RECENT FLUCTUATIONS AND DAMMING OF GLACIAR PERITO MORENO, PATAGONIA, OBSERVED BY MEANS OF ERS AND ENVISAT IMAGERY

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ABSTRACT

Frontal positions and a lake damming event are investigated for Glaciar Perito Moreno, one of the main calving outlet glaciers of the Southern Patagonia Icefield, using ERS SAR data available since 1992 and Envisat ASAR data since 2002. The satellite data, in synergy with field measurements, confirm the stability of the glacier, showing only minor frontal fluctuations and indicating an approximately balanced mass budget since many years. This is in contrast to the majority of Patagonian glaciers which have been subject to considerable retreat during the last 50 years. Climatic and orographic factors of relevance for differences in glacier response are discussed, based on a comparison of Moreno glacier with the adjoining Ameghino glacier which is retreating. ASAR data are also used to study the recent damming event of Moreno glacier that started in mid-October 2003 after a minor frontal advance, and ended with a collapse of the ice dam in March 2004. Due to the rise of the water level by more than 8 metres, 22 km^2 of pasture land were flooded in the southern arm of Lago Argentino. The motion behaviour and frontal observations suggest that the damming was triggered by minor fluctuations of mass fluxes of a glacier close to equilibrium and does not represent a surge event.

1. INTRODUCTION

Glaciar Perito Moreno is the most famous glacier of the Parque Nacional Los Glaciares in southern Argentina, a UNESCO World Heritage Site. It is one of the main outlet glaciers of the Southern Patagonia Icefield towards east, covering 259 km^2 in area and flowing over a length of about 30 km from the continental divide down to Lago Argentino. Fig. 1 shows a photo of the glacier with the calving terminus in the foreground and the continental divide culminating on the peak Cerro Pietrobelli (2950 m a.s.l.) in the background.

Fig 1. Oblique view of Moreno glacier from Cerro Buenos Aires, in the background the continental divide with Cerro Pietrobelli, in the foreground Canal de Los Tempános (right) and Brazo Sur (left) of Lago Argentino.

The Southern Patagonia Icefield (SPI) is the largest contiguous mid-latitude ice mass, covering about 13000 km^2 in area and stretching for 350 km from 48.3° S to 51.5° S [1]. SPI comprises several icefields and ice caps, with average elevations between 1500 m and 2500 m, which are independent entities in terms of ice dynamics. The central ice plateaus nourish large outlet glaciers which in the west calve into the Pacific fjords and in the east into the large Patagonian lakes, the largest of which is Lago Argentino covering 1560 km^2 in area with the lake surface at 185 m above sea level. Because Patagonia is the main landmass in this southern latitude zone and because of its closeness to Antarctica, the SPI is of great significance for studies of climate history and ice/climate interactions [2].

We carried out glaciological field measurements on Moreno glacier since 1995 in half-yearly or yearly intervals and operated an automatic climate station [3]

[4], in cooperation with Instituto Antártico Argentino (IAA), Buenos Aires. In this paper we report on the study of recent frontal fluctuations and on a lake damming event, based on ERS SAR data since 1992, made available by ESA for the projects ERS-AO2.A101 and VECTRA (ERS-AO3.108), and on Envisat ASAR data (project AOE-308).

2. FRONTAL FLUCTUATIONS

Fig. 2 shows a section of a geocoded ASAR image, providing an overview of Moreno glacier and its surroundings. The figure represents the mean amplitude of the following five images of track 382 in IS2 VV mode (descending orbit): 12 October 2003, 25 January 2004, 29 February 2004, 4 April 2004, 13 June 2004. Digital elevation data (DEM) of the Shuttle Radar Topography Mission (SRTM), acquired by SIR-C in February 2002 and made available by NASA [6], were used as topographic basis for terrain corrections in the geocoding procedure based on the range-doppler approach.
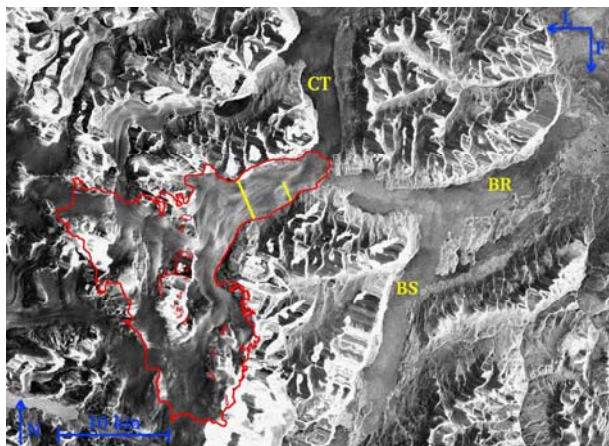

