Subpolar glaciers network as natural sensors of global warming evolution

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ABSTRACT
In the expeditions carried out both to temperate and subpolar glaciers in both hemispheres, we have observed the existence of endoglacier and subglacier flows and drainages also in subpolar glaciers. Our main work hypothesis is centred on investigating the role played by subpolar glacier discharge in global warming, as we consider this discharge may represent that unknown third of sea level increase (a third of the increase in sea level is considered to be due to water thermal dilatancy and other third would come from the melting of temperate glaciers, being unknown the origin of the last third).
Response in glacier discharge is so immediate and sensitive to any variation in environment temperature that we consider that glaciers work as natural sensors of Global Warming and may offer registers of great utility as indicators to estimate its evolution. Using long time series (multiannual) of glacier discharge we will know the temporal evolution of global warming and implementing more catchment areas in both hemispheres we will be able to know the latitude distribution of glacier discharge.

We present here our actual strategy of research for implementing glaciers as natural sensors of global warming, using them as a continuous register to estimate the temporal evolution of global warming and its distribution according to latitude in both hemispheres. Thus we will have at our disposal a glacier observation network according to different latitudes in both hemispheres, which allow a comparative control of glacier discharge according to climate evolution. We are working in this matter from 2001 when we began with the GLACKMA Project.

KEY WORDS: annual discharge wave, cryokarst, endoglacier conduits, experimental catchment area (CPE), glacier discharge, moulins, spectral analysis, subpolar glaciers, time series, wavelet analysis

Foundations and purpose

The global warming the planet suffers, generated by the greenhouse effect, results in a gradual increase of its environmental temperature (Braithwaite, 1995; Braithwaite, Oleson, 1989; Daoke, Vaughan, 1991; Eraso, Domínguez, 2001; Mercer, 1987; Oerlemans, 1991; Oppenheimer, 1998; Rott, Skvarca, et al., 1996. As a consequence of this increase in temperature, the ice mass in the great polar icecaps decreases due to melting, and the sea level rises.

In the old general models of glacier mass balance (Drewry, 1985), the annual quantity of snow fallen on the great polar icecaps was considered as input. The output in these models was estimated measuring from satellite the ice floes, which separate from the great floating ice platforms where the polar glaciers of these icecaps reach (mainly in the Antarctic and in Greenland). We also consider output the water discharged from temperate glaciers. The balance was rounded up measuring the variations in width of the polar icecap (visually from satellite) and thickness (through radio-echo-sounders, from satellite, airborne or on the field).
We know now that the ice floe output considered in that balance may be much earlier – by hundreds or thousands of years – than the input. The balance is not therefore synoptic, being wrong to use it in the predictive models.

Anyway, the validation of these models is made measuring the real increase of the sea level, as a consequence of the last glacier melting. In the work hypotheses presently in use we estimate that one third of the increase in sea level is due to the water thermal dilatancy, another third would come from the melting of temperate glaciers, being unknown the origin of the last third (Remy, Ritz, 2002).

In the expeditions we have carried out both to temperate and subpolar glaciers in both hemispheres, we have observed the existence of endoglacier and subglacier flows and drainages also in subpolar glaciers. They are not so intense, but they are similar to those existing in temperate glaciers. The specific glacier discharges that have been measured give values like these:

- 0.9-1.2 m$^3$·s$^{-1}$·k$^{-2}$ in temperate glaciers (Lat. 64ºN; Lat. 51ºS),
- 0.2-0.3 m$^3$·s$^{-1}$·k$^{-2}$ in subpolar glaciers (Lat. 79ºN; Lat. 62ºS).

But we also must take into account that the planet surface covered by temperate glaciers is much smaller than that corresponding to subpolar glaciers:

- More than 70 000 km$^2$ for temperate glaciers,
- More than 750 000 km$^2$ for subpolar glaciers.

Our work hypothesis is centred, with all the previous considerations, on investigating the role of subpolar glacier discharge in the Global Warming, as we believe this discharge might represent that unknown third in sea level increase (Eraso, 2004).

As part of a project we set in motion 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 time 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.

With the registers obtained from these already implemented stations, we seem to be finding that glacier specific discharge is almost immediate and very sensitive to any variation in environmental temperature. This allows us to establish a sound start hypothesis for this research, considering glaciers as natural sensors of Global Warming. We could establish a net of CPE stations, generating continuous records of glacier discharge, which would be used as indicators to assess the evolution of Global Warming (Domínguez MC, Eraso A, 2002). We would use long time series (multiannual) of glacier discharge from the CPE already installed, allowing us to know the time evolution of Global Warming and we would implement more CPE’s in both hemispheres which would let us know the latitude distribution of glacier discharge (Eraso A, Domínguez MC, 2004a).

Thus we would have at our disposal a glacier monitoring network at different latitudes in both hemispheres that would allow a comparative study of glacier discharge according to climate evolution.

This project, GLACKMA, is included into the activities of the International Polar Year, through two leading projects, one for investigations taking place in Antarctic (CICLOPEN) and the other for those in the Arctic (GLACIODYN).

