Analysis of subpolar glaciers discharges using correlation and spectral analysis

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Abstract.

The main purpose of this work is to use Correlation and Spectral Analysis to investigate the processes controlling the evolution of the discharge of subpolar glaciers, possibly associated with the global warming. In particular, here we analyse the time series obtained for the annual discharge wave –year 2002- from the experimental catchment area (CPE-BCAA-62ºS) in the Small Dome or Bellingshausen Dome in the Collins glacier icecap, which occupies King George Island in South Shetland, Antarctica.

The analysed time series for meteorological variables are: precipitation, atmospheric pressure, global solar radiation, air temperature and relative air humidity. Time series for hydraulic variables, related to the glacier discharge, are: river level (deduced from the water level series), water flow, water conductivity and water temperature.

Correlation and Spectral Analysis are used to establish the cause-effect relationship between glacier discharge and main meteorological variables. Indeed, this analysis points out the "regulatory" character of the glacier: the glacier responds to daily thermal pulses with a daily variation of the drainage as well.

The main result is a direct possible cause-effect relation between air temperature and glacier discharge (water level), with an average time lag of 3.5h. However, short-term relation between precipitation and glacier discharge is very small, which could be due to the high proportion of precipitation that occurs in form of snow, and does contribute to the general discharge only in a long-term relation. In addition, a daily periodicity has been found, not only in the air temperature series, but also in many others data series like water level, water conductivity and relative humidity time series. In terms of water conductivity, an inversely proportional relation has been found with the glacier discharge.

Correlation and Spectral Analysis has showed to be useful to study meteorological and hydraulic time series coming from subpolar glaciers measuring cam-

paigns. Some important relations and a better characterization of the glacier discharge behaviour have been established in this work.

1 Introduction and objectives

For investigating the role played by the discharge of subpolar glaciers (Eraso and Pulina 2001) in the global warming the GLACE Project: “GLAciers, Cryokarst and Environment” (Project GLACKMA: “GLAciares, CrioKarst y Medio Ambiente”) was started in 2001, with the implementation of experimental pilot catchment areas able to register the glacier discharge at high latitudes. One of these catchment areas is the named (CPE-BCAA-62ºS), implemented in order to study the discharge from the Small Dome or Bellingshausen Dome in the Collins glacier icecap (see Fig. 1), which is placed on King George Island in South Shetland (Antarctica).

On the one hand, meteorological variables are: precipitation, atmospheric pressure, global solar radiation, air temperature and relative air humidity. On the other hand, variables related to the glacier discharge are: river water level, water flow (through a calibration curve), water conductivity and water temperature.

With Correlation and Spectral Analysis techniques we try to analyse the cause-effect relationship between glacier discharge and main meteorological variables, mainly with air temperature. It seems that air temperature is the main determining factor of glacier drainage dynamics. With Simple analysis, autocorrelation of air temperature and discharge time series have been studied to search if there is a tendency in the long-term and to study the glacier regulator character, i.e. whether if the glacier responds with a daily variation of the drainage to the daily thermal pulses or not. The relationship existing between air temperature and discharge has been analyzed with Cross analysis. The relationship between both variables for daily variations and the time lag has been deduced.

For the atmospheric pressure variable, periodicities and influence on the glacier drainage have been studied. Cross-correlograms of the relations temperature-discharge and pressure-discharge have been compared, to study the relation between atmospheric pressure and temperature.

Relation between relative humidity and glacier discharge seems to occur through the air temperature. To study that, the cross-correlogram between air temperature (as cause) and relative humidity (as effect) has been analyzed.

In the catchment area of the studied glacier, the main precipitation events are in form of snow, which means that its relation with glacier discharge is not direct. That has been analyzed with the cross-correlogram between those time series.

The daily cycle component of global solar radiation and its influence on the glacier water dynamics has also been analysed. However, it would be very interesting to study the cross-correlogram of the radiation and relative humidity variables with sublimation. Finally, the relationship between discharge and water conductivity has been analysed to study the chemical variations on the water.