Fig. 2. Section of geocoded Envisat ASAR amplitude image, track 382, IS2 VV, descending orbit, covering and area of 55 km x 40 km, with Moreno glacier and surroundings. Average of five images acquired between 12 Dec 2003 and 13 June 2004. CT – Canal de los Témpanos of Lago Argentino, BS – Brazo Sur, BR – Brazo Rico. Red line - boundary of Moreno glacier. Arrows: flight (F) and radar look (L) direction. Yellow lines: two profiles of field measurements on Moreno glacier.

In very steep terrain (foreslopes and backslopes) the SRTM DEM has gaps which we interpolated linearly to obtain complete coverage. The comparison of the geocoded SAR images with glacier boundaries measured in the field by means of GPS rover and with mapped lakeshores shows mean differences of 1 to 2 pixels of 25 m size. The errors are larger at those sections where the SRTM DEM has gaps. We used for

ASAR the mode IS2 VV to obtain a consistent time series with ERS SAR. This mode reveals significant layover in steep mountains. The large glaciers are less affected by layover because their surface topography is gentler.
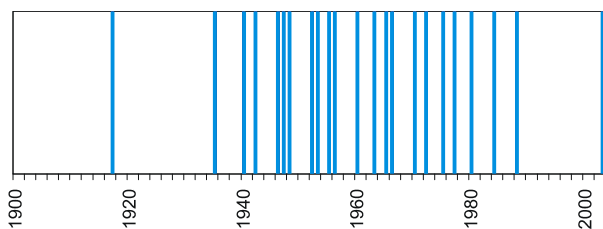

Fig. 3. Diagram showing years of Moreno damming events.

The front of Moreno glacier terminates with calving cliffs rising 50 to 80 m above the water surface. Ice calves off in the form of many small icebergs, with about 70 % ice export into Canal de los Témpanos of Lago Argentino, and about 30 % into the southern arm (Brazo Rico and Brazo Sur, Figs. 1 and 2) [3] [4]. The glacier behaves differently than the majority of glaciers in Patagonia. Moreno glacier advanced in the late 19th and early 20th century, damming the southern arm the first time in 1917 by reaching the opposite bank at Peninsula Magellanes [6]. Since that time the frontal position has fluctuated by a few hundred metres and has dammed the southern arm many times [7] (Fig. 3). Between 1934 and 1988 the temporal sequence of damming events was quite close. After 1988 there was a break of 15 years until damming started in October 2003. The damming episodes were ended by spectacular bursts of the water through the glacier front at the peninsula.

Between 1940 and 1992 only few air photos and optical satellite images of the Moreno front have been acquired [3]. Since 1992 SAR image sequences of ERS-1, ERS-2 and Envisat ASAR enable the detailed study of frontal fluctuations. The images show that the glacier front has been in an advanced position at least since 1992, with seasonal fluctuations. Whereas in summer a small channel opened between the front and Peninsula Magellanes, the ice reached the eastern shore in winter, but the water drained through channels in or below the ice without damming.

Fig. 4 illustrates the variation of frontal fluctuations of the last years. The ERS image shows the front on 2 March 1997 in a typical position for late summer. The front in the ASAR image of 12 October 2003 corresponds to the maximum advance of the last several years. In Brazo Sur the difference in the typical frontal position at the end of summers before 2002 was about 150 m, whereas in Canal de los Témpanos the advance

up to October 2003 amounted only to only 80 m in the average. This corresponds to our observations, that the frontal fluctuations have not been very significant since 1994 and that the front in Canal de los Témpanos is even more stable than in Brazo Sur.
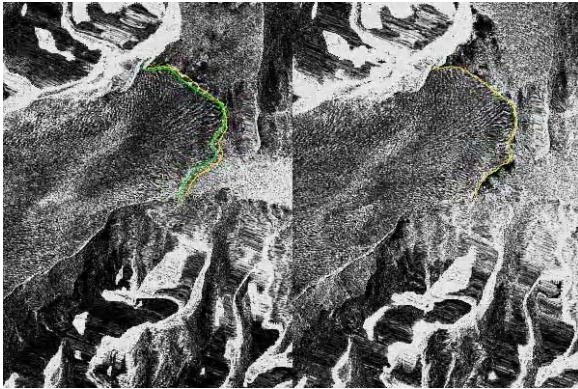