- CICLOPEN: Impact of CLImate induced glacial melting on marine and terrestrial COastal communities on a gradient along the Western Antarctic PENinsula, counts with scientists from fifteen countries and is coordinated by Dr. Doris Abele from the Alfred-Wegener Institute for Polar and Marine Research, Germany, and Dr. Irene Schloss from the Argentine Antarctic Institute, Argentina.
- GLACIODYN: The dynamic response of Arctic glaciers to global warming, with scientists from seventeen countries, is coordinated by Dr. Johannes Oerlemans from the Institute for Marine and Atmospheric Research, Utrecht University, The Netherlands, and Dr. Jon-Ove Hagen from the Dep. of Geosciences, University of Oslo, Norway.

**Background and present state**

**CO$_2$ registers. Global warming**

Test drillings with recovery of continuous ice cores have been carried out at different places in the Antarctic and Greenland glacier icecaps, since the eighties, as part of the PIGA (International Programme of Antarctic Glaciology) programme. The paleoclimatic register reached then a time length of 160 000 years.

After that, by the end of 1999 in the EPICA (European Programme on Ice Core in the Antarctic) project the 420 000 years of antiquity were reached in a test drilling of 3.5 km of depth performed beside the Russian Base Vostok in the centre of Eastern Antarctic (Petit et al. 1999). Nowadays, in this same project, the mentioned paleoclimatic calendar is reaching 900 000 years of antiquity, with yearly intervals. This is being carried out thanks to the 3 km depth test drill made at Dome C in Eastern Antarctic, opposite the Pacific Ocean icefield.

With we can see that CO$_2$ concentration in the Earth atmosphere for the past 800,000 year to the present warm period (about two centuries back), has ranged from 180 ppm (parts per million in volume) in the coldest periods, to 290 ppm in the warmer ones (McManus, 2004). This variation in the atmospheric content of CO$_2$ answers to natural causes, whose triggering mechanisms (conflicting and thus self-regulating) are mainly two:

- CO$_2$ produced by volcanic eruptions that increased its presence in the atmosphere
- Atmospheric CO$_2$ digestion by the formation of reefs in warm and shallow seas, which reduces its content.

CO$_2$ acts as a green house effect gas. The higher its proportion in the atmosphere, the lower the thermal radiation part – albedo – reflected to space by the Earth. Its thermal effect remains in the atmosphere, which consequently increases its temperature.

For that natural increase in CO$_2$, between 180 and 290 ppm correspond to an increase in average annual environmental temperature in the order of ten degrees Celsius ($10^\circ$C) and vice versa.

Global warming due to the greenhouse effect generated by natural causes as described above is valid just until halfway into the 19$^{\text{th}}$ century; from then on, CO$_2$ concentration in air has been gradually increasing, but in an accelerated way: in 1910 it reached the figure of 300 ppm, in 1950 it passed 310 ppm, in 1975 it was already at 330 ppm, in 2000 it bordered on 370 ppm and it goes on increasing. From the beginning of the industrial age, the consumption of coal and other fossil fuels, such as oil, generates new sources of CO$_2$ production, and this interferes with the natural climate evolution.

Comparing the paleoclimatic registers of glacier ice to present registers of CO$_2$ increase in the South Pole station (Antarctic), in the centre of the Pacific (Mauna Loa, Hawaii) and in the Norwegian Arctic (Zeppelin, Ny-Alesund) – which have the same tendency though different variance – we can point that CO$_2$ values beyond 290 ppm are now due to man’s activity (Eraso, Domínguez, 2005).

If we also take into account that increases in CO$_2$ correspond with increases in environment temperature, it means that nowadays, temperature should be a few degrees higher than it is. If this is not yet evident, it is due to the regulating effect of sea water, whose thermal inertia is very high, but the process is already set in motion.
Rise in sea level

The general rise in environment temperature causes an immediate increase of glacier liquid discharge. When glacier discharge increases – continental ice – the sea level rises as it is filled, being it possible for it to reach – if all the glacier mass melted – a level 70 m higher than the present one. It is advisable to note here that in times of glacier maxima, when the continental ice mass covered three times as much surface as it does know, the sea level must have been 120-130 metres lower than it is now.

When sea level increases, its evaporating surface increases, too. Both the increase in evaporation and its cause, the rise in temperature, cause an increase in the atmospheric enthalpy. As the atmosphere responds with processes characteristic of a radiation-turbulence system, the meteorological phenomena will become more violent and random, being more difficult to predict.

Global sea level is rising with a speed from 10 to 20 cm per century (Church, Gregory, 2001). This increase in the last 100 to 150 years is only partially understood. Estimates of the contribution of thermal dilatancy obtained from models applied to oceans indicate a range between 3 and 7 cm for the period of 1865-1990 (De Wolde et al. 1995; Church, Gregory, 2001).

Meteorological records are being used to estimate glacier discharge in polar glaciers and icecaps. By means of glacier mass balance models, Zuo and Orlemans (1997) calculated a contribution of 5 to 8 cm to the increase of sea level for the period 1865-1990 from temperate glaciers in the Arctic and Greenland glacier icecap. Church and Gregory (2001) estimated that the range would be from 2 to 4 cm for the 20th century just from the Arctic temperate glaciers. Anyway, from these results we can deduce that the observed increase in sea level can only be partially explained with thermal dilatancy and temperate glacier discharge.