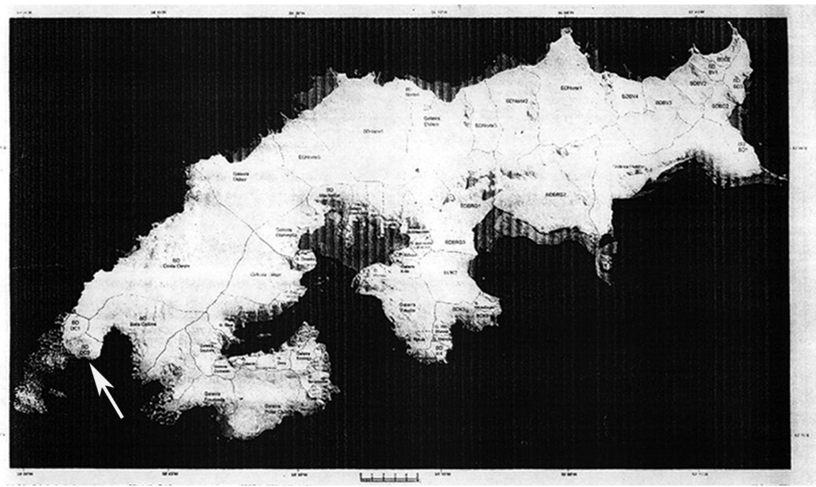


Fig. 1. Small Dome or Bellingshausen Dome in the Collins glacier icecap, in King George Island (Antarctica)

2 Experimental pilot catchment area

2.1 Location and field works

Between December 3rd, 2002, and January 5th, 2003, the "Antarctica 2003" expedition to the Collins glacier icecap in King George Island (South Shetland, Antarctica) took place, with logistic help from the Bellingshausen Russian Base. Thus we continued the studies carried out in the same icecap in the two previous expeditions: summers of 2000 and 2002.

During the summer of 2000 an experimental station, CPE-SC-62ºS, had been installed in the slope towards the Drake Strait of the Small Dome or Bellingshausen Dome of the aforementioned icecap (Eraso et al. 2004). Later on, in the summer of the 2002, other catchment area was selected in the Small Dome. In this last case we selected the catchment area corresponding to the SW sector of the dome, as the river responsible for this discharge from the glacier in its route to the Bransfield Strait passes in its final stretch by the Artigas Uruguayan Base BCAA, and there was an entry bridge to the base over the river which made the installation of the measurement station easier (Fig. 2) (Domínguez et al. 2004).

This station, CPE-BCAA-62ºS, was left working all along the year, and not only in summer periods, as it had been done until then. Although glacier discharge has not happened during the winter, it was considered convenient that the device remains fixed to have always the same reference level and to assure the completeness of the time series. The data logged round the year at the experimental pilot catchment area were collected during this "Antarctica 2003" expedition.

Fig. 2. Experimental station in the bridge of the Uruguayan Base Artigas, CPE-BCAA-62ºS

2.2 Characteristics of experimental station

The surface of the selected glacier catchment area, corresponding to the SW sector of the Small Dome or Bellingshausen Dome was established on the base of radio-echo sounder studies. However, its cartography was completed by means of GPS readings of the perimeter moraine and the surfacing nunataks in this SW sector of the Small Dome in Collins glacier. Its characteristics were thus defined as follows: total surface of the glacier catchment area: 1,3 km^2; ablation area surface: 1,17 km^2; accumulation area surface: 0,13 km^2; altitude of firn line: 270 m. asl.

The glacier catchment area drains through a series of perimeter streams from the moraine delimiting the glacier end on its SW side. These streams, after different courses, converge into the lagoon by the Ionospheric Station of the Scientific Antarctic Base Artigas "BCAA". From there they flow as an single stream, a river that runs under the entry bridge to the abovementioned BCAA. It was under this bridge where the experimental station CPE-BCAA-62ºS was left installed. Its coordinates in GPS reading are: latitude: S 62º 11' 035; longitude: W 58º 54' 414; altitude: 24 m. asl.

