Substantial changes happened during the last years in the icecap of King George, Insular Antarctica

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ABSTRACT
One of the areas on Earth where more significant effects of the Global Warming are being found is the area of the Peninsular and Insular Antarctic, between latitudes 62ºS - 63ºS. And in this part we have located one of the register stations of glacier discharge within the GLACKMA Project, the one called CPE-KG-62ºS, in the Collins icecap in the King George Island. The time series of glacier discharge obtained during these last years shows that differential aspects in the habit of its annual hydrograph are beginning to become evident. The glacier is losing characteristics typical of subpolar glaciers and beginning to show some more typical of temperate glaciers.
In addition, with the generated time series of glacier discharge, it has been possible to register how the discharge wave begins earlier every year and ending later, increasing therefore the number of days that the discharge lasts every year. Discharged volume also increases in a significant way.
Besides these data obtained from the recorded time series, from January, 2001, very significant qualitative changes in the glacier catchment area have been observed: increase in the speed of glacier sliding, increase in the fragile answer of the glacier ice, appearance of new moulins and appearance of new cracks and faster evolution of the existing ones.

KEY WORDS: annual discharge wave, cryokarst, experimental catchment area (CPE), glacier discharge, moulins, subpolar glaciers, seracs, time series

Introduction

As part of the GLACKMA Project that we began to develope in 2001, we have already implemented six Experimental Catchment Areas (CPE), three in the northern hemisphere and three more in the southern one (8670 data per year per measured parameter in each station). These six stations register temporal series with hourly intervals of, among other parameters, glacier discharge.

In the Southern Hemisphere:

- CPE-ZS-51ºS, in the Chilean Patagonia;
- CPE-KG-62ºS, in Insular Antarctic;
- CPE-VER-65ºS, in Antarctic Peninsula.

In the Northern Hemisphere:

- CPE-KVIA-64ºN, in Iceland;
- CPE-TAR-67ºN, in the North of Sweden;
- CPE-ALB-79ºN, in Svalbard;

In the present work we analysed registered data obtained during these years in the monitoring station of the Insular Antarctica CPE-KG-62ºS.

During this period substantial changes have been detected in the glacier icecap (subpolar glacier). These changes indicate a tendency in its behaviour more similar to the tempered glaciers than to the subpolar glaciers (Six *et al.*, 2001; Vincent *et al.*, 2004; Dyurgerov, 2003; Swift *et al.*, 2002; Swift *et al.*, 2005).

We based on a karstic approach to glacier drainage, which has been widely studied by Eraso and Pulina (2001). Now we will review the basic concepts and briefly present this approach.

Based on the chart that summarises the different classification of glacier types (Baranowski, 1967), (Eraso, Pulina, 2001), we can state that:

- in cold glaciers of polar type, with ice temperature always below zero, there is no criokarst,
- in transitional glaciers of subpolar type, with ice temperature below zero at some points and equal to ice melting at others, it appears in four of the five existing types, and
- in glaciers of temperate type, with all the glacier mass at 0ºC, we have criokarst.

This means that karst in ice evolves in glaciers located in: the Antarctic and Greenland periphery, the big islands of the Canadian Arctic, the Arctic and Antarctic archipelagos and their influence areas (Iceland, for instance), the great mountain ranges on the planet and some mountains not too high (for example, Patagonia).

Main evidence on which the importance of measuring glacier discharge is based, are enumerated below:

1. The existence of criokarst, responsible for intraglacier (endoglacier and subglacier) drainage, which appears in glaciers when their temperature is 0ºC (Badino, 1991; Mavlyudov, 1994; Rehak, Rehak, 1994; Reynaud, Moreau, 1994; Schroeder, 1994).
2. The peculiar organization of intraglacier drainage, which follows specific modal directions, dependent on glacier anisotropy (Eraso *et al.*, 1992, 1996, 1997; Domínguez *et al.*, 2001; Domínguez, Eraso, 2001).
3. The evidence, through ‘in situ’ observation inside glaciers, that the mechanism that widens endoglacier drainage conduits is melting friction (Röthlisberger, 1996).
4. The directly proportional influence of air temperature on glacier internal ablation responsible of the glacier discharge (Pereyma, 1991).
5. The verification that some internal reflections found through radio-echo-sounder inside glacier ice, correspond to drainage conduits or endoglacier rivers (Glazowsky, Jania, Moskalevsky, 1991; Moskalevsky, 1994; Macheret *et al.*, 1996).
6. The relevance of glacier discharge in subpolar glaciers against temperate ones (Domínguez, Eraso, Lluberas; 2004; Domínguez, Eraso; 2001; Eraso, 2004; Eraso, Domínguez, 2004).

Field site and monitoring

The study area is located on the SSW flank of the Collins icecap, also called Smaller Dome or Bellinsghausen Dome, located on the SW of the King George Island, next to the Uruguayan Antarctic Base Artigas (BCAA).

Collins glacier, with 1313 km^2 of width, occupies almost all of King George Island, except its south-western end where Fildes Peninsula, one of the main doors to the Antarctic by air, is located.

Hydric discharges from the selected glacier icecap in the Smaller Dome generate a fluvial network composed by nine springs that flow into both sides of the coast, both the slope of the Drake Straits (North side of the island) and the slope of Bransfield (South side).

Discharge into the Bransfield side is represented by 5 springs that, after diverse proglacier routes, converge all at a small lagoon (where the ionospheric observation station is located) next to Base Artigas. The referred lagoon flows into the sea by a unique river that runs next to said Base. Under the access bridge to this Base, our measuring station, called CPE-KG-62ºS, is installed.

The sector of the glacier icecap from which the five rivulets that drain to our CPE river discharge, constitutes a catchment area whose characteristics are:

- surface of the glacier catchment area = 1,31 km^2;
- surface of the peripheral moraine = 0,25 km^2;
- surface of the fluvial catchment area = 1,36 km^2;
- total surface = 2,92 km^2.

The surface of the glacier catchment area has been determined by radar geophysical workings (radio-eco-sounder) based on the topography of the base rock, under the glacier ice (Braun *et al.*, 2001a, b, 2003). The rest of the cartographic information comes from satellite photos, local maps with known error, and direct field measurings with GPS, made to determine the surface of the proglacier fluvial catchment area, upriver from the CPE, whose coordinates are: Lat: S 62º 11' 035, Long: W 58º 54' 414, Alt: 24 m AMSL.

The measuring station has been equipped with register instruments of SEBA *Hydrometrie* Company, from Germany. We are working at the six CPE's monitored until now with this type of instruments. There are different models according to the measuring sensors they are equipped with, but basically they can be classified in two types, the MPS type sounders and the MDS type sounders.

In January 2002, we began to work at this station with an MPS type sounder, that is to say a multiparametric sounder that registered conductivity, water temperature and level. After continuous measuring with hourly records during two complete years, flaws in the external data-logger appeared due to the hard meteorological conditions during the winter months and a phenomenon of spring-event. This originated a non-valid register during the summer of 2003/04. After that, we replaced it by an MDS type sounder. In this case only river level is measured, but it is an exceptional sounder regarding its resistance to the low temperatures in which it must work. In addition, its battery and data-logger are water-proof, continuous reading of the river surface level by means of a pressure-measuring cell with piezoresistant sensor, with automatic hourly recording.

In order to generate the time series of glacier discharge from the river level one, we used the calibration curve between volume and level. This curve is an exponential function that we determined by means of a concise campaign of gaugings, carrying out systematic measurings at different level values.

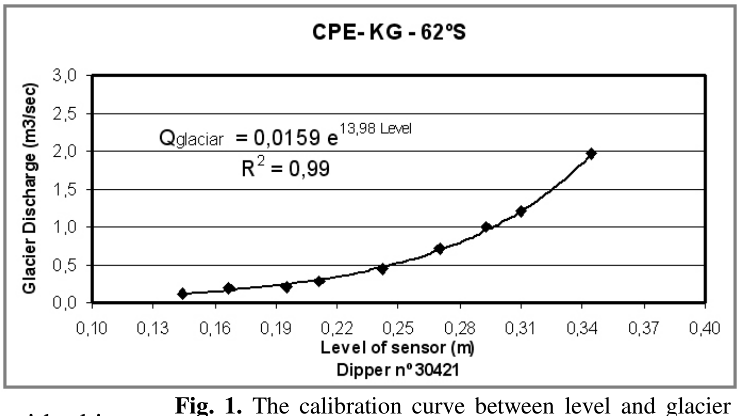

Fig. 1. The calibration curve between level and glacier discharge for CPE-KG-62ºS

The depth profile of the river is measured each time we gauge since it usually changes due to the abrupt swellings that take place in the river. We work according to a protocol of gaugings that we have elaborated, and with special software that we have designed specifically for the characteristics of the catchment areas where we work (Domínguez, 2004). The material used for the gaugings is a universal windlass F1, also from SEBA *Hydrometrie*, that is designed to determine water speed in rivulets and rivers, with defined algorithm and dynamic range.