It is very likely that changes on the long run in the great polar icecaps (Antarctic and Greenland) may be important enough to mean a relevant contribution in the increase of sea level. The results from some 3D thermo-mechanical models in the Antarctic glacier icecap indicate this might be possible (Huybrechts, De Wolde, 1999). The Antarctic polar icecap might be losing mass related to sea level increase, associated to polar icecaps reduction in the Northern Hemisphere along the last interglacier period. Similar studies in the Greenland icecap show a situation in which the polar icecap could be very close to the balance made under the present climatic conditions (Huybrechts, 1994; Van de Wal, 1999; Church, Gregory, 2001).

Glacier Hydrogeology

The problem of ice permeability in temperate glaciers is perhaps one of the most controversial topics among glaciologists, where opinions seem conflicting. There are authors (Nye, 1976) who present arguments in favour of its existence, establishing the concept of free run-off through a vein system formed by the borders of three adjacent ice grains. Other authors (Lliboutry, 1968, 1983) question its existence arguing that a permeable glacier would disappear due to frictional melting, the first ones oppose in turn that the necessary supply of water for this to happen is missing.

Evidence, based on proven facts, of percolation though the ice mass are quite conclusive. Harrison (at Röthlisberger, 1972), basing his opinion on assessments of vein size – in the order of just 25 µm, concludes that percolation is meaningless. Eventually, nevertheless, the same author presented evidence of percolation in test drilling ice cores, where some gaps reached a few millimetres, so glacier run-off would not be so meaningless then.

Whatever the truth may be, with Shreve (in Röthlisberger, 1972) it is admitted the existence of a tree-shaped vein network, combined with tubes a bit wider which are connected to broad original conducts from wells or drains opened in the glacier surface, which are known as moulins in Glaciology. Based on that model, a series of rules and principles on intraglacier drainage is formulated, in terms of water pressure
Subpolar glaciers network as natural sensors of global warming evolution

potential inside the mentioned network, in a way similar to the concepts used in classical hydrogeology. Introducing the concept of potential in the ice mass, the conclusion is that the general direction of the drainage will be perpendicular to the equipotential lines. To practical effects, flow directions deduced from the previous premises will be – in the direction of the glacier movement – steeper the more horizontal the glacier surface slope.

As a rule, water flow is commonly described in terms of water pressure potential (Shreve 1972; Lawson 1993). Analyses have been carried out about water circulation in endoglaciers conduits (Van der Veen, 1999; Röthlisberger, 1972; Nye, 1953). If flow is turbulent inside the drainage conduit, the empiric formula of Manning is normally used (Francis, 1969). Instead of this, there are other expressions relating water flow to conduit size (for example, Lawson 1993). Nevertheless, whichever the relation used, the procedure is the same. If the glacier end reaches ground above sea level, we can take as border condition the fact that water pressure is the same as atmospheric pressure, and for glaciers whose glacier tongue reaches the sea (tidewater), we can consider water pressure to be the hydrostatic one. However, the adoption of balance state is not completely realistic. There are important temporal changes in the water quantity that flows through the conduits. This set of events, referred to in glaciological literature as “spring events” (strong discharges that usually take place at the beginning of spring) (Röthlisberger & Lang, 1987), implies that even a seasonal time scale for the evolution of the draining system must be incorporated to the model, as well as modelling in the case of water circulation in the draining system when it does not completely fill up the conduit.

A karstic approach to glacier drainage has been widely studied along the last two decades (Eraso, Pulina, 2001).

Glacier drainage

Water circulation on ice
This is a prime question in Glaciology, and so it has been subjected to important discussions, still going on, for a long time. Among its basic principles we may highlight the following:
1. Regarding the processes with influence on drainage conduit evolution, there are mainly two: heat transference between running water and the ice surrounding it and ice deformation.
2. Based on these processes, the factors that control conduit diameter are:
   - Ice melting in the conduit wall as a result of the friction heat generated by running water, which causes drainage conduit widening and increases water volume.
   - Conduit closure due to plastic deformation of ice, as a result of the weight upon it, when this is higher than water pressure inside the conduit.
   - The gaining or loss of energy resulting from the conditions adjustment to water melting point, as a function of the hydraulic charge existing in the drainage conduit, which may generate either melting of the conduit walls or freezing of part of the running water.
3. In general, it is accepted that the section of a conduit in full load (that is, one completely filled by running water) must be circular and when it is not so, this is believed to be due to the following reasons:
   - ice mass heterogeneities,
   - anisotropic pressure distribution in the ice of the conduit walls,
   - characteristics typical of flowing water, which has a tendency to form meanders, whirlpools, and sometimes drags sediments that may erode the conduit walls changing its original form.

Formation of endoglaciers conduits
The existence of intraglacial conduits and galleries, generally with underground rivers is an actual fact. They are due to water tendency to move in favour of gravity, from the glacier surface to its bed.

The glacier bed represents the major existent discontinuity, given the differential
conditions from the mechanical point of view between the ice and the rock bed.

In general, regarding water flow inside the glacier, we can consider two groups of processes:
- Percolation.
- Direct drainage through big conduits, originated when melted water from the glacier surface sinks inside a moulin, whose role in the formation of intraglacier landscape is of extreme relevance in glaciology.

Moulins are sinkholes or drains in the glacier surface (Photo 1). The water that runs into a moulin falls vertically inside the glacier body.