2.3 Annual series of input and output variables

The station had been equipped with a multi-parameter sounder (MDS-"Insider 2" Seba-Hydrometrie) with sensors for water level (cm), water temperature (ºC) and conductivity (microS/cm). Combining the data registered during the preceding summer campaign, the ones logged by the station during the whole year and the ones recorded during the period of the present expedition, we were able to complete an annual series which covers from January 21th, 2002, to January 5th, 2003. Fig. 3 shows the annual series object of this study.

To be able to obtain the discharge (m^3/sec) from the water level time series logged by the sounder we have used the calibration curve which, with a correlation coefficient of R=0.98, was obtained during the previous summer gauging campaign (Eraso and Domínguez 2004).

The meteorological variables taken into account were: air temperature (ºC), relative humidity (%), solar radiation (W/m^2), precipitation (mm) and atmospheric pressure (mbar). These time series were supplied by the Meteorological Station of the Bellingshausen Russian Base.

2.4 Time distribution of glacier discharge

Focusing on glacier discharge, which is the main objective of our research, the information covers:

- Period from 20th January to 11th of March 2002, discharge corresponding to summer 2001/2002.
- There is no discharge between 11th of March and 14th of December 2002, corresponding to the southern winter period.
- Period from 14th December to 31th of December 2002, which is the initial stretch of the discharge corresponding to the southern summer of 2002.

Though in this work we focus our attention on discharge of year 2002, it is important to notice that, up to now, the pilot station continues generating time series hourly.

3 Correlation and spectral analysis techniques

The Correlation and Spectral Analysis (Jenkins and Watts 1968; Box and Jenkins 1976) is a powerful statistical tool for the qualitative analysis of time series (Cañamón et al. 2004, Mangin 1984, Mangin 1994), in both time and frequency domains. It offers information about the impulse response of the system, and also about the structure of the time series and multiple input-output links. In this methodology the time series are analyzed from a descriptive point of view, in order to establish their structure: trend, periodic components and random components. The identification of these structures and their isolation after decomposition are used to explain the processes that are responsible for them. Thus, with these techniques, no hypothesis is imposed on the series to be analyzed and no pre-treatment (filtering, etc) is necessary. However, the time series must be long enough to give prominence to the structures they express and should not be incomplete (interpolation should be done if necessary).

