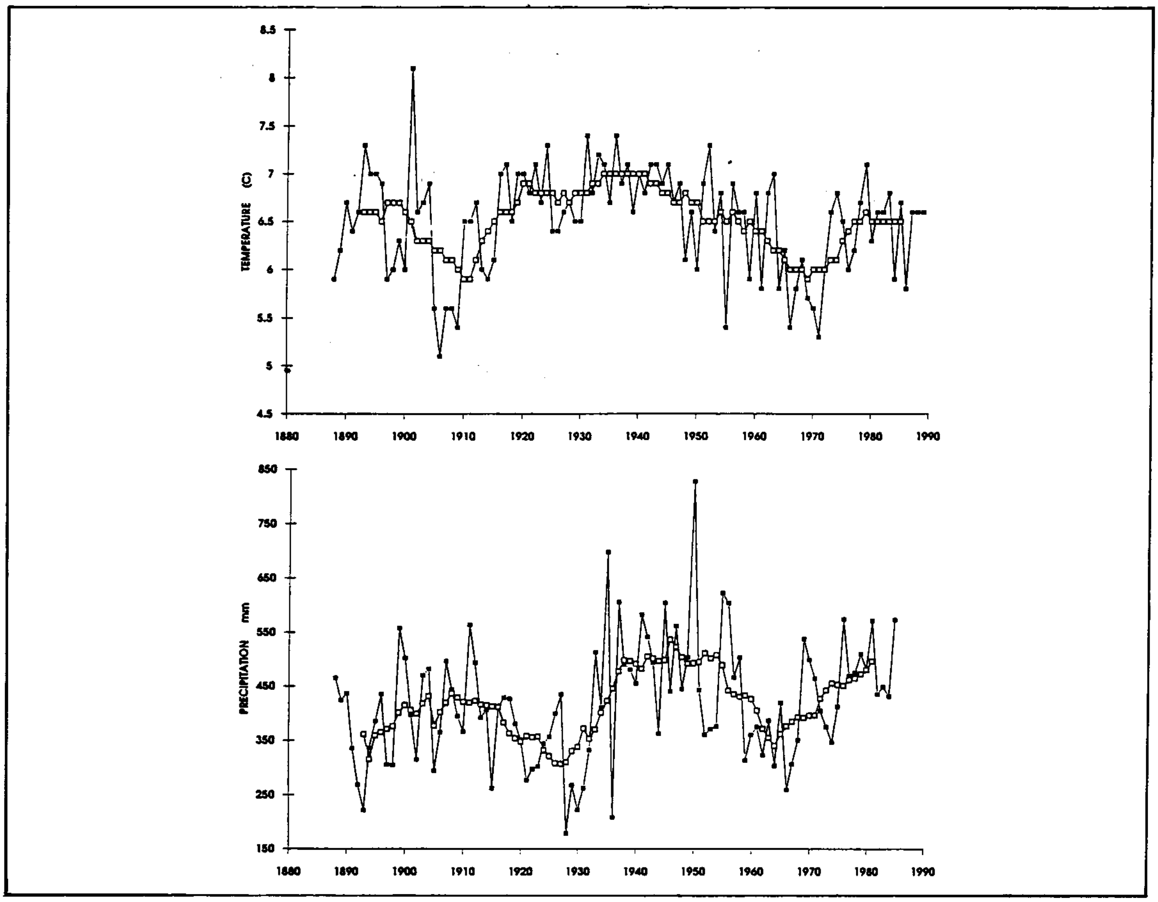

Fig. 1: Mean annual precipitation and temperature records from Punta Arenas, 1888-1990 with 10-year running means. Location is shown on Fig. 2(II). The town is at sea level and is in the rainshadow zone east of the Andes.