Fig. 4. Section of ERS image of 2 March 1997 (left) and ASAR image of 12 October 2003 (right) with frontal positions outlined in green (1997_03_02) and yellow (2003_10_12).

3. THE DAMMING EVENT 2003/2004

In summer 2002/2003 the ice front remained in a slightly more advanced position than in previous summers. After further advance in winter 2003 by about 100 m and thickening of the ice, the glacier started to block the water flow on 15 October 2003, and the lake level rose initially by 4 cm per day. Fig. 5 shows two photos of the glacier front, taken from the southern shore of Brazo Sur towards Peninsula Magellanes. The photo from 3 April 2002 shows a typical late summer position of the front, with the water draining from Brazo Sur to Canal del los Témpanos through a channel 30 to 40 metres wide.

The photo from 27 October 2003, two weeks after damming had started, shows an advanced position of the front, with the channel closed and ice piling up about 40 m high on the shore. The two photos, taken from exactly the same point of view, reveal also significant thickening of the glacier not only where the ice touches the shore, but along the whole glacier front. With the front rising between 50 and 80 m above the water surface, and lake depths between 50 m and 100 m along the central part of the front in Brazo Sur, the ice rest firmly on ground. Also the front in Canal del los Témpanos does not float, though the lake is somewhat deeper with maximum depth of 140 m.

With glacier melt intensifying, the rise of the water level accelerated, peaking at about 10 cm per day in January and February 2004. This caused major flooding along the eastern shore of Brazo Rico where the terrain is flat

Fig. 5. The front of Moreno Glacier at Peninsula Magellanes, photos taken from the southern shore of Brazo Sur toward north on 3 April 2002 (top) and on 27 October 2003 after start of damming (bottom).

(Fig. 6). On the other parts of the lake, except a few small section of Brazo Sur, there was little impact of the rising lake level, because the shore is steep. The ASAR image of 29 February 2004 shows the flooded area of 22 km^2 on the eastern section of Brazo Rico. The lake level had risen by about 8 m. For some of the previous damming events higher lake levels had been reported, up to a maximum rise of 22 m, as inferred from the height of the undisturbed vegetation above the water level.

As for several of the previous ruptures, the collapse of the dam happened in late summer. On 12 March 2004 the water started to drain first through fissures and then through a tunnel which opened in the afternoon. Two days later the ice bridge above the widening tunnel and part of the adjoining ice front of 60 m height collapsed in a spectacular burst. The ASAR image of 4 April 2004 shows the shoreline in Brazo Rico at pre-damming position. The pasture land that had been flooded, reveals higher backscattering intensity than the surroundings because of increased backscattering due to high soil wetness. In a later ASAR image from 13 June 2004, the backscattering coefficient of this area had decreased to a lower value typical for dry grassland.
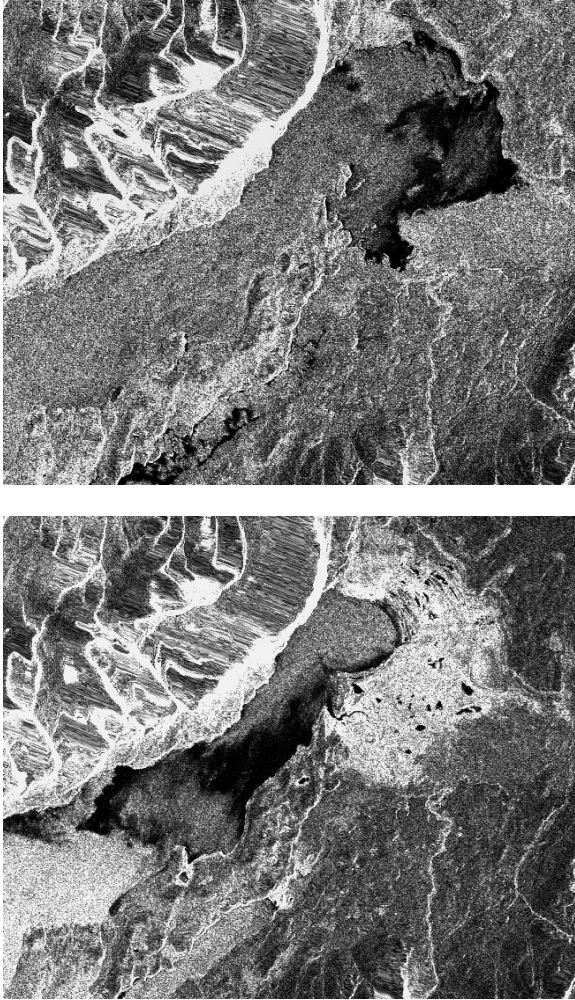
Fig. 6. Section of geocoded ASAR image, track 382, at Brazo Rico, on 29 February 2004 near the maximum of the flood (top) and 4 April 2004, three weeks after the rupture of the dam (bottom).