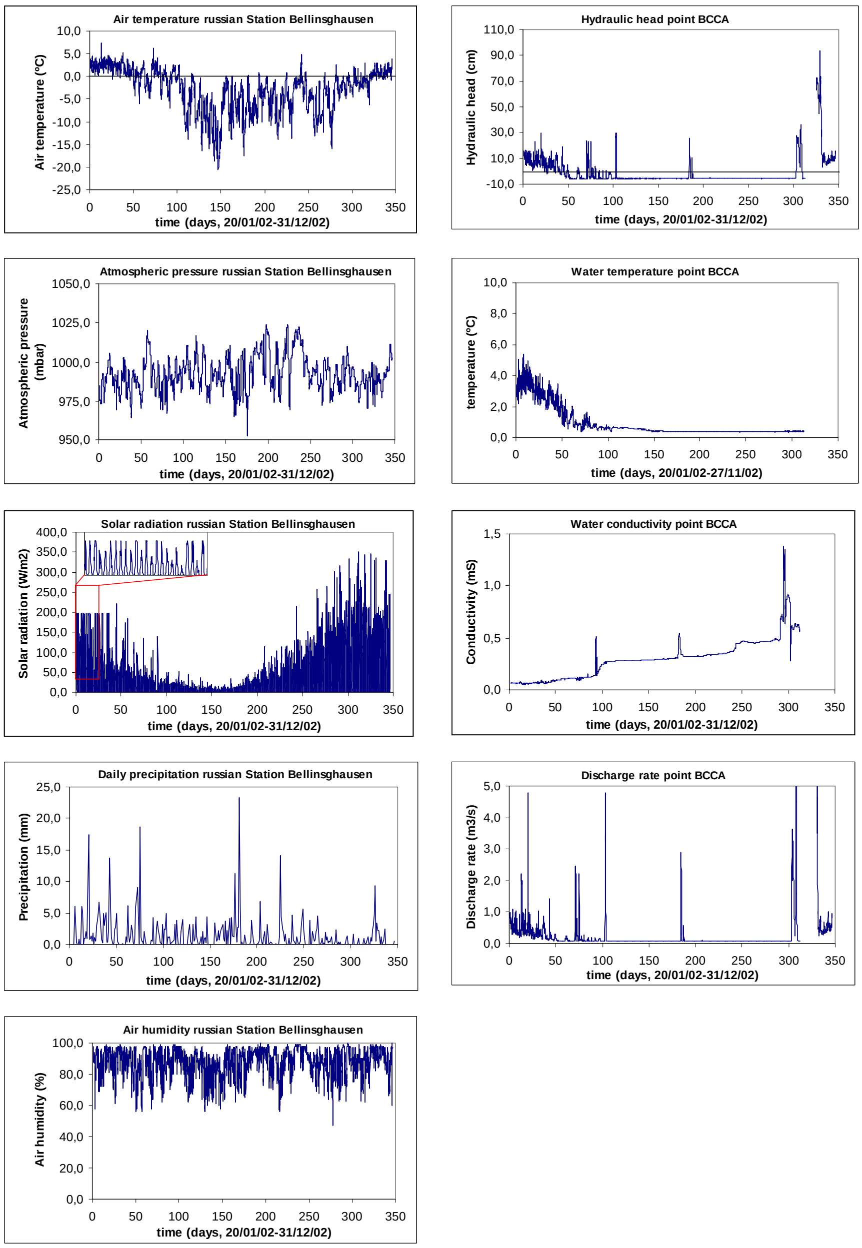


Fig. 3. Meteorological (first column) and glacier discharge (second column) parameters (January 20th to December 31st 2002).

3.1 Simple correlation analysis (univariate)

In the simple correlation analysis, the time series is supposed to be the response of the system to a random function (‘white noise’) at the input (Jenkins and Watts 1968). Because of this intrinsic hypothesis of the methodology, the analysis leads to the identification and description of the components of the time series (trend, periodicity and randomness).

The *autocorrelation function* shows how the events are linked to each other for different time intervals. It is obtained using the following formula (Eq. 1), proposed by Jenkins and Watts (1968):

$$r_k = \frac{C_k}{C_0} \quad with \quad C_k = n^{-1} \cdot \sum_{i=0}^{n-k} \left(x_i - \bar{x}\right) \cdot \left(x_{i+k} - \bar{x}\right) \tag{1}$$

The time series, which is defined by its $\{x_0, x_1, ..., x_n\}$ values (n being the length of the time series), has an average value $\bar{x}$; r_k is the value of the autocorrelation function with k as the time interval; k is the lag and varies from 0 to m, which is called the truncation point; the factor C_0 is the spectral variance of the series.

The *spectral density function* corresponds to the change from a time domain (time series space) to a frequency domain by changing variables (Fourier’s transformation of the correlogram). The formula used is that proposed by Jenkins and Watts (1968):

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

where k is the lag and $F=j/2m$ ($j \equiv$ step; $m \equiv$ truncation point). The factor D_k is a window that filters the signal in order to decrease the relative importance that noise acquires in the high frequency band. In this study, Tukey window has been used.