Promedios anuales de precipitación y temperatura de Punta Arenas, 1988-1990, y promedios cada 10 años. La localidad es mostrada en la Fig. 2 (II). La ciudad está a nivel del mar y en la zona de sombra de lluvia al este de los Andes.

to Quaternary and recent environmental change, and, in particular, the extent to which recent glacier oscillations have been controlled by the interaction between glacio-dynamics and topography (Warren & Sugden 1993, Warren et al. 1994b). This case study of the historic oscillations of Pio XI Glacier was undertaken using published material supplemented with vertical and oblique aerial photographs dating from 1945, 1975, 1981 and 1984, and LANDSAT imagery from 1976 and 1986. In addition, during a field visit in February 1992 the position of the ice front and water depths close to the tidewater calving cliff were measured, together with qualitative observations of glacier characteristics.

HISTORIC CLIMATE CHANGE AND BEHAVIOUR OF PATAGONIAN GLACIERS

Figure 1 shows meteorological data from Punta Arenas. This is the longest data se-

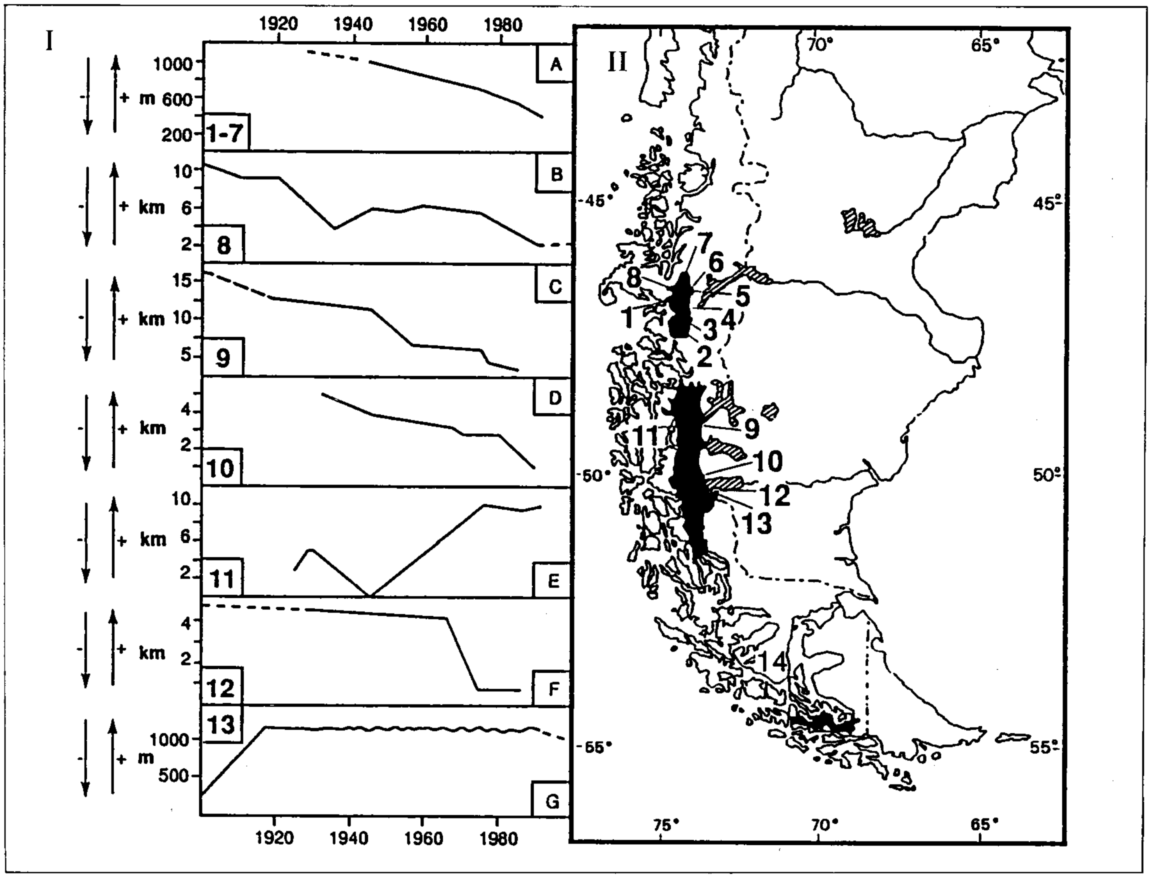

Fig. 2: I. Twentieth century fluctuations of 13 Patagonian glaciers. Note the variable distance scales, and that the scale for glaciers 1-7 and 13 is in metres while that for glaciers 8 - 12 is in kilometres.A. Mean retreat rate of seven non-calving outlet glaciers of the North Patagonian Icefield. The glaciers are San Quintin (1), Pared Sur (2), Arco (3), Soler (4), Leones (5), Fiero (6) and Explorades (7). B. San Rafael (8). C. O'Higgins (9). D. Upsala (10). E. Pio XI (11). F. Ameghino (12) G. Moreno (13). Data have been collated from Lliboutry (1956), Aniya (1988,1992), Mercer (1982), Aniya et al. (1992) and fieldwork in 1992 and 1993. II. Map showing the location of the glaciers used (1-13) and of Punta Arenas (14).

I. Fluctuaciones de 13 glaciares patagónicos durante el siglo XX. Notese que las escalas de distancia son variables; la escala para los glaciares 1-7 y 13 es en metros, mentras que para los glaciares 8-12 es en kilómetros. A. Tasa de retroceso promedio de siete glaciares no desprendentes del Hielo Patagónico norte. Los glaciares son San Quintín (1), Pared Sur (2), Arco (3), Solar (4), Leones (5), Fiero (6) y Explorades (7). B. San Rafael, (8). C. O'Higgins (9), D. Upsala (10). E. Pio XI (11), F. Ameghino (12) G. Moreno (13). Los datos han sido extraidos de Lliboury (1956), Aniya (1988.1992), Mercer (1982), Aniya el al. (1992) y trabajo de campo en 1992 y 1993. II. Mapa mostrando la ubicación de los glaciares usados (1-13) y de Punta arenas (14).