4. GLACIER RESPONSE TO CLIMATE FACTORS

Most of the glaciers of the Southern Patagonia Icefield have been subject to considerable retreat during the last 50 years, but there have been a few striking exceptions [1, 8, 9, 10]. A few glaciers, such as Moreno glacier, have been stationary or advanced. Most remarkable is the net advance of about 10 km of Pio XI glacier from 1945 to 1995. Pio XI is a tide water glacier on the west coast covering 1260 km^2 in area [11].

The asynchronous behaviour of calving glaciers can partly be explained by processes acting at the glacier bed and a strong influence of the orography at the terminus [12]. This may retard the advance in case of increased net accumulation, as assumed for Moreno glacier in the late 19th century, or it may accelerate

retreat, in particular if the glacier front moves into deeper water [13].

The climate of the Patagonia Ice Sheets is governed by strong and persistent westerly winds resulting in a very high percentage of days with dense clouds and precipitation [14]. The Andes mountains act as orographic barrier, resulting in strong west-east gradients of precipitation with maxima of mean annual precipitation of about 8000 mm, falling mainly as snow on the accumulation plateaus of the icefield. In El Calafate, situated on Lago Argentino 50 km to the east of the Moreno terminus, the annual precipitation amounts only to 200 mm. Because of the influence of the cold ocean and the vicinity to Antarctica, the mean air temperatures are lower than in comparable latitudes of the northern hemisphere, in particular in summer.

The measurements at the climate station, located close to the glacier margin on Brazo Sur at an elevation of 192 m a.s.l, confirm the strong influence of maritime air masses also on the lee side of the Andes mountains. The mean monthly temperatures of the 8 years time series vary between +2.3° C in July and +10.1°C in January, a small annual amplitude that is typical for maritime climate. The absolute minimum temperature of the time series between November 1995 and October 2003 amounted to -9.7°C. In Fig. 7 mean temperatures are plotted in three seasons: the main ablation season on the glaciers (November to March), the winter months June to August, and the transition period (April, May, September, October).
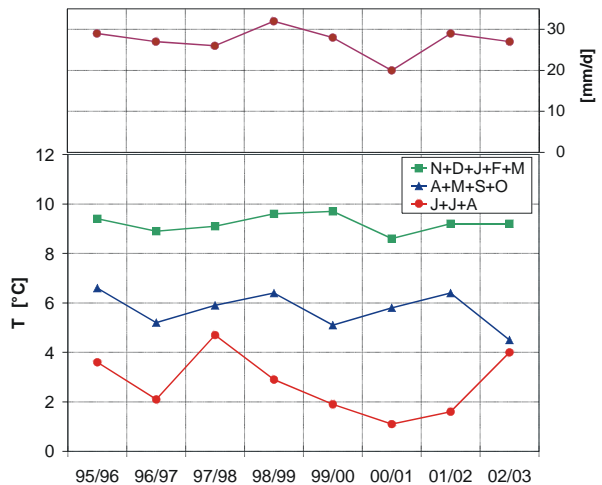

Fig. 7. Air temperature and ablation measurements on the Moreno terminus. 1 November 1995 to 31 October 2003. Top: Mean annual ablation in mm/day at the centre of the lower profile. Bottom: Mean temperature for the main ablation season (November to March), the transition period (Aug., May, Sep., Oct.) and winter (June to August).