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

3.2 Cross correlation analysis (Bivariate)

In this type of analysis, the time series is considered to be the response of the system to another time series as an input (‘cause-effect’ relation). The causality is a mathematical hypothesis of the methodology, as described in the simple correlation analysis, fulfilled or not in the real data analysis. To accomplish the cross-analysis, there are similar tools to those of the simple analysis, with some specific considerations:

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

$$r_{+k} = r_{x,y}(k) = \frac{C_{x,y}(k)}{S_x \cdot S_y} \quad with \quad C_{x,y}(k) = n^{-1}\sum_{i=1}^{n-k}\left(x_i - \overline{x}\right)\cdot\left(y_{i+k} - \overline{y}\right) \tag{3}$$

$$r_{-k} = r_{y,x}(k) = \frac{C_{y,x}(k)}{S_x \cdot S_y} \quad with \quad C_{y,x}(k) = n^{-1}\sum_{i=1}^{n-k}\left(y_i - \overline{y}\right)\cdot\left(x_{i+k} - \overline{x}\right)$$

$$and\ with \quad S_x^2 = n^{-1}\sum_{i=1}^{n-k}\left(x_i - \overline{x}\right)^2 \quad and \quad S_y^2 = n^{-1}\sum_{i=1}^{n-k}\left(y_i - \overline{y}\right)^2$$

where x is the input signal, y is the output signal, S_x and S_y are the spectral variances respectively, and $C_{x,y}(k)$ are the covariance between x and y for a time lag k.

4 Results and discussion

4.1 Preliminary considerations

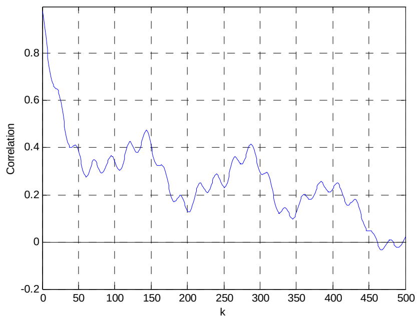
During the winter period (April-October 2002), sensor measurements were constricted to very low values in some cases (water temperature, water discharge rate, water level). The results of correlation and spectral analyses may thus be masked by the zero stationary part. For this reason, we have only considered the richest part of the series (summer period, here called "truncated series") in some analyses, which goes from 20th of January (day 1) up to 30th of April (day 70).

Otherwise, we have preferred to use for the analyses the measured water level time series instead of the discharge rate time series, which was obtained through the correlation function built by direct gauging and contains high peaks that could mask any other information in the analyses.

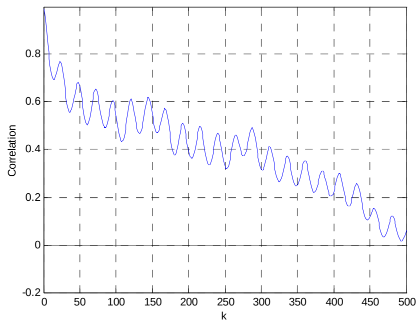
In some cases, 1st Order Differentiation has been used in some cases to eliminate the trend of the series (here called "derived series"). Particularly, we have differenced the series whenever there was an important trend that could mask the information concerning the periodicities and the noise of the time series. This fact is specified in the caption of the corresponding figures of the results.

4.2 Air temperature – Water level relation

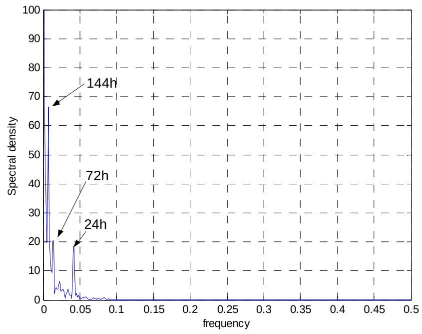
Simple correlation study of these time series evidences the "regulatory" character of the glacier: Fig. 4a and Fig. 4b show the autocorrelation of the air temperature and water level truncated series respectively. The autocorrelation of the water level series decreases much more slowly than the air temperature one.