![Photo 1. Detail of a moulin entrance at Kviarjökull glacier (Iceland). Depth: 45 vertical metres.](image)

**Approach to drainage from a karstic point of view**

A karstic approach to glacier drainage has been studied in depth by Eraso along the last decade. Some of the last novelties discovered are exposed in the book Eraso A., Pulina M. (2001) (see Chapter 6).

This study of glacier ice karstification to give rise to the so called criokarst, as accorded by the International Commission “Glacier Caves and Karst in Polar Regions” during the III Symposium held at Chamonix in 1994, is based on the following:

**a) Karst and Form Convergence in Ice**

In certain soils, part of the rain and river waters infiltrates the subsoil, through interconnected fissures and cavities, widening them by dissolution, and forming conduit, gallery and cavern networks through which underground rivers flow.

This underground drainage is organised in a directional way, as a function of the anisotropy of the rock massif, the hierarchy in the drainage network, and the forms it generates keep remarkable similarities though created on different rocks.

To this similarity in dissolution forms, which appear in the different karstifiable rocks, and to the similar disposition of underground drainage networks, is what we call *form convergence* (Eraso, 1973).

In nature, this convergence is as frequent as it is evident. It obeys a geodynamical imprint that makes us think, when facing the analogous effects, in a similarity of causes. Actually it is a natural model of which we just see the results; it entails the existence of an auto-similarity in the acting processes.

All these phenomena of form convergence, though appearances disguise them, are related by a set of circumstances that make them dynamically similar.

Form convergence is seen in evaporate (gypsum and salts) and carbonate (limestone, dolomites, marbles, conglomerates and sandstone) rocks, and sometimes, when their geological age is considerable, in rocks that are apparently very little soluble (quartzite and granite), and, in great abundance, in glacier ice.

In the case of rocks, dissolution is the mechanism that conditions the change of the rock constituent molecules from solid to liquid phase. In the case of ice, the phase change takes place through the frictional melting mechanism, similar to dissolution both in its effects (establishing of the karst) and in the mathematical formulae that rule them:

**Dissolution:**

\[
dC/dt = D \cdot \Delta C - \vec{v} \cdot \text{grad } C
\]

where,

- \( C \) – solute concentration,
- \( t \) – time,
- \( D \) – diffusion coefficient,
- \( \vec{v} \) - vector that designates the speed of the fluid in movement.
Friction Fussion:
\[
\frac{dT}{dt} = D \cdot \Delta T - \nu \cdot \text{grad} T
\]
where,
- \( T \) – temperature
- \( t \) – time
- \( D \) – transfer coefficient
- \( \nu \) - vector designates the speed of the fluid in movement.

Water temperature in intraglacier rivers remains at 0ºC, as the heat generated by water flow is spent in melting part of the conduit wall ice, simultaneously increasing both the conduit size and the running water volume. The greater the length of an endoglacier draining conduit (that is, its walls – floor and ceiling are ice), the greater the water volume flowing inside it, without any need for other contributions or tributaries. Volume is directly proportional to the length of the wet ice section perimeter.

In consequence, our knowledge of glacier underground world – still under development – already offers remarkable results. Exploration of ice potholes has reached depths of 200 m in Greenland, reconnoitring cave networks over 6 km in Svalbard, and listing underground rivers of more than 25 m\(^3\)·s\(^{-1}\) in Patagonia (endoglacier conduits over 3 km long, etc).

The existence of karst in ice, or criokarst (Photo 2), is overwhelmingly plentiful. Its evolution is as fast that it becomes observable at a human time scale, and its study permits the quantification of glacier recession.

b) Where does criokarst evolve?

Karst in ice evolves in glaciers of a certain entity, located in both polar areas and on the main mountain ranges in the planet.

Every glacier has two clearly distinguishable zones: the accumulation one (ZACC), located in its upper part, and the ablation one (ZABL) at its bottom, where criokarst development prevails, especially in places where ice temperature is 0ºC.

Based on the chart that summarises the different classification of glacier types (Baranowski, 1997; Eraso, Pulina, 2001), we can state that:
- in cold glaciers type 1 or polar, with ice temperature always below zero, there is no criokarst,
- in transitional glaciers type 2 or subpolar, 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 type 3 or temperate, 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 in the planet and some mountains not too high (for example, Patagonia).

Glacier hydrogeology is very complex; however, let’s have a look at the following generalities. In the first place, where can water flow in a glacier?
- on its surface or supraglacier,
- at the interface between basement rock and the ice bottom or subglacier,
- inside the ice mass or endoglacier.
temperate glaciers and several hectometres in subpolar ones (Photos 3, 4 and 5). This fact contrasts with the tacit acceptance in classical Glaciology, which presupposes supraglacier run-off generated by solar radiation to cross straight to the ice bottom and flow between the rock bed and glacier ice as soon as it sinks though a moulin or drain. That is, in a subglacier way. We want to highlight this in not necessarily so.

In its turn, drainage organization takes place according to two main systems: peripheral and central.

- Peripheral systems have contribution from the outer slopes by the glacier, as well as supraglacier drainage; both directly feed subglacier flow.

- Central systems are fed by supraglacier run-offs, and they generate and endoglacier organized network that ends up feeding subglacier flows until they evacuate at the glacier front, after routes much longer than those supposed in theory.