ries in Patagonia. Temperature and precipitation exhibit wide interannual variability, mean annual figures ranging respectively over 3°C and 648 mm. The 1930s was the warmest decade, followed by steady cooling to a low in 1971. The last two decades have seen renewed warming but mean annual temperatures during the 1980s were still 1.2°C lower than those in the 1930s. This further emphasizes the point well made by Jones & Briffa (1992) that any trend towards 'global warming' is far from uniform. Precipitation has oscillated cyclically, the wettest periods being around the turn of the century, mid-century, and most recently. Local climatic gradients are steep (Ohata et al. 1985) so records beyond the immediate vicinity of the icefields may not reliably indicate climatic trends affecting the outlet glaciers (Burgos et al. 1991), but long-term, ice-proximal records do not exist. The short data series that do exist show even greater interannual variability than the Punta Arenas record (Warren 1993) and reveal the significance of localised topographic effects on the icefield climate.

Despite pioneering work by Lliboutry (1956) and several recent studies (Aniya & Enomoto 1986, Aniya et al. 1992, Naruse & Aniya 1992), remarkably little is known about the glaciology of the Patagonian icefields. What is clear, however, is that the outlet glaciers of the icefields have responded to twentieth century climate change in contrasting ways (*Fig*.. 2). The dominant regional trend throughout this century has been consistent retreat from prominent 'Little Ice Age' maxima. However, the large calving glaciers have oscillated in ways which contrast sharply, both with each other and with this regional trend (Lliboutry, 1956; Warren & Sugden 1993). Such variability is typical of the non-linear response of calving glaciers to climate change (Warren 1992).

Fig. 3: Pio XI Glacier and Fiordo Eyre from the western valleyside, February 1992.

Glaciar Pío XI y Fiordo Eyre desde el lado occidental del valle, Febrero de 1992.