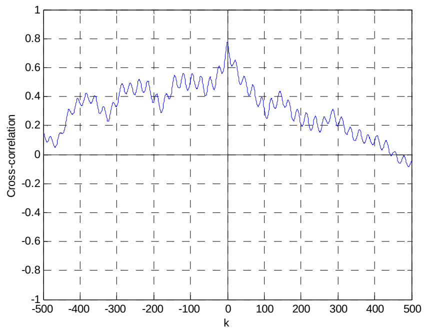
a. Autocorrelation of air temperature truncated time series.



b. Autocorrelation of water level truncated time series.



c. Spectral density of air temperature truncated time series.



d. Cross-correlation of air temperature – water level truncated time series.

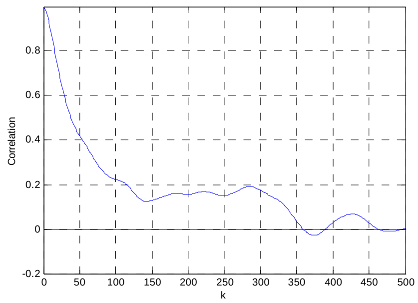
Fig. 4. Simple analysis and Cross analysis for the relation between air temperature and water level time series. Time period analyzed: 20/1/02-30/04/02.

The memory effect can be evaluated by determining the value of k when the autocorrelation reaches 0.2, which in the case of the water level series corresponds to $k = 415$ (17 days approx.). In terms of spectral density, two kinds of periodicities are found in the air temperature series (see Fig. 4c): the expected daily periodicity and a longer one of 144h (6 days approx.). The periodicity of 72h corresponds also to the longer one, and appears due to the asymmetric form of the periodic curve. That kind of curve needs to be decomposed in Fourier in two sinusoidal curves: one with the period of the process and the other with half the period.

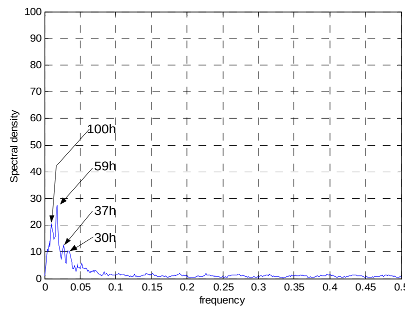
The cross-correlation between those series yields to a strong direct daily relationship, that is, the increase of air temperature produces an increase of water level with a daily periodicity and without any time lag (Fig. 4d). Same periodicities of 24h and 144h can also be observed in the cross relationship.

4.3 Atmospheric pressure – Water level relation

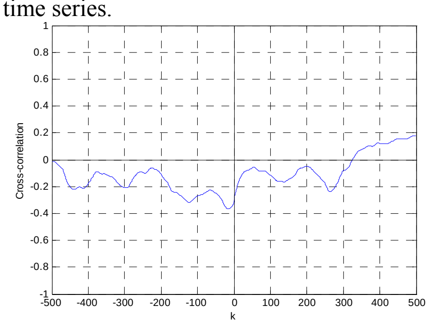
Atmospheric pressure seems to play a complex role in the glacier's drainage dynamics. Atmospheric pressure has a much less structured (inertial) correlogram (Fig. 5a). To better identify periodicities with the spectral density function, the atmospheric pressure derived series has been used. By doing so, the trend peak disappears and periodicity peaks show up in a clearer way. There appear several periodicities in the spectrum different to those found for the air temperature (Fig. 5b). There is an inverse cross-correlation with water level series, but is not very important (Fig. 5c). Nevertheless, the same long-term periodicity of 6 days also appears in the cross-correlation spectral density, what can be appreciated in the Fig. 5d.



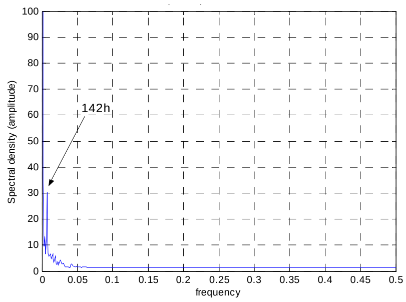
a. Autocorrelation of atmospheric pressure time series.



b. Spectral density of atmospheric pressure derived time series.



c. Cross-correlation of atmospheric pressure – water level truncated time series.



d. Spectral density (amplitude) of atmospheric pressure – water level truncated time series .