However, the interrelation between these two drainage types is complex and affects in different ways their hydrochemistry, pattern of hydrographs, drainage character and type, and duration in time, depending on the draining means. All this has a great influence on the glacier integrated discharge, whose study is necessary to estimate glacier recession, as we will know the loss of ice mass in form of water (Eraso, Pulina, 2001).

Glacier discharge is caused by solar radiation – as primary cause –, but environment temperature and glacier slide also have an influence. The melting of part of the ice comes from the transformation of this energy into heat, and is responsible for establishing the drainage.

We do not consider here the local geothermal effects which, being singular, usually cause terrible disasters. Already adopted by the international glaciological lexicon, the Icelandic word jokulhlaup – glacier jam or jelly – reflects them.

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Photo 3. Endoglacier hydrogeological tract (Patagonia, Argentina). Distance from the moulin: 2.8 km; arrival time: 5 hr. 30 min; conduit diameter: 1.55 m

Photo 4. Conduit before arriving the fluorescein of Photo 3

Photo 5. Same conduit of Photo 4 with fluorescein at Perito Moreno, Patagonia.
c) Predictive Method of the Main Directions of Underground Drainage

Going a little further, when observing the topography of the cavern network of the great karstic systems in the world, it becomes evident that gallery direction is not random. On the contrary, they follow specific modal directions, typical of the rock massif where they are located. These characteristics reflect the massif anisotropy, which is a consequence of the strains it has had to withstand.

During his research on karstic drainage, Eraso (1985/86) has drawn out the “Predictive Method of the Main Directions of Underground Drainage”. This method is based on two work hypotheses:

- The qualitative one is based on the existence of a tectonic preparation of the karst, which prefigures the disposition of the three-dimensional network of draining conduits as a function of its structural history.

- The quantitative one indicates that the most likely drainage directions are organized in the planes that contain the highest $\sigma_1$ and the intermediate $\sigma_2$ components of the different ellipsoids measured, that is, the $(\sigma_1,\sigma_2)$ planes (weakness or extensional planes). Thus, in each case they are orthogonal to the minimum $\sigma_3$ components of the ellipsoid.

There is a computerized version of the method, implemented by Carmen Domínguez, and it is the one presently in use. To apply this method it is necessary to carry out an identification and inventory of tectoglyphs or permanent deformations, of varied nature. The most important are those of extensional character, as its genesis corresponds with the formulated quantitative hypothesis.

Based on the form convergence previously mentioned at point a), where we have seen the existence of criokarst, that is, karstic phenomena in glacier ice, it is possible to use here the Predictive Method of the Main Directions of Underground Drainage.

Glacier ice, which has been under different strains due to its movement, contains in its ablation area a large number of extensional tectoglyphs that, represented by recrystallization dams, constitute the weakness planes which prefigure the glacier directional anisotropy. Thus, this method will let us assess the characteristic anisotropy of each glacier and, as a consequence, predict its main draining directions (Photo 6).

Photo 6. Endoglacier conduit without circulation (Perito Moreno glacier, Patagonia).

This method has been applied over a hundred times at different places in Europe, Liberia, Latin America, Northern Africa, Middle East, Polar Regions and China.

Presently it is imparted at the Instituto Politécnico of Toulouse, French (50 hours) (Second Cycle), and the Universidad Politécnica of Madrid (Second Cycle, as a free choice official subject).

List of Organisms and Institutions that back up this Method (an original letter from each organism is at our disposal): UNESCO, SCAR, OSU (The Ohio State University), International Water Resources Association, University of Illinois, WFEO (World Federation of Engineering Organizations), ISSS (International Society of Soil Science), Statkraft (Norway), CNRS (Centre National de la Recherche Scientifique), DMAMI (Department of Applied Mathematics and Computerized Methods, Universidad Politécnica of Madrid UPM, Spain), IMWA (International Mine Water Association, Spain), DINGE (Department of Geological Engineering, UPM, Spain).
Record of global warming from glaciers

Evidence found

The background that suggests the necessity to make continuous measures of glacier discharge are to be found in the works coordinated by the “International Commission of Glacier Caves and Karst in Polar Regions”, which are compiled in Symposia organized for it: the first one in Madrid (Spain), 1990 (Publisher: Eraso), the second in Silesia (Poland), 1992 (Publishers: Pulina-Eraso), the third in Chamonix (France), 1994 (Publishers: Griselin-Eraso), the fourth in Salzburg (Austria), 1996 (Publisher: Slupetzky), the fifth in Coumayeur (Italia), 2000 (Publisher: Badino), the sixth in Ny-Alesund (Svalbard), 2003 (Publishers: Eraso, Domínguez), the seventh in Kabardino Balkaria (Caucasus), 2005 (Publisher: Mavlyudov).

Main evidence on which the importance of measuring glacier discharge is based:

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 and Rehak, 1994; Reynaud, Moreau, 1994; Schroeder, 1994).

2. The peculiar organization of intraglacier drainage, which follows specific modal directions, dependent on glacier anisotropy (Eraso, Martínez, Pérez, Fernández, 1992; Eraso, Badino, Mecchia, Gavilán, Bernabei, 1996; Eraso, Jonsson, Domínguez, 1997; Domínguez, Eraso, Badino, Jonsson, 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).