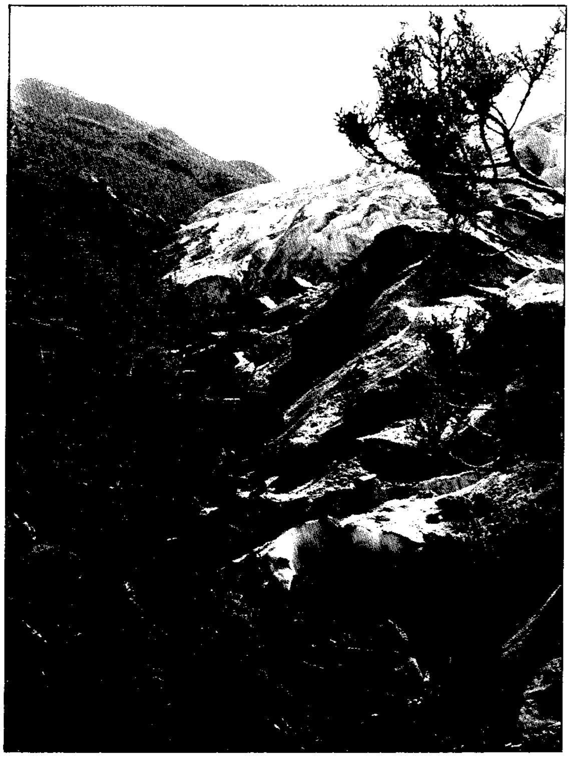

Fig. 4: The north margin of Pio XI Glacier advancing into mature forest, February 1992.

El margen norte del Glaciar Pío XI avanzando en bosque maduro, Febrero 1992.

PIO XI GLACIER: DESCRIPTION AND HISTORIC FLUCTUATIONS

Description

Pio XI (or Brüggen) Glacier (49°13'S, 74°00'W) is one of the major western outlet glaciers of the Southern Patagonian Icefield (*Figs*. 2 & 3). It is about 53 km long (Aniya et al. 1992) and velocities near the terminus were estimated by Marangunic (1964) at 750 m -1. The surface is everywhere crevassed, broken and largely inaccessible, with steep margins. The ice is clean in most areas except for prominent medial moraines and where tephra bands outcrop to form distinctive surface patterns. The source of the tephra is presumed to be Volcan Lautaro (49°05'S, 73°30'W), an active nunatak volcano 3380 m high which abuts the accumulation area of the glacier.

The glacier bifurcates into two large distributaries, one arm terminating at a 4 km-long tidewater front in Fiordo Eyre and the other terminating at a 4.5 km-long freshwater calving cliff in an unnamed ice-dammed lake in what was formerly the Greve Valley. This lake, unofficially named 'Lago Greve', has a surface area of approximately 240 km^2 and overflows along the margin of Hammick (or Occidental) Glacier over a col at a height of c.150 m. Water depths in the lake are unknown. However, given that the former valley was a flat outwash plain close to sea level, the calving front is probably standing in water not much less than 150 m deep, depending on sedimentation rates.

In February 1992 strong advance was in progress along the western flank of the tidewater arm where a steep (70 - 80°) ice wall some 30 m high was destroying ancient, mature forest composed of southern beech (*Nothofagus* spp.) and *Pilgerodendron uviferum* (*Fig.*. 4). The tidewater front was 15 - 35 m high.

Water depths 50 m in front of the calving front were uniformly shallow, between 17 and 22 m, but calving events were observed to produce sediment-laden spray, suggesting that at the front itself water depths were even less. Only the central 1500 m of the terminus was standing in water. Along the rest of the front, at both margins, the proglacial delta had aggraded to sea level to form extensive intertidal mud flats, and concentrations of suspended sediment in the proglacial water body were high. Glacial deformation and shearing of