The upper graph in Fig. 7 shows the mean annual ablation (in mm water per day) measured in the centre of the glacier at the lower profile, 200 m in elevation above the climate station. The annual periods for ablation and temperature shown in the figure range from 1 November to 31 October of the next year. The total melt varies between 7.3 m in the year 2000/2001 up to 11.7 m in the year 1998/1999. Extrapolating the air temperature at the station to the elevation of the profile, a positive degree-day factor (the coefficient converting degrees above 0°C to mm of melt) of 6 mm d^{-1} $°C^{-1}$ is derived for the main melt period [3]. This is a comparatively low value for mountain glaciers [15] and can be explained by the fact that the ice is very clean. Towards the margin of the glacier, where the albedo of the ice is lower, the degree-day factor increases by about 20%. Towards the winter months the degree day factor decreases significantly because of reduced solar irradiance.

We estimated the various components of the glacier mass balance by spatial extrapolation of ablation and calculation of mass fluxes derived through the upper profile on the glacier and through the calving front [3], [4]. The numbers indicate that Moreno glacier has an approximately balanced mass budget. The motion field for calculating the mass fluxes was derived by means of interferometry based on one-day repeat pass C-band SAR data of the Shuttle Radar Topography Mission, complemented by GPS motion measurements at stakes. The bedrock topography at the profiles was measured by seismic reflection survey, revealing a maximum ice thickness of 700 m in the centre of the upper profile. As an average value for the accumulation area the specific annual net accumulation is estimated at 5500 mm water equivalent which is among the highest values worldwide. About 64% of the accumulated mass are lost by surface melt, and 36% by calving.

The stability of the glacier front, revealing only small fluctuations since 80 years, is also a clear indication that the mass budget of the glacier has been approximately in balance since that time. Another indication are the lateral boundaries of the terminus which are very close to the maximum extent of the last centuries, marked by moraines at the margin of dense forests.

Fig. 8 shows a photo of glacier ice on the orographically right margin of the glacier, about 1.5 km above the calving front taken few days after the start of lake damming. In the background of the image, only about 40 m from the ice, the dense, old beech forest is visible. The ice pushes sideways across the lateral moraine, and is deformed as a plastic material. We observed similar advances of glacier ice onto lateral moraines in other years at the end of winter, but they were less pronounced than in winter 2003.

Fig. 8. Photo of advancing glacier ice at the right margin of Moreno glacier, taken on 25 October 2003.

Neither the temperature time series at the station El Calafate, nor the 8-year measurements at the station Moreno (Fig. 7) provide an indication that the 2003/2004 advance and damming should be understood as response to a climate signal. Because the response time of mountain glaciers is at the multi-annual to decadal time scale, depending on orography, size and mass turnover [16], the measurements series at Moreno station would be too short for detecting a climate signal. The temperature measurements at El Calafate do not reveal a clear long-term trend. On the other hand, the retreat of the majority of glaciers of the Patagonia Icefields during the last decades points out that the climate conditions have not been favourable for glaciers [8], [10].

The trends measured at climate stations in Patagonia were not very pronounced during the last century, however a slight overall trend of warming has been recognized until the mid-1980s[14]. Regarding precipitation, significant variability has been observed at decadal time scales with large differences between individual stations. Several Pacific coastal stations show an increase in precipitation after the mid-1980s [14], but it is not know how this translates to accumulation on the icefields.

A possibility for glacier advances out-of-phase with climate signals are surge mechanisms that are characterized by quasi-periodic oscillations between long periods of normal motion and brief periods of fast motion, associated with short-term changes of the basal hydraulic system of a glacier [17]. Our observations on Moreno glacier do not indicate a surge-type behaviour. The 8-year time series of ice velocity measurements shows very little inter-annual variations. In the centre of the lower profile, for example, the mean annual velocity varies between 1.44 m/day and 1.51 m/day, an overall variability of less than 5 %. Consequently the 2003/2004 damming event is very likely the effect of a

minor fluctuation of mass balance and mass fluxes of a glacier which is close to balance.