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, Moskalevsky, Simoes, Ladouch, 1996).

6. The relevance of glacier discharge in subpolar glaciers against temperate ones (Domínguez, Eraso, Lluberas; 2004; Domínguez, Eraso, 2001; Domínguez, Eraso, 2001; Eraso, 2004; Eraso, Domínguez, 2004).

Criteria for the selection of an Experimental Catchment Area (CPE)

The continuous register of glacier discharge is planned by means of implementing experimental catchment areas (CPE) in polar glaciers and icecaps located at different latitudes. The main criteria to select them are detailed below.

It is frequent to find archipelagos and islands located at high polar latitudes (Arctic and Antarctic) covered almost entirely by glacier icecaps.

Photo 7. Endoglacier conduit in the Nelson icecap (insular Antarctic).

These icecaps are subpolar glaciers where, as we have previously said, we come across evidence of internal drainages that end up flowing straight into the sea, in most cases by subglacier discharge – where the river runs along the contact surface between the ice and the rock bed – and in some cases, from endoglacier conduits (Photos 7 and 8).
In both cases, when ice reaches the shore, it is very difficult to measure the discharge of melted ice mass, basically for two reasons:
- due to the difficulty to assess the drained outflow under these conditions
- because it is very difficult to accurately know the surface of the catchment area responsible for the detected discharge.

On the contrary, if the glacier does not reach the sea, subglacier water discharges are easily located and the beds of the rivers they originate usually have a suitable place where its bank section morphology grants a water volume assessment. This is the first criterion for the selection of an experimental catchment area: glacier catchment area with terrestrial drainage.

Another question, which is the second criterion, is to know the surface of the glacier catchment area to be able to assess the specific discharge (in order to compare glaciers of different size and location). This does not depend on the surface morphology of ice, but on the topographical surface of the bedrock.

In valley glaciers it is not a problem to know the surface of their catchment area. However, in glacier icecaps, knowing the surface of the different catchment areas that drain spoke-like to the coast cannot be achieved until the bedrock surface is known.

In these cases, radio-echo-sounder techniques are used; they, through a series of longitudinal and transversal profiles, let us know the catchment area surface. If there are different discharges from the selected experimental catchment area, they must converge before reaching the point chosen to implement the measuring station with just on station. We will then be able to monitor, at just one point, the hydraulic parameters that will let us define the temporal distribution law of the water volume that the glacier discharges from the experimental catchment area.

This is the third criterion: in case of multiple discharges from the catchment area, they must all converge into just one stream.

**CPE’s network**
Following this plan, we began our work in 2001, within the so-called GLACKMA Project (Photo 9), and are presently monitoring six experimental catchment areas:

In the Southern Hemisphere:
- CPE-ZS-51°S, in the Chilean Patagonia,
- CPE-KG-62°S, in Insular Antarctic,
- CPE-VER-65°S, in Antarctic Peninsula.

In the Northern Hemisphere:
- CPE-KVIA-64°N, in Iceland,
- CPE-ALB-79°N, in Svalbard.

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At present and continuing with the development of this GLACKMA Project, the operative above mentioned stations are supported and we are planning to implement some new more CPE to different latitudes.

**Time series for system**

**Time outflow series. Hydraulic registers**

All these experimental catchment areas to be implemented will register time series of different hydraulic parameters with hourly intervals. The most important of them will be glacier discharge.

For this, at the selected catchment areas and with the previously mentioned criteria, the measuring stations will be located and equipped with different register sounders of the SEBA Hydrometrie brand in Germany. This type of devices is the one we are already using at the implemented CPE and we know of their resistance to the low temperatures they must work under. There are different models according to the measure sensors they have, but we can group them in two kinds: MPS type loggers and MDS type loggers. Presently, they are undergoing some considerable improvement regarding security, data storage capacity and resistance to low temperatures. That is why, at some of the four stations already implemented, the old versions will be replaced by these new ones.

**Loggers type MPS**

Used to measure the following parameters simultaneously: pH value, Redox potential, conductivity, temperature, water level, dissolved oxygen, turbidity. Types: MPS/2, MPS/3, MPS/4, MPS/5, MPS/6, MPS/7, MPS/8

**Discharge-level adjustment curve. Protocol of gauging campaigns**

We use the river level to generate the time series of glacier discharge at each of the stations, where we have installed the piezoresistive sensor which registers the river water surface level every hour. For this we use the calibration curve between volume and level, a curve which is typical and specific for each station on each river. It is an exponential function we determine as follows:

Systematically, at different level values we make assessments of the river. Firstly we obtain the depth profile of the river at each measured point. This profile is not stable and changes with level fluctuations, especially when they are strong and there is considerable dragging. We split this profile into sections, measure water speed with a precision micro-propeller, and thus, section and speed permit us to calculate the water volume for that level in the river. We have gauging software developed on the premises (Domínguez, 2004), especially designed for the characteristics of the catchment areas we work in. To get a good correlation coefficient, we establish a continuous vigilance on the river, thus to be able to select the adequate level values: a wide range of them, maximum values, minimum values and interspersing non-repetitive intermediate values.

With this work strategy, we are obtaining adjustment curves with very high coefficients from the CPE’s already implemented, which
let us devise a precise discharge law for each glacier. The material used for gaugings is an universal propeller F1 of SEBA, which is designed to determine water speed in streams and rivers.