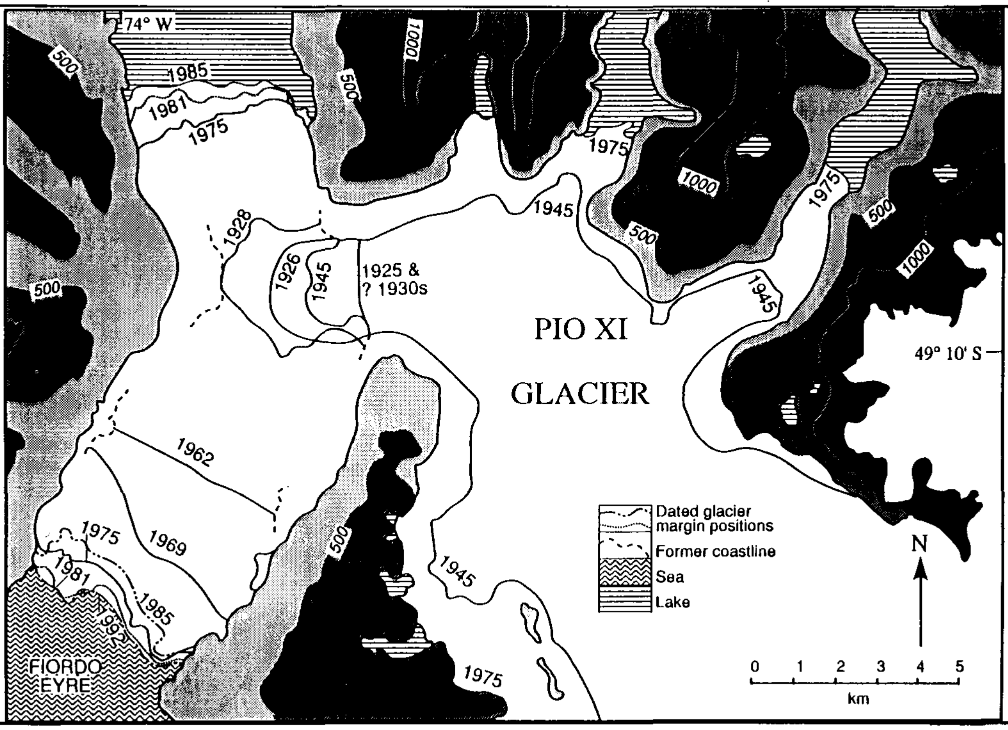

Fig. 5: Twentieth century fluctuations of Pio XI Glacier compiled from references discussed in the text and field observations in 1992.

Fluctuaciones del Glaciar Pío XI durante el siglo XX recopiladas de las referencias discutidas en el texto y observaciones de campo en 1992.

these sediments by the advancing ice front had in places formed accumulations 5 - 10 m above sea level which the glacier was overriding.

Calving activity at the tidewater front was small-scale and infrequent. Most icebergs were less than 5 m long and no berg larger than 20 m was observed. By contrast, there were many large icebergs in 'Lago Greve', confirming that water depths there are considerably greater. Mercer (unpublished) also noted that the freshwater terminus calves many bergs that are an order of magnitude larger than any in Fiordo Eyre. The 1975 aerial photograph shows 15 bergs more than 100 m long within 5 km of the calving front.

Historic fluctuations

The glacier's twentieth century behaviour (*Fig.* 5) has been anomalous relative both to the general regional pattern of glacial fluctuations (Mercer 1982) and to climatic change. The glacier has advanced and retreated rapidly several times since 1830 (Mercer 1964). The earliest reliable observations were made by Agostini (1945:59 - 62) who vividly described the dramatic events of the late 1920s and mapped the glacier terminus in 1928. During 1926 the glacier began to advance rapidly from its fjord-head position. During a few weeks in September and October of that year the glacier advanced a kilometre at rates of up to 20 m d^{-1} (Lliboutry 1956:231 & 389). This advance blocked the mouth of the Greve Valley which then became inundated, forcing the precipitate abandonment of a sheep farm established the previous year. The calving front was about 100 m high at that time. Contemporary photographs (Agostini 1945) show that active calving was taking place along the majority of the front, producing a a profusion of icebergs, but that the central part of the glacier which advanced onto the western headland was advancing on a morainal bank at sea level.