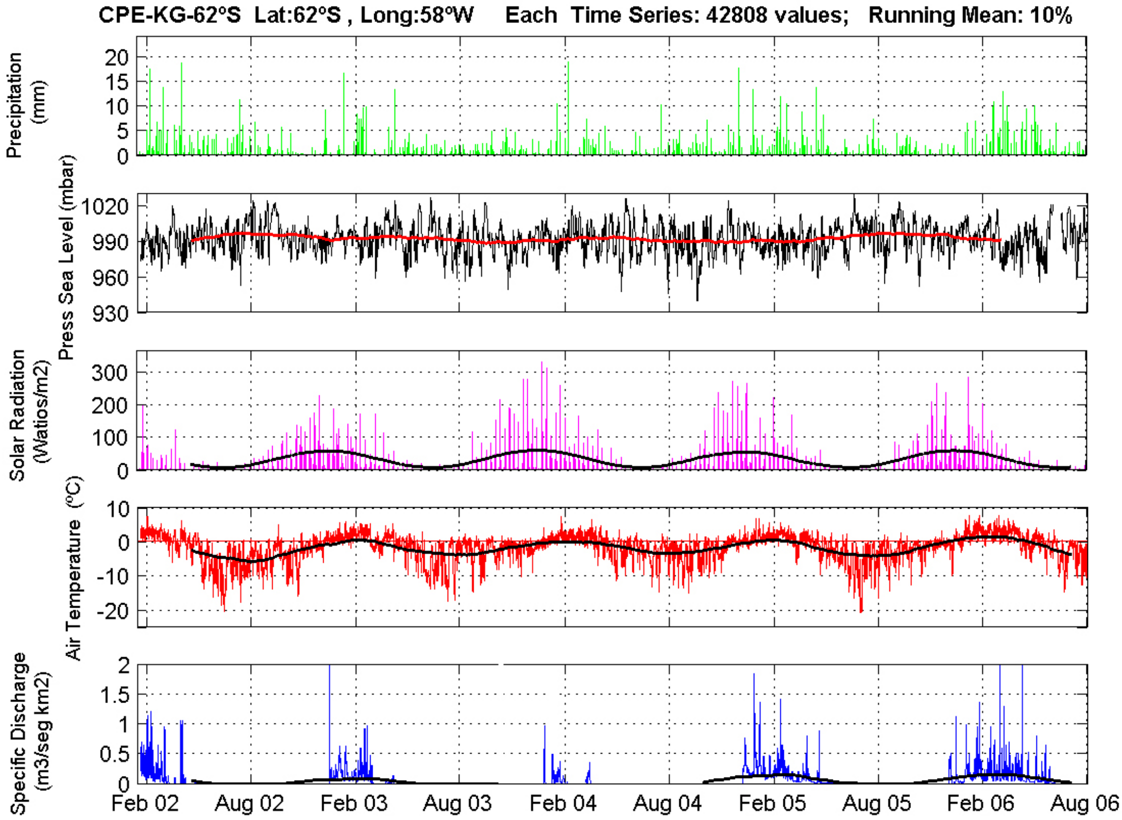

Fig. 2. Time series for both the meteorological and glacier discharge parameters.

The calibration curve between level and volume for CPE-KG-62ºS station with correlation coefficient $R^2 = 0{,}99$, is shown in Fig. 1 and it lets us get an accurate discharge law for this glacier.

Time series of meteorological parameters (air temperature, solar radiation, atmospheric pressure and precipitation) are obtained from the weather station of the Antarctic Russian Base Bellinsghausen, located 4 km from the glacier edge, where CPE-KG-62ºS station is installed.

Fig. 2 shows time series for both the meteorological and glacier discharge parameters, this last one obtained from the level time series measured by the previously mentioned sounder and the adjustment curve between both parameters (Fig. 1):

$$Q_{glacier} = 0{,}0159 e^{13{,}98 \cdot level}$$

Each time series consists of 42808 synoptic values for the represented period, from the 20th of January, 2002, to the 31st of September, 2006. They are hourly measures for each parameter, except precipitation, which is given in accumulated daily values. For each complete data series we represent the one obtained after using a noise filter, we have used a moving average of 10% on the whole set of data. In the summer of 2003/04 is when the installed sounder was damaged by the extreme winter conditions and the spring-event that took place at the beginning of summer. Later it was replaced by a tougher one of MDS type, as described in the first section. That is why, in the glacier discharge time series represented in Fig. 2, we cannot consider the data from the 2003/04 summer, as its information is wrong due to the flooding of the CPU sounder.

Glacier discharge analysis

Characteristics of the glacier discharge

Before analysing the previous data for each year, we will describe, in a general way, some characteristics of glacier discharge.

The time series of glacier discharge is characterized by having differential aspects in its annual hydrograph habit. Its typology displays 4 different habits:

The annual discharge wave

It is the most important, and consists of a section in the time series that begins with an increasing tendency, reaches a maximum that corresponds to the higher atmospheric temperatures – its barycentre usually coincides with midsummer – to continue with a decreasing tendency.

In glaciers of the South hemisphere, these higher values usually coincide with the last days of January and first of February, whereas for the North hemisphere the dates correspond to the last days of June and first of August.

The discharge wave usually lasts from 2 to 6 months, being shorter the higher the latitude and/or the altitude are.

Generally more than 90% of the drained volume or the volume discharged by the glacier corresponds to the annual discharge wave.

The threshold of glacier discharge

It consists of a section of the time series that refers to small volumes that glaciers sometimes discharge during the corresponding winter time (austral or boreal, depending on the hemisphere). Their values are smaller than the annual mean value of the discharge.

Discharge threshold usually lasts from 5 to 10 months, being null its discharge when dealing with subpolar or polythermal glaciers. On the contrary, in temperate glaciers, the discharge threshold can get to drain small volumes all along the year.

Aftershocks

They are kicks in the glacier drainage that may appear when the annual discharge wave seems to be over.

They are due to alternating cold and heat episodes that cause fluctuations in the habit of the discharge hydrograph. They are more characteristic of temperate glaciers. In subpolar glaciers they predict, in a certain way, an increase in the duration of the discharge wave that will show in the following years.

"Spring-events" or bursts

They consist of episodes or events, as brief as violent, in which the glacier brutally discharges a great water volume. They generally disappear in a few hours.

Their explanation is the plasticity of ice: when the discharge wave finishes and the inner conduits of the glacier stop draining water; they tend to close by deformation, sealing the horizontal sections of the underground

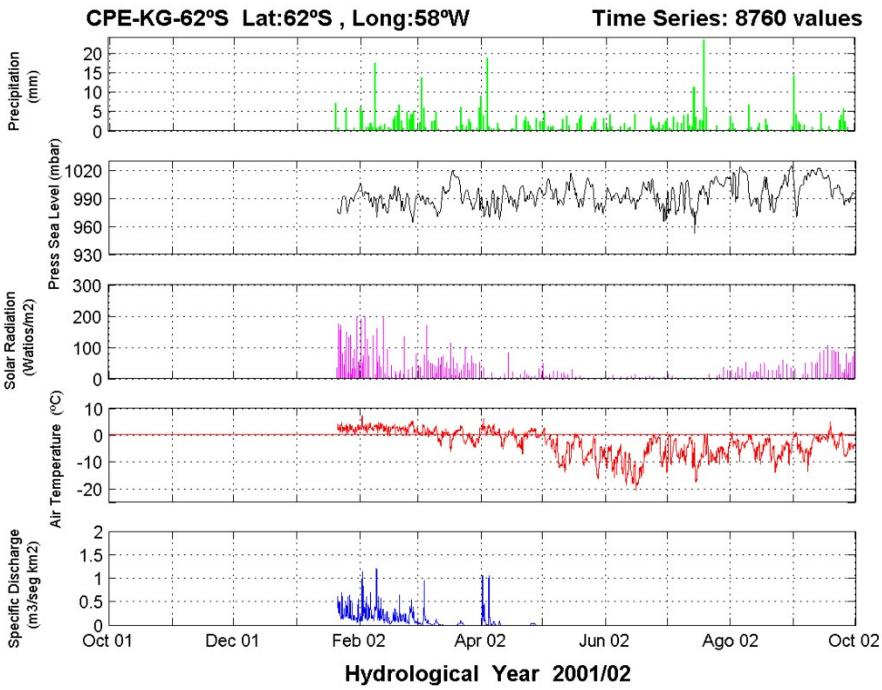

Fig. 3. Time series corresponding to the hydrologic year 2001/02.