The question why Moreno glacier behaves differently from other glaciers can be explained by the particular glacier geometry and the lake bottom topography at the calving front, which on one hand retarded the frontal advance during glacier-friendly climatic conditions, on the other hand seem to inhibit further advance by blocking the ice flow. Another reason is the comparatively steep surface topography at the boundary between accumulation and ablation area (the equilibrium line). Shifts in the elevation of the equilibrium line due to unfavourable climatic factors (higher temperatures and/or reduced snowfall) cause only a small relative decrease of the ratio of accumulation area to ablation area [4], [18]. This is evident by comparing the snowline on Moreno glacier with that of the adjoining Ameghino glacier which was affected by major retreat after 1970, accelerated due to formation of a pro-glacial lake [3].
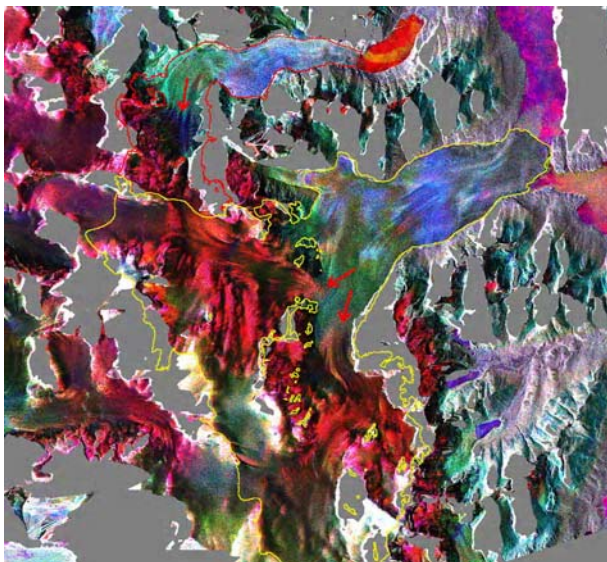

Fig. 9. Section of geocoded ERS-2 SAR image, track 247, descending orbit, colour composite of 3 dates. Blue: 20 October 1995. Green: 2 February 1996. Red: 8 March 1996. Grey: layover areas. Ameghino glacier is outlined in red, Moreno glacier in yellow. The red arrows point to the snowline on 2 Feb 1996.

Fig. 9 shows a section of a multi-temporal composite of geocoded ERS-SAR images of descending orbit, with Moreno glacier and Ameghino glacier (glacier area 62 km^2) outlined. The colours indicate different backscattering amplitudes at the different dates. The red colour of the lake in front of Ameghino glacier, for example, can be explained by high backscattering of the wind-roughened water surface on 8 March 1996. The ice surfaces on the glaciers reveal only small differences in backscattering between the three dates, resulting in greyish-green to pale blue colour in the composite image. Because the reflectivity of the snow at melting stage is particularly low in the image of 2 February 1996, the snow areas show up in purple colour.

On Moreno glacier the snow line was situated at an elevation of about 1100 m on 2 February and on 8 March 1996, on Ameghino glacier at 900 m and 950 m, respectively. On Ameghino glacier the snow area retreated further between the two dates; this area is characterized by dark blue colour in Fig. 9. On the average over several years the snowline in late summer corresponds to the equilibrium line. With this assumption the snow boundary in the image of 8 March 1996 infers a ratio of accumulation area to total glacier area $S_c/S = 0.71$ for Moreno glacier and $S_c/S = 0.42$ for Ameghino glacier. For maritime, non-calving glaciers S_c/S–values of 0.6 are typical for balanced mass budgets. For calving glaciers the ratios should be higher to be in balance, depending on the magnitude of the calving flux. The SAR images, which are available since 1992, show low S_c/S ratios for Ameghino glacier through all the years, a clear hint to persistent negative mass balance. For Moreno glacier the interannual variations of the equilibrium line are small.

5. CONCLUSIONS

Satellite-based SAR images of ERS and Envisat enable long-term observations of glaciers world wide with high temporal and spatial resolution, thus providing an excellent basis for documenting the climate response of glaciers and investigating processes of glacier/climate interaction.