At some time between 1928 and 1945 the glacier retreated between 3 and 5 km (Mercer 1964, Lliboutry 1956:389) to or behind its fjord-head location. This allowed the lake that had formed in the Greve Valley to drain, exposing the lowland. Aerial photographs of 1945 show a clean, steep calving front, convex in plan, advancing from this position accompanied by active calving. By 1962 the glacier had advanced 5 km and doubled the length of its tidewater calving front (Mercer 1964). Another 4 km of advance had occurred by 1976 (Iwata 1983).

The rate at which the glacier advanced down Fiordo Eyre between 1945 and 1975 changed little, averaging 290 m a^{-1}. Only small-scale calving was occurring in 1975 and tidal flats had formed at both margins. Prominent plumes of turbid meltwater emerged from both margins, the eastern plume extending 4 km across the mouth of Fiordo Exmouth. The northern glacier distributary also advanced between 1945 and 1976, at the lower rate of 132 m a^{-1}, once again blocking the Greve Valley, allowing 'Lago Greve' to reform, and initiating freshwater calving at this terminus. Between 1975 and 1985 this freshwater front advanced a further 1.1 km, accompanied by large-scale calving, but the tidewater front behaved asymmetrically. The eastern side continued to advance slowly, reaching a maximum in about 1983 from which it had retreated about 200 m by the austral summer of 1984/1985. This position is about 10 km down-fjord from its 1945 location and was the glacier's Neoglacial maximum (Clapperton & Sugden 1988, Mercer unpublished). The western side advanced some 1200 m between 1975 and 1981 before retreating almost 1900 m in the following 4 years. In 1989 the entire terminus was many hundreds of metres behind its early 1980s maximum (E.Garcia, personal communication 1993). In 1981 a western tributary valley 5 km behind the tidewater front was occupied by an ice-dammed lake whereas in 1975 the river drained under the glacier. This lake has persisted since that time. Rapid readvance of the tidewater front occurred between 1989 and 1992, bringing it close to its recent maximum position and parts of the margins in contact with undisturbed forest. The freshwater front, observed from a distance, appeared to have continued its uninterrupted advance.

DISCUSSION

It has long been recognized that simple assumptions of linear glacier response to climate change are inadequate and can lead to erroneous conclusions (Porter 1981). Complexities introduced by varying mass balance regimes, hypsometry, topography and flow dynamics can not only result in variable glacier response to a particular climatic stimulus but may also produce misleading geomorphological evidence. Some degree of asymmetry and asynchrony is therefore to be expected within any regional population of glaciers. However, it has become clear that calving glaciers are particularly prone to large-scale (>10 km), non-climatic oscillations, mainly because of the instability introduced to the glacier system by the calving process.

The twentieth century behaviour of Pio XI Glacier is a striking example of glacier behaviour that cannot be explained with reference to climate change alone. The fluctuation pattern contrasts with those of neighbouring glaciers and does not appear to relate to regional trends of precipitation or temperature. The most extreme contrast is that with the O'Higgins Glacier (48°55'S, 73°08'W), an eastern outlet at almost the same latitude, which has retreated some 12 km (*Fig.*. 2, Glacier 9) while Pio XI Glacier has advanced 10 km. It is also an interesting example of the theory proposed by Mercer (1961) that the advance of a tidewater glacier down a fjord of uniform width and depth can continue irrespective of regional climatic change.

An explanatory model

The paucity of glaciological and meteorological data at present forbids any rigorous investigation of this remarkable phenomenon. However, the salient features of the recent oscillation history can be explained through a simple descriptive model which combines the available empirical evidence with current glaciological theory. The primary theoretical premises incorporated in this model are:

1. Active proglacial sedimentation at a calving front can permit glacier advance that is unrelated to climate by reducing effective water depths and hence the calving speed (Alley 1991, Powell 1991).