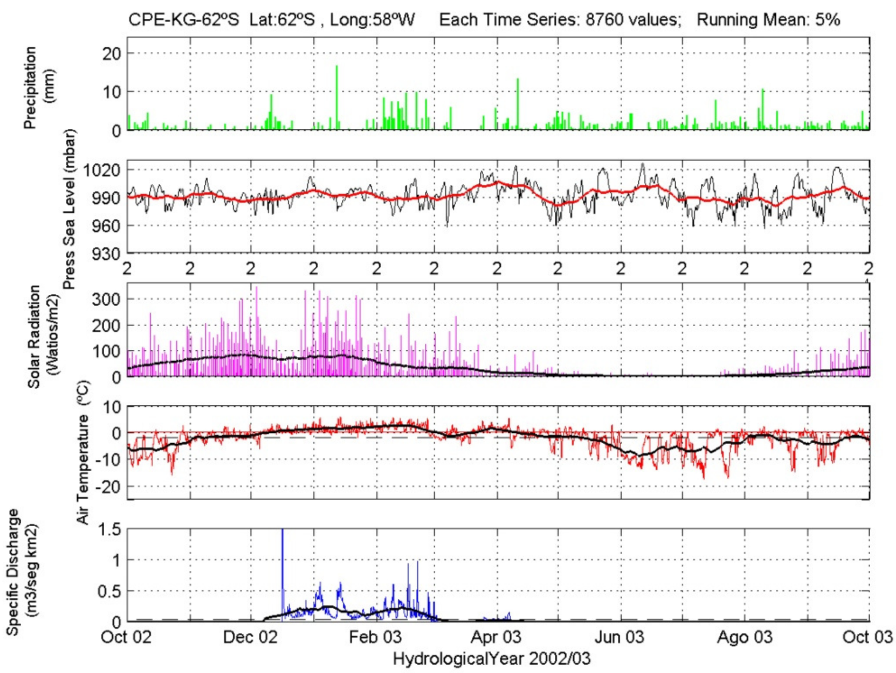

Fig. 4. Time series for the hydrologic year 2002/03, the complete series of data and the ones obtained using a moving average filter of 5%.

Table 1. Different meteorological and hydrological parameters for each one of the parts of the hydrologic year 2003/04.

HYDROLOGIC YEAR 2002/03

Description			Hydrologic Year	W.+ A.+ Mi Th. (*)	Wave + Aftersho.	Wave	Aftershock
Date		Beginning	01/10/2002 00:00	16/12/2002 03:00		16/12/2002 03:00	25/03/2003 00:00
		End	30/09/2003 23:00	07/04/2003 11:00		02/03/2003 10:00	07/04/2003 11:00
Number of Data	(0)		8760	2697	2156	1832	324
Temperature (°C)	(1)	Mean Value	-2,11	1,07	1,54	1,53	1,61
Solar Radiation (KW/m^2)	(2)	Accumulated value	288,9	131,7	114,3	109,8	4,4
Precipitation (mm)	(3)	Accumulated value	455,5	155,9	144,4	128,5	15,9
Total volum. specif. preci. (hm^3/km^2)	(4)	Accumulated value	0,456	0,156	0,144	0,129	0,016
Glacier discharge (m^3/sec)	(5)	Mean Value	0,058	0,187	0,234	0,264	0,064
Specific Discharge ($m^3/sec\ km^2$)	(6)	Medios (1,31 km^2)	0,044	0,143	0,179	0,201	0,049
Volume (hm^3)	(7)	Accumulated value	1,815	1,815	1,815	1,741	0,074
Specific Volume (hm^3/km^2)	(8)	Accumulated (1,31 km^2)	1,385	1,385	1,385	1,329	0,057
(8) - (4) (hm^3/km^2)	(9)	Accumulated (1,31 km^2)	0,930	1,229	1,241	1,201	0,041
K2	[(6) * (0) / 24]		16,06	16,07	16,08	15,34	0,66

(*) W.+ A.+ Mi Th. = Wave + Aftershock + Minimun Threshold

Table 2. Different meteorological and hydrological parameters for each one of the parts of the hydrologic year 2004/05.

HYDROLOGIC YEAR 2004/05

Description			Hydrologic Year	W.+ A.+ Mi Th. (*)	Wave + Aftersho.	Wave	Aftershock
Date		Beginning	01/10/2004 00:00	06/12/2004 18:00		06/12/2004 18:00	15/04/2005 03:00
		End	30/09/2005 23:00	18/05/2005 19:00		01/04/2005 11:00	20/04/2005 18:00
Number of Data	(0)		8760	3914	2914	2778	136
Temperature (°C)	(1)	Mean Value	-2,04	0,10	0,81	0,92	-1,47
Solar Radiation (KW/m^2)	(2)	Accumulated value	275,7	142,2	132,8	131,4	1,4
Precipitation (mm)	(3)	Accumulated value	650,3	355,8	294,4	260,9	33,5
Total volum. specif. preci. (hm^3/km^2)	(4)	Accumulated value	0,650	0,356	0,294	0,261	0,034
Glacier discharge (m^3/sec)	(5)	Mean Value	0,100	0,223	0,286	0,292	0,151
Specific Discharge ($m^3/sec\ km^2$)	(6)	Medios (1,31 km^2)	0,076	0,171	0,218	0,223	0,115
Volume (hm^3)	(7)	Accumulated value	2,997	3,147	2,997	2,923	0,074
Specific Volume (hm^3/km^2)	(8)	Accumulated (1,31 km^2)	2,288	2,403	2,288	2,231	0,056
(8) - (4) (hm^3/km^2)	(9)	Accumulated (1,31 km^2)	1,638	2,047	1,994	1,970	0,023
K2	[(6) * (0) / 24]		365,00	163,09	121,43	115,76	5,67

(*) W.+ A.+ Mi Th. = Wave + Aftershock + Minimun Threshold

Table 3. Different meteorological and hydrological parameters for each one of the parts of the hydrologic year 2005/06.

HYDROLOGIC YEAR 2005/06

Description			Hydrologic Year	W.+ A.+ Mi Th. (*)	Wave + Aftersho.	Wave	Aftershock
Date		Beginning	01/10/2005 00:00	30/11/2005 09:00		30/11/2005 09:00	30/04/2006 04:00
		End	30/09/2006 23:00	04/06/2006 16:00		21/04/2006 10:00	28/05/2006 23:00
Number of Data	(0)		8760	4472	4102	3410	692
Temperature (°C)	(1)	Mean Value	-1,44	1,07	1,27	1,65	-0,61
Solar Radiation (KW/m^2)	(2)	Accumulated value	293,4	168,9	166,7	164,4	2,3
Precipitation (mm)	(3)	Accumulated value	627,4	425,8	409,4	328,8	80,6
Total volum. specif. preci. (hm^3/km^2)	(4)	Accumulated value	0,627	0,426	0,409	0,329	0,081
Glacier discharge (m^3/sec)	(5)	Mean Value	0,109	0,214	0,229	0,254	0,110
Specific Discharge ($m^3/sec\ km^2$)	(6)	Medios (1,31 km^2)	0,083	0,164	0,175	0,194	0,084
Volume (hm^3)	(7)	Accumulated value	3,449	3,449	3,389	3,116	0,273
Specific Volume (hm^3/km^2)	(8)	Accumulated (1,31 km^2)	2,633	2,633	2,587	2,378	0,209
(8) - (4) (hm^3/km^2)	(9)	Accumulated (1,31 km^2)	2,006	2,207	2,178	2,049	0,128
K2	[(6) * (0) / 24]		30,30	30,56	29,91	27,56	2,42