**Time input series. Meteorological registers**

In those CPE located near to Arctic or Antarctic bases, the meteorological parameter series generated by their meteorological stations are used. The rest will be equipped with outdoor loggers and micro meteorological stations. In these cases we are working with HOBO-Onset material.

**Mathematical analyses for the treatment of the time series**

We present here briefly the skills used for the treatment of the time series that we are generating at the different stations.

**Spectral analysis**

**Introduction and objectives**

On the one hand, meteorological variables are: precipitation, air temperature and relative humidity. On the other, variables related to glacier discharge are: river water surface level, glacier discharge (obtained through the calibration curve), water conductivity and water temperature.

With the Correlative and Spectral Analysis techniques, we try to analyze the cause-effect relation between glacier discharge and the major meteorological variables, mainly air temperature. The first analyses made up to date point to air temperature as the main factor determining the glacier discharge dynamics. It is possible to analyze by simple analysis the auto-correlation of the temperature and discharge time series, with the intention of finding out, if there is one, a long-term tendency and studying the glacier regulating role, that is, whether the glacier responds with a daily drainage variation to the daily thermal pulses. The cause-effect relation existing between temperature and discharge can be studied with cross-analysis and, besides it is possible to determine the relation between both variables for daily variations, as well as the time lag.

Regarding the atmospheric pressure variable, we have been finding periodicities and influences on glacier drainage. Comparing the cross-correlograms of the temperature-discharge and pressure-discharge relations we can analyse the relation between atmospheric pressure and temperature.

With the cross-correlograms between air temperature (as cause) and relative humidity (as effect) we can study the apparent relation between humidity and glacier discharge through air temperature.

It is also interesting to analyse the component of the daily cycle of global solar radiation and its influence on the dynamics of glacier discharge. Finally the relation between water conductivity and glacier discharge can also be analysed to study the chemical variations in water.

**Techniques of Correlative and Spectral Analysis**

Correlative and Spectral Analysis (Jenkins, Watts 1968; Box, Jenkins 1976) is a powerful statistics tool for qualitative analysis of time series (Cañamón et al. 2004, Mangin 1984, Mangin 1994) in the time and frequency fields. It offers information on the system impulse response and, besides, on the time series structure and input-output multiple relations.

With this methodology, the time series are analysed from a descriptive point of view, in order to establish their structure: tendency, periodical and random components. The identification of these structures and their isolation after the factorization are used to explain the processes responsible for them. Thus, with these techniques, no hypotheses are imposed upon the series to analyse, and no previous treatment is necessary (filtering, etc).
However, the time series must be long enough to give relevance to the structures embedded in them.

**Simple Correlative Analysis**

In the simple correlative analysis we suppose the time series to be the system response to a random function (‘white noise’) in the input (Jenkins and Watts 1968). Thanks to this hypothesis, the analysis leads to the identification and description of the time series components (tendency, periodicity and randomness).

The *auto-correlation* function shows the way each event relates to each of the different time intervals. It is obtained using the following formula propounded by Jenkins and Watts (1968):

\[
r_k = \frac{C_k}{C_0} \quad \text{where} \quad C_k = n^{-1} \sum_{j=0}^{n-k} (x_j - \bar{x})(x_{j+k} - \bar{x})
\]

The time series, its values defined by \{x_0, x_1, ..., x_n\} (being \(n\) the time series length), has an average value \(\bar{x}\); \(r_k\) is the auto-correlation function value with \(k\) as time interval; \(k\) is the phase lag and varies between 0 and \(m\), which is known as the truncation point; factor \(C_0\) is the series spectrum variance.

The *spectrum density function* corresponds to the change from a temporal field to a frequency field changing variables (Fourier transformation of the correlogram). The formula used was propounded by Jenkins and Watts (1968):

\[
S_F = 2 \left[ 1 + 2 \sum_{i=1}^{n} D_k \cdot r_k \cdot \cos 2\pi Fk \right]
\]

where, \(k\) is the phase lag and \(F = j/2m\) (\(j\) = pace; \(m\) = truncation point). Factor \(D_k\) is a window filtering the signal to reduce the relative importance acquired by noise in the high frequency band.

Truncation \(m\) must always be lower than \(n/2\) (at least two values are necessary to obtain any kind of measure) and preferably lower than \(n/3\), to obtain reliable statistical data from the analyses.

**Cross-Correlative Analysis**

In this kind of analysis, the time series is considered as the system response to other time series (as input). To carry out a cross analysis, there are tools similar to those for simple analysis, with some specific considerations:

The *cross-correlogram* (or inter-correlogram) establishes the input-output relation. The cross-correlogram is obtained, by analogy to simple analysis, using the following expression (Jenkins and Watts 1968):

\[
r_{xy} = r_{yx}(k) = \frac{C_{xy}(k)}{S_x \cdot S_y} \quad \text{where} \quad C_{xy}(k) = n^{-1} \sum_{i=1}^{n-k} (x_i - \bar{x})(y_{i+k} - \bar{y})
\]

and with \(S_x^2 = n^{-1} \sum_{i=1}^{n} (x_i - \bar{x})^2\) \(y\) \(S_y^2 = n^{-1} \sum_{i=1}^{n} (y_i - \bar{y})^2\)

where, \(x\) is the input signal, \(y\) is the output signal, \(S_x\) \(S_y\) are respectively the spectrum variances, and \(C_{x,y}(k)\) is the covariances between \(x\) - \(y\) for a time phase lag \(k\).