2. In maritime environments with high precipitation, the mass balance regime of a glacier can be dominated by variations in precipitation (Brazier et al. 1992, Warren 1993). This is enhanced in the case of calving glaciers simply because large percentages of total mass loss may be achieved by calving, and calving is less sensitive to temperature changes than is melting. 3. Stability of the glacier terminus is conditioned by the topographic geometry of the fjord (Mercer 1961, Warren 1991).

In this model we propose that calving dynamics have partially decoupled the behaviour of the terminus from the climate signal. We suggest that the primary control on recent oscillations has been effective water depth at the calving front which has in turn been fundamentally controlled by proglacial sedimentation.

Our reconstruction is as follows:

1830 - 1925: During the 'Little Ice Age' climatic deterioration of the nineteenth century, when many Patagonian outlet glaciers advanced, Pio XI Glacier was unable to do so because calving rates in deep water at the head of the fjord were too great. Ice supply increased in response to the climatic signal but there was little change in terminus position because rising rates of mass loss through calving compensated for these increases (cf. Mann 1986). The calving front remained at the topographic pinning point at the head of Fiordo Eyre. 1926 - 1928: Proglacial sedimentation during the preceding stillstand progressively reduced water depths. A critical threshold was reached, probably in the early 1920s, when the calving speed fell below ice velocity, permitting advance to commence. In 1925 or 1926 the ice front passed the mid-point of the channel, after which time and place a positive feedback began to operate: advance took the terminus into progressively shallower water as it approached the headland, reducing calving rates and accelerating the advance. A photograph taken by the sheep farmer a few days before the channel was finally closed shows that the frontal cliff was advancing on a morainal bank above sea level (Agostini 1945:60). Calving rates would thus have been minimal and the rate of advance would have almost equalled the ice velocity.

1929 - 1945: Two possible explanations exist for the retreat during the 1930s. The prime cause may be climatic. During the previous two decades temperatures were rising and precipitation was falling (*Fig.*. 1), a combination which should cause glacier retreat. Another possibility is that catastrophic drainage of 'Lago Greve' triggered rapid retreat. A jîkulhlaup draining a lake of this magnitude would generate very large peak discharges which would not only erode the ice directly but, more significantly, would remove large volumes of sediment, dramatically increasing the water depths at the terminus. Calving rates would therefore rise substantially, triggering rapid retreat to the stable location at the fjord head. A similar lake outburst at the terminus of Hubbard Glacier, Alaska, in 1986 eroded 50 m of bedrock from the headland (Mayo 1988). It may be that both these processes operated, climate initiating ice thinning which then permitted a jîkulhlaup.

1945 - 1975: Renewed sediment accumulation combined with the return to high rates of precipitation from the mid-1930s produced a readvance. The Greve Valley was again blocked, but this time the lake level reached the height of the overflow along the margin of Hammick Glacier. The system thus attained a measure of stability and the potential for a jîkulhlaup was much reduced. With this 'danger' removed, the glacier was able to advance steadily down the fjord. This advance most probably occurred on a morainal bank which moved with the terminus through a process of erosion on the proximal side and deposition on the distal side. This process can permit a tidewater glacier to advance slowly even down a deep fjord (Trabant et al. 1991), but in this case water depths were not great. Bathymetric charts based on soundings in the 1950s show that water depths in Fiordo Eyre were nowhere greater than 35 m, and this permitted steady, relatively rapid advance.

1976 - 1992: The position reached in the early 1980s appears to be a quasi-stable location around which the terminus is fluctuating. The retreat that began in the early 1980s may have been a response to the period of reduced rainfall in the 1960s. Renewed advance in the early 1990s is probably due to the return to high annual precipitation during the 1970s and 1980s combined with the continued proglacial sedimentation which has arrested calving along two thirds of the terminus.