(*) W.+ A.+ Mi Th. = Wave + Aftershock + Minimun Threshold

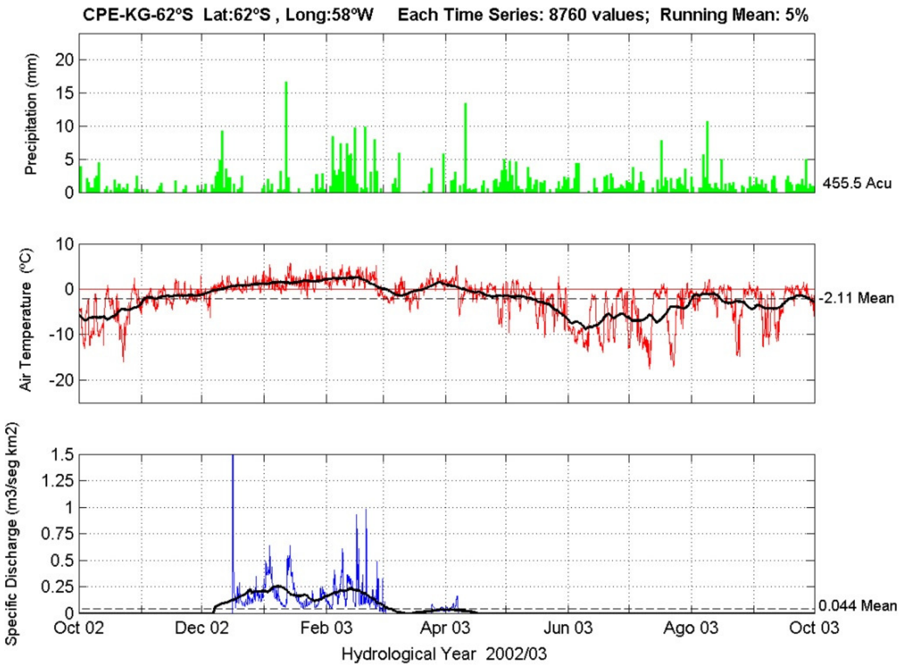

Fig. 5. As Fig. 4 but only for the air temperature and precipitation, contrasted with the specific glacier discharge.

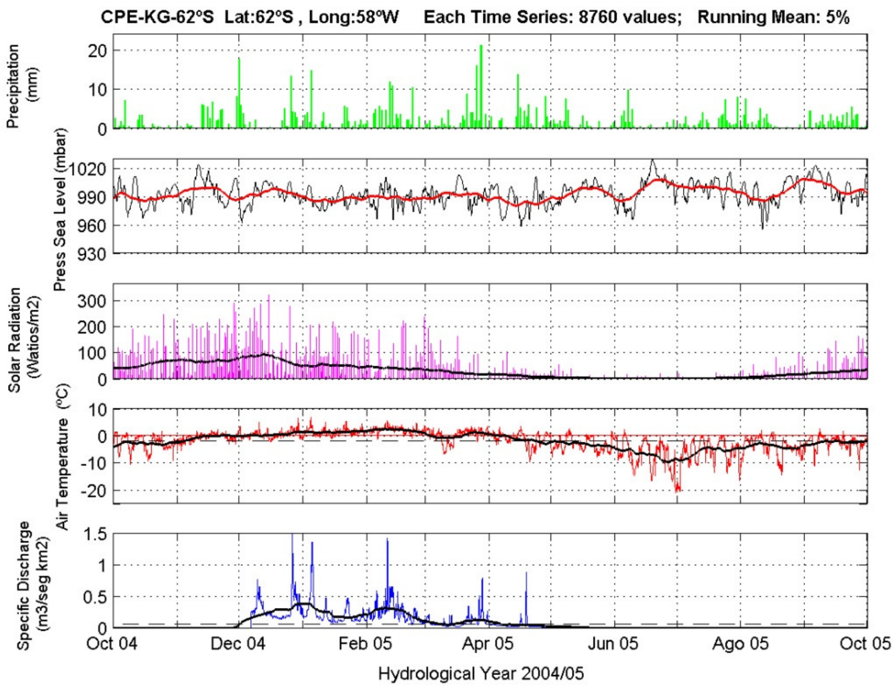

Fig. 6. Time series for the hydrologic year 2004/05, the complete series of data and the ones obtained using a moving average filter of 5%.

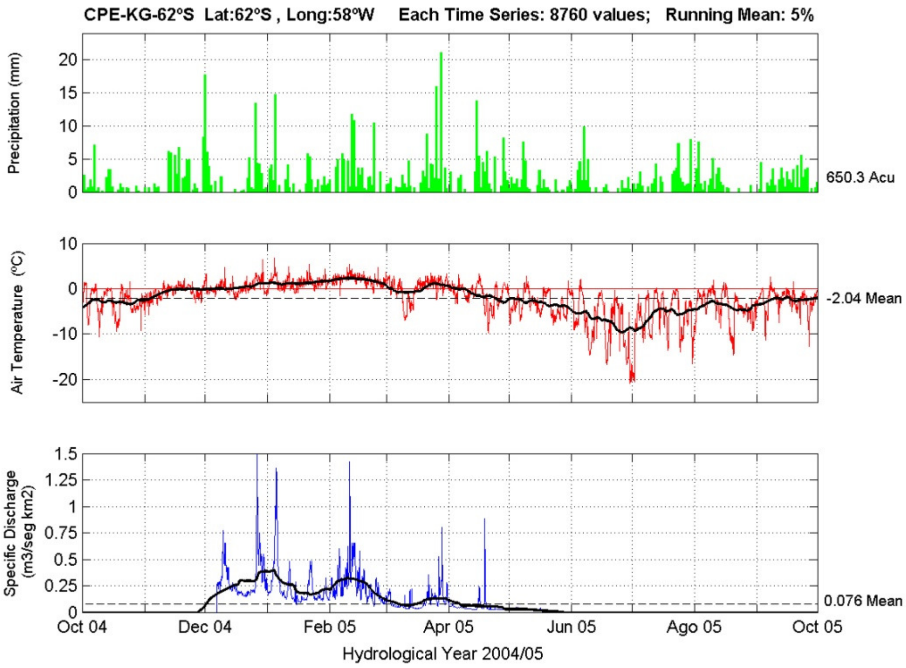

Fig. 7. As Fig. 6 but only for the air temperature and precipitation, contrasted with the specific glacier discharge.

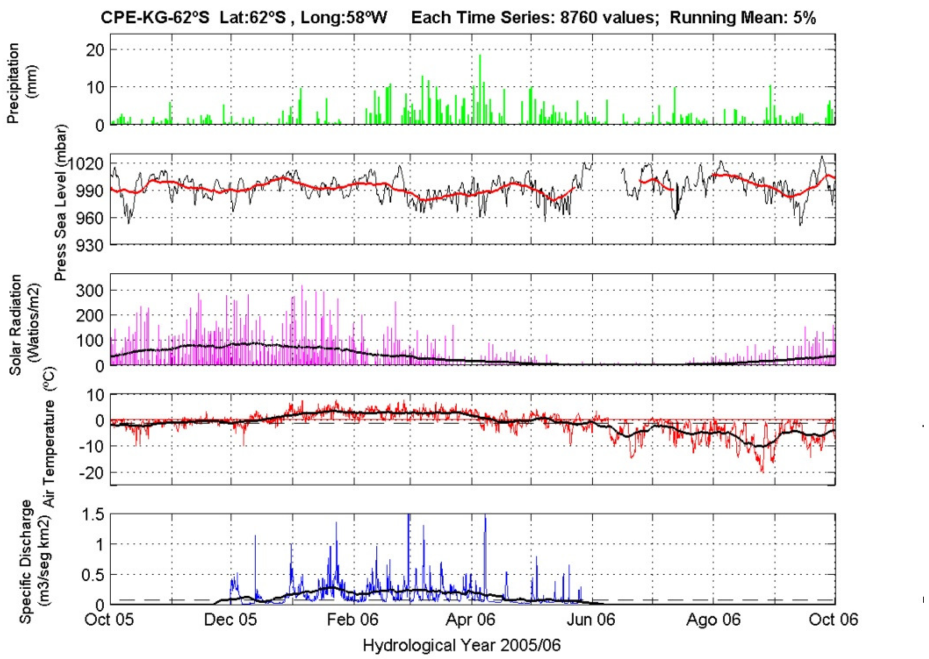

Fig. 8. Time series for the hydrologic year 2005/06, the complete series of data and the ones obtained using a moving average filter of 5%.

