

**SUBPOLAR GLACIERS NETWORK AS NATURAL SENSORS OF GLOBAL WARMING
EVOLUTION**

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Abstract. Obvious increase in sea level. In the work hypotheses now in use, 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.

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.

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 (pluriannual) 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.

1. 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 m³/sec km² in temperate glaciers (Lat. 64°N; Lat. 51°S)

0.2 – 0.3 m³/sec km² in subpolar glaciers (Lat. 79°N; Lat. 62°S)

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 km² for temperate glaciers

More than 750,000 km² 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 four Experimental Catchment Areas (CPE), two in the northern hemisphere and two more in the southern one (8670 data per year per measured parameter in each station). These four stations register temporal series from then with hourly intervals of, among other parameters, glacier discharge. In the Southern Hemisphere: CPE-BCAA-62°S, in Insular Antarctic and CPE-ZS-51°S, in the Chilean Patagonia. In the Northern Hemisphere: CPE-ALB-79°N, in Svalbard and CPE-KVIA-64°N, in Iceland

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 project, 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 (pluriannual) 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, 2004 a).

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, as SUGLANET, presented at the first convention of the International Polar Year, has been accepted and is presently included in two leading projects, one for investigations taking place in Antarctic (CICLOPEN) and the other for those in the Arctic (GLACIODYN).

2. Record of global warming from glaciers

2.1. Evidences 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 Courmayeur (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 0°C (Badino, 1991), (Mavlyudov, 1994), (Rehak and Rehak, 1994), (Reynaud, Moreau, 1994) and (Schröder, 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), (Eraso, Pulina, 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 temperature on glacier internal ablation (Pereyema, 1991), (Calle, Domínguez, Eraso, 2001).

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 MC, Eraso A, Lluberas A; 2004), (Domínguez MC, Eraso A; 2001), (Domínguez MC, Eraso A; 2002), (Eraso A; 2004b), (Eraso A, Domínguez MC, 2004b).

2.2. 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.

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.

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 one 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.

2.3. CPE's network: actual and future

Following this idea, we began our work in 2001, within the so-called GLACKMA Project (GLAciares, CrioKarst y Medio Ambiente), and are presently monitoring four experimental catchment areas:

In the Southern Hemisphere:

CPE-BCAA-62°S, in Insular Antarctic

CPE-ZS-51°S, in the Chilean Patagonia

In the Northern Hemisphere:

CPE-ALB-79°N, in Svalbard

CPE-KVIA-64°N, in Iceland

We plan to keep these already existing CPE's working and implement new ones at different latitudes. To implement new CPE's at different latitudes to generate more continuous registers, and so, to be able to establish global warming evolution according to latitude. Altitude will also be varied in some of them, in order to be able to study its effect on glacier discharge. The new possible locations are: Antarctic Peninsula, near the Ukrainian Base Vernadsky (Lat. 65°S); Continental Antarctic, near the Russian Base Novolazarevskaya (Lat. 71°S); Insular Antarctic, cape Shirreff, Livingston island (Lat. 62°S); Canadian Arctic, Ellesmere, Grisefiord glacier (76°N); Russian Arctic, Obruchev (Lat. 67°N) and IGAN (Lat. 67°N) glaciers, at different altitudes (397 to 650 m. above sea level for the first, and 820-1225 m. above sea level for the second); and in Swede, Storglaciären glacier (67°N) with 1130-1750 m. above sea level of altitude (the last three ones would be used to analyse the influence of altitude).

3. Volume-level adjustment curve. Protocol of gauging campaigns

We use the river level to generate the temporal 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 each 25 cm, 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 MC, 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.

4. Examples

Here we show some of the results in the station CPE-KVIA-64°N in Iceland. We decide to mean measuring values in order to speed up the graphic, so using the "running mean" as statistic operator tool, we fix the data field gathering 36 values (Figure 1) (Fig.1-4 see the color paste). This amount of values is equivalent to one and half day in the hourly time series.

In general it is possible to appreciate a direct correspondence between the discharge glacier and the temperature. Nevertheless the shape of discharge-graphic for the high values is not always in correspondence with the shape of temperature-graphic (for example, from the 27th June until the 3rd July 2004). This fact is due to the effect of rain in glacier discharge, which superimposes to the effect of temperature (Domínguez MC., Eraso A., Lluberas A., 2003), (Eraso A., Domínguez MC., Lluberas A., 2003).

5. Future objectives to long term

1) To implement 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.

2) To be able to use glaciers as present time indicators of the said warming, it follows that it is necessary to implement Experimental Catchment Areas (CPE) at different latitudes to register continually the hydraulic parameters of glacier discharge.

3) To keep the four CPE already installed in the first stage of the GLACKMA Project working: CPE-BCAA-62°S in Insular Antarctic, CPE-ZS-51°S in the Chilean Patagonia, CPE-ALB-79°N in Svalbard and CPE-KVIA-64°N in Iceland.