**Wavelet analysis**

**Introduction and objectives**

This technique was developed as an alternative to get over the resolution problems of the Short-Term Fourier Transform (STFT), making it possible a good signal representation both on time and frequency in a simultaneous way, which let us determine the time interval in which specific spectrum components appear.

The problem of the time-frequency resolution results from Heisenberg’s uncertainty principle and shows up whatever transform we use. However, wavelet analysis of Wavelet Transform analyses the signal for different frequencies with different resolutions. Each spectrum component, therefore, is not resolved in the same way as in the case of the STFT. In this sense, it is a multi-resolution analysis. The multi-resolution analysis is designed to give a good time resolution and a poor resolution in frequency for high frequencies, and a good resolution in frequency and low in time for low frequencies.
This treatment acquires special meaning when
the signals to work with have short-term high
frequency components and long-term low
frequency components, which constitutes a
common characteristic of the data series
coming from nature.

Continuous Wavelet Transform
The continuous Wavelet transform is
defined as follows:

\[ C_{j}(a, b) = \int_{-\infty}^{\infty} f(t) \cdot \psi_{j, a}(t) \, dt \]

where:

\[ \psi_{j, a}(t) = \frac{1}{\sqrt{a}} \psi \left( \frac{t - b}{a} \right) \]

As we can see in the preceding equation,
the transformed signal is a function of two
variables, \( a \) and \( b \), translation and scale
parameters respectively. Given two values \( a \)
and \( b \), we calculate a coefficient \( C(a, b) \)
using the previous equations, which represents
the correlation between the wavelet and the
section of the signal under analysis. The
definition of the CWT shows that wavelet
analysis can be interpreted as a measure of the
similarity between the base functions
(wavelets) and the studied signal, where this
similarity is in the sense of a similar content in
frequency, thus the calculated coefficients of
the CWT indicate how near the signal is to the
wavelet in a specific scale. The greater they
are, the greater the similarity; which makes it
interesting to mark that results will depend on
the wavelet form. \( \Psi_{j, a}(t) \) is the transformation
function, and it is called “mother wavelet”.
This type of functions (window) is of finite
length (of compact support) and oscillatory
nature. Also, the mother wavelet is the
prototype to generate other window functions
of the multi-resolution analysis by means of
translation and scaling operations.

Discreet wavelet transform. Multi-resolution
analysis
The continuous wavelet transform gives
information that is highly redundant to
reconstruct the signal. This redundancy also
means a significant increase of the calculation
time. That is why the discreet wavelet
transform (DWT) was devised. It is able to
give enough information both for analysis and
signal reconstruction with a considerable
reduction of processing time; besides, it is
much easier to implement than the CWT.

Let the signal to analyse \( f[n] \) be a discreet
function. In this case, the wavelet transform of
this signal is given by

\[ f(t) = \sum_{j \in \mathbb{Z}} \sum_{k \in \mathbb{Z}} c_{j, k} \cdot \psi_{j, k}(t) \]

where \( \psi_{j, k}(t) \) is a discreet wavelet defined
as:

\[ \psi_{j, k}(t) = 2^{j/2} \psi(2^j t - k) \]

where, \( a \) and \( b \) parameters are defined here
according to the dyadic scale, so that \( a = 2j \)
and \( b = 2j k \). If the transform is orthogonal,
then it can be build by means of a multi-
resolution analysis.

Multi-resolution analysis was introduced by
Mallat (1989), and it is based on a pyramidal
algorithm of consecutive signal filtering with
high pass and low pass filters. In this case,
mirror filters in quadrature are included. The
factorization process begins by passing the
discreet sequence corresponding to the signal
through a half band low pass filter with
response to the impulse \( h[n] \). This filter
removes the frequency components above half
the signal band amplitude. This process is
repeated with the residual signal obtained from
the previous filtering, and this goes on until at
the end we obtain the signal components for
each dyadic frequency used.

Some conclusions
We can summarized briefly some general
conclusions that we are finding out with this
investigation that we are developing at the
different stations of measurement implemented
till now:
- Exponential growth of glacier discharge in all implemented stations until now (the two ones with most distant between them, is more than 16,000 km from distance).
- To the same latitude in both hemispheres, the discharge glacier is from 3.5 to 4 times major in the Arctic than in the Antarctica.
- The Arctic station (CPE-ALB-79ºN) and the Antarctic one (CPE-KG-62ºS) present practically the same quantity of specific glacier discharge, that means, it is necessary to rise 17º in latitude in the Arctic, to find similar values to the Antarctic ones.

- In summer time, glacier discharge in Antarctica doubled in 13 years, during the period from 1987 to 2000.
- With the continuous and pluriannual time series of glacier discharge glacier that we have registered in the Antarctica, we found out that the discharge has doubled in the last 3 years (from 2002/03 to 2005/06).
- In summer period, from 2005/06, at the Antarctic station (CPE-KG-62ºS) implemented in the subpolar glacier Collins, indicates that the increase of the discharge glacier specific comes closer to proper values of tempered glaciers.

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