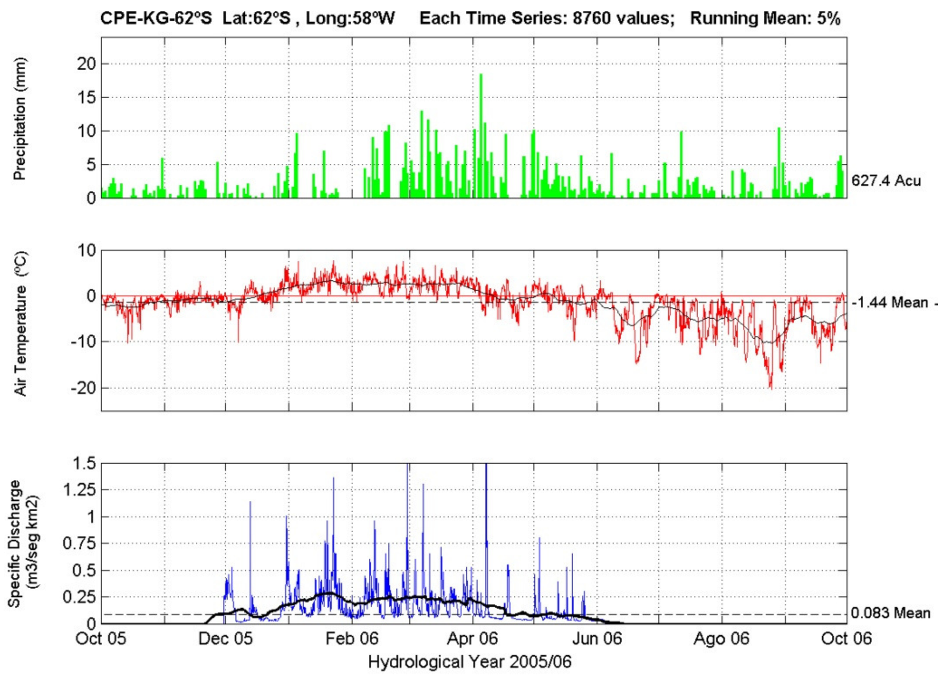

Fig. 9. As Figure 8 but only for the air temperature and precipitation, contrasted with the specific glacier discharge.

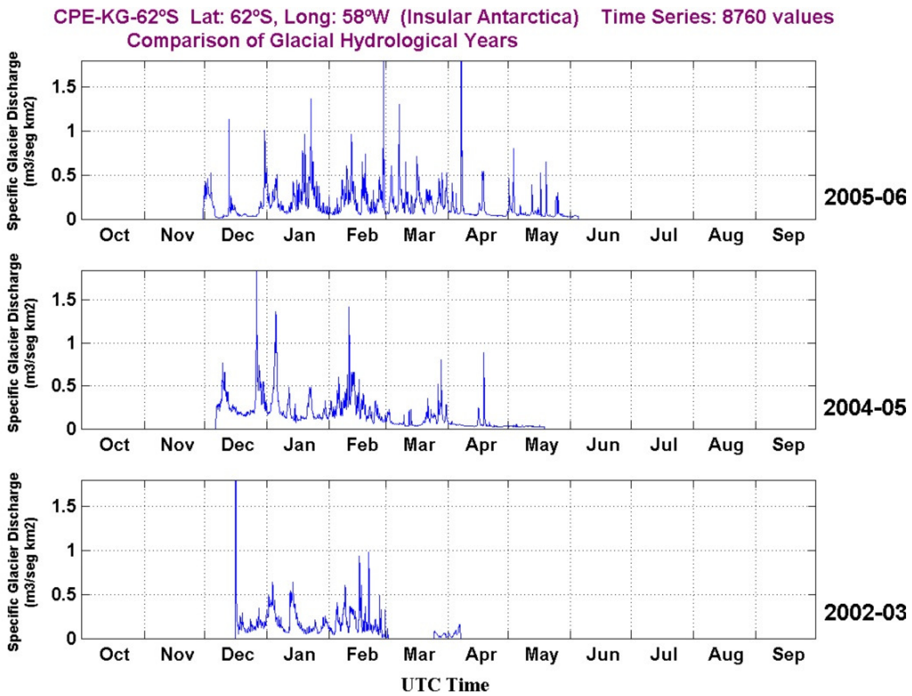

Fig. 10. Time series of glacier discharge for the three hydrologic years whose complete discharge wave we have at our disposal: 2002/03, 2004/05 and 2005/06.

drainage network. On the contrary, in vertical wells this sealing does not take place and, by slow percolation, they can get to fill during the polar winter, accumulating a latent hydraulic load that is freed at the beginning of the following summer.

When the sun rises at the beginning the following polar summer, solar radiation favours the glacier sliding, increasing it. The bottom seal of the vertical wells loaded with water is broken, violently discharging their content and opening a new drainage network whose establishment will condition the following wave of glacier discharge.

This phenomenon is typical of subpolar glaciers within the polar circles.

Analysis of the glacier discharge for each year

Taking into account the previous characteristics, and the glacier catchment area analyzed here corresponding to a glacier of subpolar type located in the Southern Hemisphere, we go on to make an analysis of the continuous time series for each year. Observing the period during which the glacier discharge takes place, we have considered the beginning of the hydrologic year for this hemisphere to be the 1st of October and its end the 30th of September of the following year.

In Fig. 3 we can see the time series corresponding to the hydrologic year 2001/02 represented. The installation of the register measuring station was carried out in January, when the hydrologic year we have just defined had already begun, therefore in this first represented year the data begin on the 20th of January, 2002.

Hydrologic year 2002/03 is synoptically represented in Fig. 4 and 5, in both cases besides the complete series of data, the ones obtained using a moving average filter of 5% on the whole data are superimposed. In Fig. 4 all the series of parameters are represented and, in Fig. 5, just air temperature and precipitation, always contrasted with the specific glacier discharge ($m^3 \cdot s^{-1} \cdot km^{-2}$). This specific unit for discharge allows us to compare big glaciers with small ones, as well as Arctic glaciers with Antarctic. Its utility at the time of interpretation is most important.

Considering the different parts of the glacier discharge wave throughout the hydrologic year that have been previously described, we elaborate a Table in which we analyze separately: the complete hydrologic year, the period included in the discharge wave, the aftershocks and the minimum threshold, the period that includes the wave and the aftershock if it takes place, the period with only the discharge wave and the period with only the aftershock if this one happens.

Thus, for each of these defined periods, we calculate:

- the number of data (that will correspond therefore to number of hours);
- air temperature: mean value (°*C*);
- solar radiation: accumulated value ($kw \cdot m^{-2}$);
- for precipitation: on the one hand, the accumulated seasonal value (*mm*) and on the other, the accumulated of total volume of specific precipitation on the glacier catchment area that drains to the measuring station ($hm^3 \cdot km^{-2}$);
- for glacier discharge: mean value ($m^3 \cdot s^{-1}$) and mean specific value by kilometre of glacier catchment area ($m^3 \cdot s^{-1} \cdot km^{-2}$);
- we express glacier discharge in drained volume and calculate: accumulated volume (hm^3), specific accumulated volume by kilometre of glacier catchment area ($hm^3 \cdot km^{-2}$) and specific accumulated volume by kilometre of glacier catchment area taking away the total of specific volume of precipitation in the glacier catchment area ($hm^3 \cdot km^{-2}$);

- finally we define the index *K2*, that relates the specific mean glacier discharge to the number of days it lasts:

$$K2 = q\ t \cdot 24^{-1}$$

where,
q- mean specific discharge;
t- number of hours.

These values are calculated for each of the parts of the hydrologic year previously indicated, obtaining Table 1.

It was during hydrologic year 2003/04 when our measuring sounder was damaged, and it was replaced by a new one with water-proof battery and data-logger, so we cannot operate with those measured values. Thus, we go on to represent the following hydrologic year 2004/05 in Fig. 6 and 7, also superimposing the series obtained when using a moving average filter of 5% on the total data. In Fig. 6 all the parameter series are represented and in Fig. 7 just discharge, air temperature and precipitation. And Table 2 is constructed as in the previous case.

Finally in Fig. 8 and 9, the series of hydrologic year 2005/06, as well as the corresponding filtered ones with moving average of 5% on total data are represented. In the series of atmospheric pressure there is a small data blank (15 days) during the first half of June, due to damages caused to the weather station by strong katabatic winds. Following the same previous strategy, in Figure 8 all the series of parameters are represented and in Figure 9 just discharge, air temperature and precipitation with the average values indicated in both first cases and the daily accumulated one for precipitation. Finally Table 3 is constructed following the same strategy used to represent the previous years.