Weaknesses of the model

The primary weakness of the model is that it cannot be tested. Glacier advance has obliterated the evidence. Important data that are accessible, such as ice velocity fields, the bathymetry of 'Lago Greve', the Equilibrium Line Altitude and the size of the accumulation area, do not exist. These data would enable some of these theoretical ideas to be tested. Furthermore, there are several questions to which the model does not provide clear answers. The rates of advance in 1926 reported by Agostini (1945) are characteristic of ice velocities during glacier surges and an order of magnitude higher than the velocity reported by Marangunic (1964), yet there is no evidence to support the idea Pio XI Glacier is a surging glacier. Surface tephra bands and medial moraines do not show the looped, distorted patterns typical of surging glaciers. However, the rates are based on the description by the sheep farmer and so may be overestimated. It nevertheless seems clear that the advance was anomalously rapid and this remains unexplained at present.

It is not immediately apparent why the advance in the late 1920s was terminated by a jîkulhlaup while the post-1945 advance was able to survive the build up of 'Lago Greve'. Two possible explanations are that the later advance was more powerful due to high annual precipitation, and/or that water depths were less at that time due to continued sedimentation.

A final question is the reason why the calving terminus in 'Lago Greve' continued to advance uninterruptedly after 1975 while the tidewater front fluctuated. One possibility is that freshwater calving termini are more stable mechanically than tidewater fronts. Observations in West Greenland (Warren 1991) and Alaska (A.Post personal communication 1993) have found this to be the case. Moreover, in any given water depth, calving rates in freshwater are an order of magnitude lower than in tidewater (Funk and Rîthlisberger 1989, Warren et al. submitted). Consequently, although water depths in 'Lago Greve' must be much greater than those at the tidewater front, the calving speed may be less. If the mean depth at the ice front in 'Lago Greve' is 100 m the calving speed will be about 200 m a^{-1} (Funk and Rîthlisberger 1989) whereas the calving speed in a mean tidewater depth of 20 m is greater than 500 m a^{-1} (Brown et al. 1982).

Another factor which could perhaps affect the behaviour of the glacier is the presence of the active volcano Volcan Lautaro at the margin of the accumulation area. Deposits of tephra on the glacier surface and increased geothermal heat flux could significantly affect surface and basal melt rates respectively, with consequences for ice velocities. However, the dates of eruptions during this century are not known, and data to test this possibility do not exist.

Wider implications

Despite the uncertainties concerning the details, it is clear that, throughout this century, Pio XI Glacier has not been responding directly to climate change. The varied, contrasting behaviour of other calving outlets of the Patagonian icefields (*Fig*.. 2) shows that indirect climatic response of calving glaciers may be the rule and not the exception, at least on century timescales. This has indeed been found to be the case amongst other regional populations of glaciers (Meier & Post 1987, Warren 1992).

This has significant implications for the Late-Glacial and Holocene chronologies of glacier oscillation in Patagonia, because the chronology of Patagonian glacier fluctuations since the last glacial maximum rests on the dated fluctuations of a small number of glaciers, many of which calve into lakes or the sea. The regional glacio-climatic chronology therefore rests largely on the oscillations of calving glaciers (Mercer 1982,1984, Clapperton & Sugden 1988, Clapperton 1993). Until well-dated glacial records can be constructed that are free from large-scale glacio-dynamic interference of this kind, the recent patterns of behaviour will leave a question mark over the existing framework (Warren et al. 1994b) This note of caution will become increasingly significant as the temporal resolution of the chronology is improved. While the majority of Patagonian glaciers have consistently retreated this century, Pio XI Glacier has advanced 10 km. Its behaviour cannot be explained with reference to climate alone. It seems that climate has had only a minor role in controlling the direction and speed of terminus changes, and that the primary controlling factors have been sediment budget, sediment accumulation rates and the topography of the glacial trough. Many other calving glaciers in Patagonia have responded indirectly to climate change during historical time. The main implication of this work concerns the accepted regional glacio-climatic chronology which rests to a significant degree on the dated oscillations of calving glaciers. The recent large-scale, asynchronous behaviour of Patagonian calving glaciers suggests that this chronology should not be uncritically accepted and applied.

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