4) To implement new CPE's at different latitudes to generate more continuous registers, and so, to be able to establish global warming evolution according to latitude. Altitude will also be varied in some of them, in order to be able to study its effect on glacier discharge. The new possible locations are: Antarctic Peninsula, near the Ukrainian Base Vernadsky (Lat. 65°S); Continental Antarctic, near the Russian Base Novolazarevskaya (Lat. 71°S); Insular Antarctic, cape Shirreff, Livingston island (Lat. 62°S); Canadian Arctic, Ellesmere, Grisefiord glacier (76°N); Russian Arctic, Obruchev (Lat. 67°N) and IGAN (Lat. 67°N) glaciers, at different altitudes (397 to 650 m. above sea level for the first, and 820-1225 m. above sea level for the second); and in Swede, Storglaciären glacier (67°N) with 1130-1750 m. above sea level of altitude (the last three ones would be used to analyse the influence of altitude).

5) To establish in each case the law that quantifies discharge evolution along time.

6) To differentiate the annual discharge wave, the aftershocks and drainage threshold in each annual hydrograph from each CPE. This discharge wave represents the main part of the melting process that affects glacier ice, mainly in its interior and of endoglacier nature. It consists in the glacier icecap response to climate imprints and global warming.

7) The influence of different meteorological variables on glacier drainage will be studied applying spectrum and correlative analysis, which gives interesting information about the behaviour of glaciers as drainage systems. Taking as input functions the appropriate meteorological variables (precipitation, atmospheric pressure, relative humidity, solar radiation, etc) and as output function the volume drained by the specific glacier, its response to each of the input functions can be analysed.

References

Braithwaite R.J., 1995; Positive degree-day factors for ablation on the Greenland Ice Sheet studied by energy-balance modelling; *Journ. Glaciol.* 41: 153–160.

Braithwaite R.J., Oleson O.B., 1989; Calculation of glacier ablation from air temperature, West Greenland.; In: *Glacier fluctuations and climatic change*. J. Oerlemans (ed.). Kluwer Acad. Publ., Dordrecht: 219–233.

Daoke C.S.M., Vaughan D.G., 1991; Rapid desintegration of the Wordie Ice Shelf in response to atmospheric warming; *NATURE*, (350), págs. 328–330.

Domínguez MC, Eraso A, (2001), GLACKMA, una aportación de Castilla y León a la investigación sobre el calentamiento global de la Tierra. *Medio Ambiente*. Junta de Castilla y León, Vol nº 16,52–54, Valladolid.

Domínguez MC, Eraso A, (2002), Los glaciares como sensores naturales del calentamiento global. *Avances en Calidad Ambiental*, Ediciones Universidad de Salamanca, Vol 1, 245–250, Salamanca.

Eraso A. (2004) El calentamiento global, su registro desde los glaciares subpolares y sus consecuencias medioambientales. Centro de Publicaciones. Ministerio de Medio Ambiente, Instituto Nacional de Meteorología, pp 16, Conferencia de Clausura de la V Edición del Curso Magister de Riesgos Climáticos e Impacto Ambiental. Madrid.

Eraso A., Domínguez M.C., 2001; El Calentamiento Global visto desde los glaciares subpolares de la Antártida. Consideraciones sobre su repercusión en la subida del nivel del mar; *RIESGOS NATURALES*, Capítulo 44, pp 819–829, Ed. Ariel, España.

Eraso A., Pulina M., 2001; *Cuevas en hielo y ríos bajo los glaciares*; 2ª Ed. Mc. Graw-Hill.299 pp, Madrid, España.

Eraso A, Domínguez MC (2004a) Subpolar glaciers and global warming, *Bestnik*, Russian Academy of Natural Sciences, vol. 4, nº1, Moscow, Russia, pp 53–57.

Eraso A., Domínguez M.C. (2004b), Implementation of experimental pilot catchment areas for the study of the discharge of subpolar glaciers. VI Symposium *Glacier Caves and Karst in Polar Regions* : 117–136. Ny-Alesund (Svalbard), Norway.

Mercer J.H., 1978, West Antarctic ice sheet and CO₂ greenhouse effectia threat of disaster, *Nature*, 271, 321–325.

Oerlemans J., 1991; The mass balance of the Greenland Ice Sheet: sensitivity to climate change as revealed by energy-balance modelling. *Holocene* 1: 40–49.

Oppenheimer, M., 1998, Global warming and the stability of the West Antarctic ice sheet, *Nature*, 393, 325–332.

Remy, F., Ritz, C., 2002, Los casquetes polares, *Investigación y Ciencia*, pp 76-85. Barcelona, Spain.

Röthlisberger H., 1972; Water pressure in intra and subglacial channels. *Journ. Glaciol.* 11: 177–203;

Rott H., Skvarca P., Nagler T., 1996; Rapid collapse of northern Larsen ice shelf, Antarctica; *SCIENCE*, (271), págs. 788–192.