Results and analysis

Both in Fig. 2, where the whole time series for the entire period are shown, as well as in the later figures, in which we have separately represented each hydrologic year, it is possible to observe the influence of solar radiation and air temperature in the time series of glacier discharge – with a certain delay in the case of solar radiation (about 40 days before), but direct in the case of air temperature.

In Fig. 10 we have represented the time series of glacier discharge for the three hydrologic years whose complete discharge wave we have at our disposal: 2002/03, 2004/05 and 2005/06. We have not represented in this case our first year, 2001/02, since we began measuring in January and, therefore, we do not have the complete discharge wave registered. Neither have we represented here

Photo 1. The burst at the beginning of the discharge wave of December of 2002.

Photo 2. The beginning of the discharge at the end of November in 2005.

Table 4. Comparison of the meteorological and hydrological parameters for the complete hydrological years (2002/03, 2004/05 and 2005/06).

Description		2002 / 03	2004 / 05	2005 / 06
		Hydrologic Year	Hydrologic Year	Hydrologic Year
Date	Beginning	01/10/2002 00:00	01/10/2004 00:00	01/10/2005 00:00
	End	30/09/2003 23:00	30/09/2005 23:00	30/09/2006 23:00
Number of Data	(0)	8760	8760	8760
Temperature (ºC)	(1) Mean Value	-2,11	-2,04	-1,44
Solar Radiation (KW/m^2)	(2) Accumulated value	288,9	275,7	293,4
Precipitation (mm)	(3) Accumulated value	455,5	650,3	627,4
Total volum. specif. preci. (hm^3/km^2)	(4) Accumulated value	0,456	0,650	0,627
Glacier discharge (m^3/sec)	(5) Mean Value	0,058	0,100	0,109
Specific Discharge (m^3/sec km^2)	(6) Medios (1,31 km^2)	0,044	0,076	0,083
Volume (hm^3)	(7) Accumulated value	1,815	2,997	3,449
Specific Volume (hm^3/km^2)	(8) Accumulated (1,31 km^2)	1,385	2,288	2,633
(8) - (4) (hm^3/km^2)	(9) Accumulated (1,31 km^2)	0,930	1,638	2,006
K2	[(6) * (0) / 24]	16,06	27,74	30,30

Table 5. Comparison of the meteorological and hydrological parameters for the discharge period including wave, aftershocks and minimum threshold when it exists (2002/03, 2004/05 and 2005/06).

Description		2002 / 03	2004 / 05	2005 / 06
		W.+ A.+ Mi Th. (*)	W.+ A.+ Mi Th. (*)	W.+ A.+ Mi Th. (*)
Date	Beginning	16/12/2002 03:00	06/12/2004 18:00	30/11/2005 09:00
	End	07/04/2003 11:00	18/05/2005 19:00	04/06/2006 16:00
Number of Data	(0)	2697	3914	4472
Temperature (ºC)	(1) Mean Value	1,07	0,10	1,07
Solar Radiation (KW/m^2)	(2) Accumulated value	131,7	142,2	168,9
Precipitation (mm)	(3) Accumulated value	155,9	355,8	425,8
Total volum. specif. preci. (hm^3/km^2)	(4) Accumulated value	0,156	0,356	0,426
Glacier discharge (m^3/sec)	(5) Mean Value	0,187	0,223	0,214
Specific Discharge (m^3/sec km^2)	(6) Medios (1,31 km^2)	0,143	0,171	0,164
Volume (hm^3)	(7) Accumulated value	1,815	3,147	3,449
Specific Volume (hm^3/km^2)	(8) Accumulated (1,31 km^2)	1,385	2,403	2,633
(8) - (4) (hm^3/km^2)	(9) Accumulated (1,31 km^2)	1,229	2,047	2,207
K2	[(6) * (0) / 24]	16,07	27,89	30,56

(*) W.+ A.+ Mi Th. = Wave + Aftershock + Minimun Threshold

year 2003/04, when the change of the damaged sounder took place. Analyzing Fig. 10, we can indicate the following:

- In the first place, it is interesting to emphasize how the phenomenon of spring-event, typical of this type of subpolar glaciers, takes place for the last time at the beginning of the discharge waves of 2002/03 and 2003/04, disappearing this habit in later years. We have been able not only to register this significant change in the glacier behaviour with the measuring station but we have also been present at it. In Photo 1, the burst at the beginning of the discharge wave of December of 2002 is observed, in contrast with the

Table 6. Comparison of the meteorological and hydrological parameters for the with the wave and the aftershock of (2002/03, 2004/05 and 2005/06).

		2002 / 03	2004 / 05	2005 / 06
Description		Wave + Aftershock	Wave + Aftershock	Wave + Aftershock
Number of Data	(0)	2156	2914	4102
Temperature (ºC)	(1) Mean Value	1,54	0,81	1,27
Solar Radiation (KW/m²)	(2) Accumulated value	114,3	132,8	166,7
Precipitation (mm)	(3) Accumulated value	144,4	294,4	409,4
Total volum. specif. preci. (hm³/km²)	(4) Accumulated value	0,144	0,294	0,409
Glacier discharge (m³/sec)	(5) Mean Value	0,234	0,286	0,229
Specific Discharge (m³/sec km²)	(6) Medios (1,31 km²)	0,179	0,218	0,175
Volume (hm³)	(7) Accumulated value	1,815	2,997	3,389
Specific Volume (hm³/km²)	(8) Accumulated (1,31 km²)	1,385	2,288	2,587
(8) - (4) (hm³/km²)	(9) Accumulated (1,31 km²)	1,241	1,994	2,178
K2	[(6) * (0) / 24]	16,08	26,47	29,91

Table 7. Comparison of the meteorological and hydrological parameters for only the wave proper of (2002/03, 2004/05 and 2005/06).

		2002 / 03	2004 / 05	2005 / 06
Description		Wave	Wave	Wave
Date	Beginning	16/12/2002 03:00	06/12/2004 18:00	30/11/2005 09:00
	End	02/03/2003 10:00	01/04/2005 11:00	21/04/2006 10:00
Number of Data	(0)	1832	2778	3410
Temperature (ºC)	(1) Mean Value	1,53	0,92	1,65
Solar Radiation (KW/m²)	(2) Accumulated value	109,8	131,4	164,4
Precipitation (mm)	(3) Accumulated value	128,5	260,9	328,8
Total volum. specif. preci. (hm³/km²)	(4) Accumulated value	0,129	0,261	0,329
Glacier discharge (m³/sec)	(5) Mean Value	0,264	0,292	0,254
Specific Discharge (m³/sec km²)	(6) Medios (1,31 km²)	0,201	0,223	0,194
Volume (hm³)	(7) Accumulated value	1,741	2,923	3,116
Specific Volume (hm³/km²)	(8) Accumulated (1,31 km²)	1,329	2,231	2,378
(8) - (4) (hm³/km²)	(9) Accumulated (1,31 km²)	1,201	1,970	2,049
K2	[(6) * (0) / 24]	15,34	25,81	27,56

beginning in later years (Photo 2, beginning at the end of November in 2005).

- Another typical characteristic of subpolar glaciers, which is the absence of what we had defined as "threshold" in the habit of the hydrograph of the discharge wave, also changes. In the hydrologic year of 2002/03, a well defined discharge wave can be observed and, separated from it by a period of null discharge, an aftershock takes place. Here there is no period with that minimum discharge of values below the annual average, defined like threshold. Nevertheless in the last two registered years, 2004/05 and 2005/06, the discharge wave and the aftershocks appear united by periods in which the existence of the minimum threshold in the discharge wave is registered. This is a typical characteristic of temperate glaciers.

- The beginning of the discharge wave is moving forward in time as years go by: 16th of December of 2002, 6th of December in 2004 and 30th of November in 2005.
- The end of the discharge wave is delayed as years go by. Here it is possible to analyze the changes in the different parts of the wave: only discharge wave (it ends on the 2nd of March in 2003, on the 1st of April in 2005 and on the 21st of April in 2006) and including in the wave the aftershocks and the periods in which minimum threshold exists (it ends on the 7th of April in 2003, the 18th of May in 2005 and the 4th of June in 2006).
- As years go by, the last aftershocks of the discharge period and the days in which there is a minimum threshold are being incorporated to the net discharge wave.