In this paper we report on glacier studies on the Southern Patagonia Icefield, a remote region of great interest for climate research and glaciology. The satellite data, in synergy with field measurements, enabled to study the changes of glacier boundaries and accumulation areas over many years. In the light of these data the 2003/2004 lake damming event due to advance of Moreno glacier can be considered as minor fluctuation of mass fluxes of a glacier close to equilibrium. The balanced budget of Moreno glacier can be explained by the particular geometry of the calving front and the steep surface topography at the equilibrium line. The majority of glaciers in Patagonia is subject to significant mass losses during the last decades, as shown for the adjoining Ameghino glacier.

6. ACKNOWLEDGEMENTS

7. REFERENCES

1. Casassa G., Rivera A., Aniya, M. and Naruse, R., Current knowledge of the Southern Patagonia Icefield, in: *The Patagonia Icefields,* (Casassa et al., Eds.), Kluwer Academic, New York etc., 67-83, 2002.

2. Warren, C. R. and Sugden D,E., The Patagonian icefields: a glaciological review. *Arct. Alp. Res.*, Vol. 25(4), 316-331, 1993.

3. Stuefer M., Investigations on mass balance and dynamics of Moreno Glacier based on field measurements and satellite imagery*, PhD Thesis, University of Innsbruck, Austria, 1999.*

4. Rott H., Stuefer M., Siegel A., Skvarca P. and Eckstaller A., Mass fluxes and dynamics of Moreno Glacier, Southern Patagonia Icefield. *Geophys. Res. Lett.*, Vol. 25(9), 1407-1410, 1998.

5. *http://www2.jpl.nasa.gov/srtm/*

6. Reichert F., *Regiones andinas inexploradas de la Patagonia austral.* In: A. Kölliker at al., Patagonia – Tomo I, Sociedad Cientifica Aleman, Buenos Aires, pp. 95-214, 1917.

7. Liss. C., Der Morenogletscher in der Patagonischen Kordillere*, Z. f. Gletscherkunde und Glazialgeol.*, *Vol. 6, 161-180, 1970.*

8. Aniya M., Sato H., Naruse R., Skvarca P.and Casassa G., Recent glacier variations in the Southern Patagonia Icefield, South America. *Arctic and Alpine Res., Vol. 29, 1-12, 1996.*

9. Skvarca P., Stuefer M. and Rott H., Temporal changes of Glaciar Mayo and Laguna Escondida, southern Patagonia, detected by remote sensing. *Global and Plan. Change*, *Vol. 22, 245-253, 1999.*

10. Rignot, E., Rivera A. and Casassa G., Contributions of the Patagonia Icefields of South America to sea level rise. *Science*, *Vol. 203, 434-437, 2004.*

11. Rivera, A. and Casassa G., Volume changes of Pio XI glacier, Patagonia: *1975-1995. Global and Plan. Change*, Vol. 22, 233-244, 1999.

12. Van der Veen C.J., Tidewater calving. *J. Glaciol.,* Vol. 42 (141), 375-385, 1996.

13. Venteris E.R., Rapid tidewater glacier retreat: a comparison between Columbia Glacier, Alaska and Patagonian calving glaciers. *Global and Plan. Change,* Vol. 22, 131-138, 1999.

14. Carrasco J.F., Casassa G. and Rivera A., Meteorological and climatological aspects of the Southern Patagonia Icefield. in: *The Patagonia Icefields, (Cassa et al., Eds*.), Kluwer Academic, New York etc., 29-41, 2002.

15. Braithwaite R.J. and Zang Y., Sensitivity of mass balance of five Swiss glaciers to temperature changes assessed by tuning a degree-day model. *J. Glaciol.*, Vol. 46 (152), 7-14, 2000.

16. Weber S.L. and Oerlemans J., Holocene glacier variability: three case studies using an intermediate-complexity climate model. *The Holocene,* Vol. 13(3)*,* 353-363, 2003.

17. Raymond C.F., How do glaciers surge ? A review. 1987. *J. Geophys. Res.,* Vol. 92(B9), 9121-9134, 2002.

18. Naruse R., Aniya M., Skvarca P. and Casassa G., Recent variations of calving glaciers in Patagonia, South America, revealed by ground surveys, satellite-data analyses and numerical experiments, *Ann. Glaciol.,* Vol. 21*,* 297 – 303, 1995.