We elaborate Tables 4, 5 6 and 7 from the previous Tables 1, 2 and 3. In these new ones we display the comparison, for the three hydrologic years (2002/03, 2004/05 and 2005/06), of the characteristics described before. Table 4 is constructed using the complete hydrologic years, Table 5 with the discharge period including wave, aftershocks and minimum threshold when it exists, Table 6 with the wave and the aftershock and Table 7 with only the wave proper. About them, it is possible to highlight the following:
- The number of hours that the glacier discharge lasts in the different periods is increasing every year: for the period that includes wave, aftershocks and threshold (2697, 3914 and 4472), for the period that includes wave and aftershocks (2156, 2914 and 4102) and for the period that includes just the wave proper (1832, 2778 and 3410).
- The average air temperature during the complete hydrologic year is increasing every year (-2,11°*C*, -2,04°*C* and -1,44°*C*).
- The accumulated solar radiation also increases: for the period that includes the wave, aftershocks and threshold (131,7 $kw \cdot m^{-2}$, 142,2 $kw \cdot m^{-2}$ and 168,9 $kw \cdot m^{-2}$), for the period that includes the wave and aftershocks (114,3 $kw \cdot m^{-2}$, 132,8 $kw \cdot m^{-2}$ and 166,7 $kw \cdot m^{-2}$) and for the period that includes only the wave proper (109,8 $kw \cdot m^{-2}$, 131,4 $kw \cdot m^{-2}$ and 164,4 $kw \cdot m^{-2}$).
- The accumulated precipitation in the different periods also shows an increasing tendency: for the period that includes the wave, aftershocks and threshold (155,9 *mm*, 355,8 *mm* and 425,8 *mm*), for the period that includes the wave and aftershocks (144,4 *mm*, 294,4 *mm* and 409,4 *mm*) and for the period that includes just the wave proper (128,5 *mm*, 260,9 *mm* and 328,8 *mm*).
- Discharged volume increases in a significant way: for the period that includes the wave, aftershocks and threshold (1,815 hm^3, 3,147 hm^3 and 3,449 hm^3), for the period that includes the wave and aftershocks (1,815 hm^3, 2,997 hm^3 and 3,389 hm^3) and for the period that includes only the wave proper (1,741 hm^3, 2,923 hm^3 and 3,116 hm^3).
- Index $K2$, previously defined, that relates the average values of glacier discharge to the number of days that it lasts, reflects very clearly this growth, in the course of the years, of the different analyzed periods: in the complete hydrologic year (16,06, 24,74 and 30,30), in the period that includes the wave, aftershocks and threshold (16,07, 27,89 and 30,56), in the period that includes the wave and aftershocks (16,08, 26,47 and 29,97) and in the period that only includes the wave proper (15,08, 25,81 and 27,56)
- Now we will study the discharged volume accumulated for each analyzed period, in specific units, that is by square kilometre of glacier catchment area. From that total drained volume we take the total volume of specific accumulated precipitation for square kilometre of glacier catchment area. In this way we obtain two limits, an upper and a lower one, between which the real value of the net glacier discharge is. For the complete hydrologic year we have, for each analyzed year, intervals

(1,385-0,930 $hm^3 \cdot km^{-2}$, 2,288-1,638 $hm^3 \cdot km^{-2}$, 2,633-2,006 $hm^3 \cdot km^{-2}$) and for the other periods they are represented in the following graphs. We observe, in all cases, a significant increase in the course of the years we are studying.

Changes observed in the glacier icecap during the summer 2005/06

Besides the evolution observed in the glacier that we have just analysed from the recorded time series, both of meteorological and hydraulic parameters, we observed very significant changes in the glacier catchment area that drains to the register station during the summer of 2005/06.

Previous situation

In January, 2000, invited by the 45th Russian Antarctic Expedition, we started our study of the glacier discharge of the Small Dome or Bellingshausen Dome in Collins Glacier, at the so called "Salamanca Canyon" which pours its waters into the Drake pass. Afterwards, in consecutive years and with the 2000 results, when we began with the Project *GLACKMA*, we implemented the monitoring station (CPE-KG-62ºS) by the entry bridge to the Uruguayan Base Artigas. It is the same glacier in which we worked in 2000, but discharging to Bransfield, not to Drake.

This circumstance allowed us to reconnoitre, explore, position and study in depth the said Minor Dome of the glacier, locating the existing seracs and moulins and defining the different catchment areas of glacier drainages.

From the security point of view, in the period from January, 2000, to February, 2005, the only places with a certain risk in the access from the Fildes Peninsula to the Minor Dome were:

- A moulin beside the intraglacier lake that, crossing the glacier perimetral moraine, feeds the mentioned Salamanca Canyon in the Drake area.
- Some low entity cracks, under the snow, on both sides of the pass that joins the Minor Dome to the Central Dome of the main icecap on King George Island.

Moreover, all the iced slopes on King George show seracs before reaching the sea on both the Drake and the Bransfield side. These are dangerous areas. The same happens in the glacier borders of Collins Cove, Marian Cove and Potter Cove in Fildes or Maxwell Bay, and the coves in Admiral Bay. Being known, they are avoided by the members of the different crews dwelling in this part of Antarctic, where there are 9 opened bases during all the year.

The glacier pass located on the connections between Marian Cove in Fildes Bay and Ezcurra Cove in Admiral Bay deserves special attention. Here there is a group of crevasses of considerable size that were located by glaciologists at King Sejong Base in past years. In winter, this pass is used for communicating by "ground", over the icecap, with snowmobiles crossing between King Sejong and Jubany bases and the ones located in Fildes Peninsula. One of those crevasses took the lives of two Argentinians from Jubany in September, 2005.

In that same period, specific glacier discharge evolution, according to the previous analysed registers from our measuring station, has been increasing in an exponential, and during the last summer with values closer to those of a temperate glacier.

Events observed in January 2006 in the glacier icecap on King George

Appearance of new seracs

- Southeast section of Yamana nunatak, Jubany slope:

Bundle of very narrow extensional fractures and extraordinarily long (some over a kilometre, Photo 3), located in the pass from Jubany to the landing place used by the light aircrafts type *twin otter* that communicate the Argentinian bases of Marambio and Jubany.

Photo 3. Bundle of very narrow extensional fractures and extraordinarily long appeared during summer 2005/06.

Photo 4. Recent crevasses in the access to the Small Dome from BCAA

- <u>Loxodromic journey through the Small Dome glacier icecap, from the surge discharge from Salamanca Canyon to the Uruguayan Antarctic Scientific Base Artigas (BCAA)</u>:

Apparition of very narrow and long cracks with north-south direction from 120m above sea level and which at 150m become wider (up to 30 cm). They are dextral shear crevasses with ice corridors that would allow their crossing even if they became wider.

Photo 5. Beacon, signalling the usual access way to the Small Dome from BCAA, beside an over 2 metre wide crevasse, with remains of the snow bridge hiding a great part of it

Photo 6. The same crevasse of Photo 5 one month later.

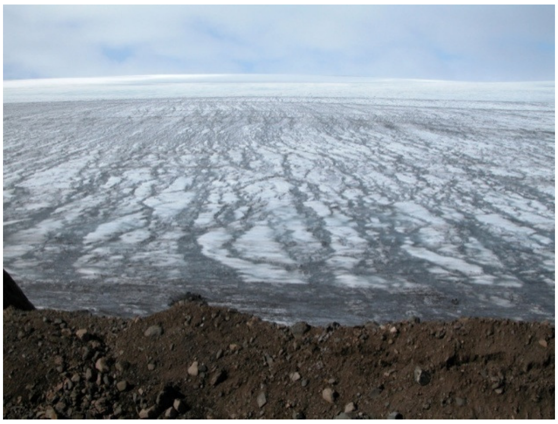

Photo 7. Supraglacier river net in Collins 2006 (greater quantity than in previous years

- <u>Marian Cove Sector, on the southern side of Weaver Peninsula</u>:

Longitudinal slot of more or less constant width, hidden in the glacier ice, that extends along several kilometres, from Marian Cove in the direction of Ezcurra Cove in Admiral Bay. All along its visible length, it is covered in sunken snow, which draws a depression that helps locating it. It seems to be an important fissure.

- Direct approach to the Small Dome from BCAA:

The direct access from the surroundings of the BCAA to the glacier icecap of the Small Dome, up to the 2004/05 summer, was an easy, risk-free journey, as there were no cracks in its trajectory. It has already been visited a few times by organized tourist groups, consisted of thirty people. The situation has drastically changed now.

Along the route, from 140m above sea level, we begin to find long crevasses from 30 to 50 cm wide, crossing the ascent route. The higher we get, the wider the cracks become and they begin to be covered by snow from the last winter. At about 170m, snow is practically uninterrupted and about 200m of height; there are wider cracks, some of which may be over 2 metres width (Photo 4). More than 40 meters of depth.

They are recent crevasses. The tear, made when they opened under the last winter snow that had covered them, presents rough borders that meteorization has not yet softened, leaving overhanging promontories over the void that it is necessary to identify to prevent accidents (Photos 5, 6).

There are two crevasse groups whose intertwining frames polygons difficult to cross, especially on those foggy days so common in the Small Dome.

This situation, which we observed here for the first time, presents a high objective risk that needs assessing. This leads us to strongly advise against visiting it, which has already become regular for organised tourist groups and some company in the sector.

Apparition of new "moulins" hidden by traps or unstable snow bridges

Glacier discharge, organized in a complex draining network both on the surface and underground, can be simplified for better understanding into three interrelated types of drainage:

-a) Supraglacier drainage is fed by the melting of last winter snow, its overlaid ice, and the melting of the glacier itself in the surface of its ablation area (Photo 7). It is due to the action of solar radiation and the increase in environment temperature, which reach their maxima in summer.

These supraglacier rivers usually sink in the glacier ice at specific points, where the drainage becomes englacial. At these points, known as "moulins", where the water from the supraglacier river enters the glacier in a usually vertical way, the underground glacier rivers begin. They are of two types:

-b) Endoglacier drainage, where water flows seeping into the ice on the floor, walls and occasionally the ceiling.

-c) Subglacier drainage, formed by rivers flowing under the glacier ice and on its bed rock.

The three types of drainage described end up coming out by the glacier borders, at specific points where surge discharges are located.

In January 2006, we have identified the existence of 12 new moulins, previously inexistent, at two places in the glacier, where it touches the perimetral moraine that closes the Small Dome icecap near the BCAA.

The geodesic location of both places is given by the following coordinates:

(Lat. S 62º 10' 731.; Long. W 58º 54' 489.; Alt. 48.0 m) and (Lat. S 62º 10' 532.; Long. W 58º 54' 820.; Alt. 58.3 m).

This year both places have been covered with snow bridges, which have begun to melt well into the second fortnight of January, 2006.

Photo 8. Moulins generated at the confluence of various supraglacier rivers

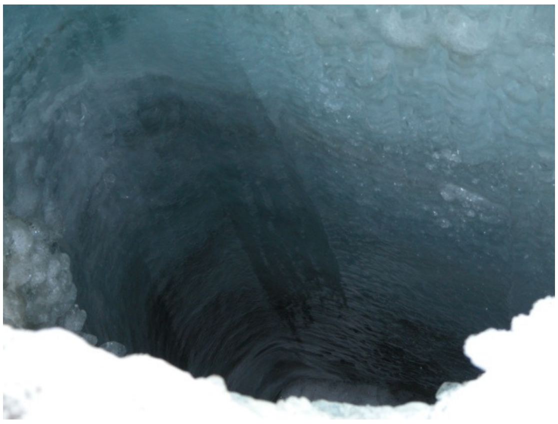

Photo 9. Moulin from the inside

This glacier icecap is, then, in an unsettled situation of increasing risk and it must be under continuous study in the following years. At the first place (Photo 8), seven supraglacier rivers converge and sink into two moulins (Photo 9), which combine to form a single vertical shaft of circular pattern, with a 2 m diameter and about 30 m deep. They end up coming out through the ice core of the perimetral moraine and plunging as a waterfall into the lagoon by the ionospheric station of the BCAA.

In the second area, five moulins converge in a steep slope, though not vertically, and cross the perimetral moraine forming a winding underground river with fast rapids which is completely masked in its last 100 m by a long snow bridge, until it reaches a remarkable surge discharge at the glacier border.

Glacier discharge reached an average of 1,1 $m^3{\cdot}s^{-1}{\cdot}km^{-2}$ in the third week of January, 2006, according to the registers from our measuring station of the Experimental Catchment Area (CPE) installed at the entry bridge to the BCAA. On its turn, environment temperature exceeded 8ºC at various times on those days.

Interpretation of happened changes

- Specific glacier discharge is a parameter we are using (GLACKMA Project) to follow the evolution of global warming, as it reacts quickly to the increase of environment temperature in a directly proportional way.
- This means that glaciers act as natural sensors of that warming, being glacier discharge and its effects consequences of it.
- Specific glacier discharge values (in $m^3{\cdot}s^{-1}{\cdot}km^{-2}$), measured at the Base Artigas CPE, have been increasing continuously along the last years, in an exponential way pattern.
- The specific glacier discharge values in January, 2006, at this CPE, show values so high (1,1 $m^3{\cdot}s^{-1}{\cdot}km^{-2}$), that they come close to those usual for temperate glaciers (between 0,9 and 1,4 $m^3{\cdot}s^{-1}{\cdot}km^{-2}$).
- Taking into account that glaciers at these latitudes (South Shetland, Antarctic Peninsula) are of subpolar type (whose specific discharges are between 0,2 and 0,4 $m^3{\cdot}s^{-1}{\cdot}km^{-2}$ during summer time), we suspect we are facing the beginning of a qualitative change in the glacier behaviour in this region.
- This qualitative change is shown as follows:
  - higher specific glacier discharge;
  - increase in subglacier circulation;
  - increase in the glacier slide speed;
  - increase in the fragile response of glacier ice;
  - apparition of new crevasses and faster evolution of the existing ones;
  - apparition of new moulins,

and, all in all: general increase in the objective risk in the passing, exploration and investigations to carry out on these glaciers.

- Considering the changes taking place in the area, and detailed in this document, the accidents involving two winter vehicles in King George glacier icecap and in O'Higgins Land at the beginning of the southern summer 2005/06, and which took the lives of three Chileans and two Argentinians used to work in the Antarctic, have in some way been favoured by the rapid changes taking places in the region glaciers.
- To this situation of increasing objective risk as response from the region glaciers to global warming evolution, it has been added another circumstance, in this case subjective and so, more difficult for us to assess: it is the introduction, so far, of tourist groups formed by thirty people each in some parts of the glaciers where these changes are taking place. As these groups are large and formed by people of scarce or none glacier experience, the probability of accidents may increase extraordinarily.
- At the request of several Antarctic directors, we elaborated a report including and describing all these events. This report has been sent by them to their respective national organizations with the aim that the risk that has turned up is known and the regulations of preventive character that may be considered necessary are established by the Antarctic Treaty.

Conclusions

One of the areas on Earth where more significant effects of the Global Warming are being found is the area of the Peninsular and Insular Antarctic, between latitudes 62ºS - 63ºS. And in this part we have located one of the register stations of glacier discharge within the GLACKMA Project, the one called CPE-KG-62ºS, whose coordinates are: Lat: S 62º 11' 035.; Long: W 58º 54' 414.

The time series of glacier discharge obtained during these last years shows that differential aspects in the habit of its annual hydrograph are beginning to become evident. The glacier is losing characteristics typical of subpolar glaciers and beginning to show some more typical of temperate glaciers. Among them, two can be highlighted:

- The disappearance of the phenomena called spring-events at the beginning of summer, which were registered for the last time in the summers of 2002/03 and 2003/04, this habit being lost in later years.
- The appearance of minimum threshold in the habit of the hydrograph of glacier discharge, a typical characteristic of temperate glaciers. This was registered in the last two summers of 2004/05 and 2005/06, joining the net discharge wave with the aftershocks.

In addition, with the generated time series of glacier discharge, it has been possible to register how the discharge wave begins earlier every year and ending later, increasing therefore the number of days that the discharge lasts every year. If we concentrate in the duration of the net wave, we have 76 days a year for 2002/03; 112 days a year for 2004/05 and 142 days a year for 2005/06. If we now consider the period that includes the wave, aftershocks and threshold, we have in 2002/03, 112 days a year; in 2004/05, 163 days a year and in 2005/06, of 186 days a year.

Discharged volume also increases in a significant way, in 2002/03, 1,815 hm^3, in 2004/05, 2,997 hm^3 and in 2005/06, 3,116 hm^3. On the other hand, the defined index $K2$, that relates the average values of glacier discharge to the number of days that it lasts, reflects very well this increase in the course of the hydrologic years: 16,06 in 2002/03, 24,74 in 2004/05 and 30,30 in 2005/06.

Besides these data obtained from the recorded time series, from January, 2001, very significant qualitative changes in the glacier catchment area have been observed: increase in the speed of glacier sliding, increase in the fragile answer of the glacier ice, appearance of new moulins and appearance of new cracks and faster evolution of the existing ones.

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