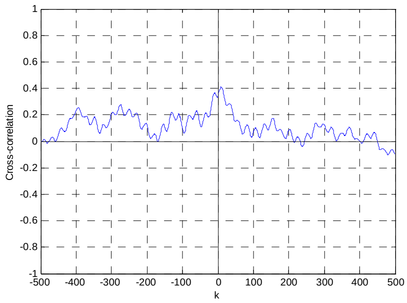
Fig. 5. Simple analysis for the atmospheric pressure time series. Time period analyzed: (**a** and **b**) 20/1/02-31/12/02, (**c** and **d**) 20/1/02-30/04/02.

4.4 Relative humidity – Water level relation

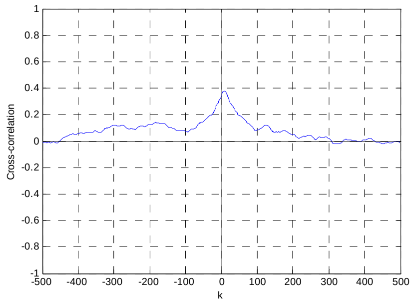
Fig. 6a shows the cross-correlogram between relative humidity and water level time series. As the cross-correlation in Fig. 6a is not very high, we can think that there is an indirect relation which has a third common cause, in this case the air temperature. The similarity of this cross-correlogram and the one presented in Fig 4.d for the relation air temperature – water level can be pointed out. Therefore, a cross-correlation between air temperature and relative humidity has been computed to study a possible causal relation, which is confirmed (Fig. 6b).

4.5 Precipitation – Water level relation

Precipitation is a meteorological parameter with an important random component. This fact can be appreciated in the poor autocorrelation for this time series (Fig. 7a). In this catchment, the rainfall occurs mainly in form of snow over the glacier surface. Therefore, rainfall does not participate in a direct way on the glacier system drainage. Lately, when the poorly compacted snow melts, it is incorporated to the drainage and can contribute to increase the flow levels. This effect can be seen indirectly in the poor short-term influence of precipitation on the water level (Fig. 7a). Therefore, solar radiation, which is the atmospheric variable directly involved in the snow melting, has been studied to analyse its influence on this process.

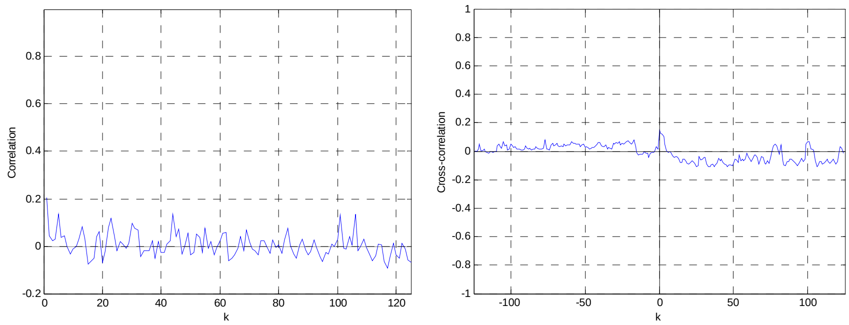


a. Cross-correlation of air humidity - water level truncated time series.



b. Cross-correlation of air temperature - air humidity time series.

Fig. 6. Cross-analysis for the relation between air humidity, air temperature and water level time series. Time period analyzed: (**a**) 20/1/02-30/04/02, (**b**) 20/1/02-31/12/02.



a. Autocorrelation of daily precipitation time series

b. Cross-correlation of precipitation - water level daily time series.

Fig. 7. Cross-analysis for the relation between precipitation and water level time series. Time period analyzed: 20/1/02-31/12/02.

4.6 Solar radiation – Water level relation

Solar radiation, in the opposite of the precipitation time series, is a parameter with an important periodic structure, what can be seen in their autocorrelation and spectral density functions (see Figs. 8a and 8b).

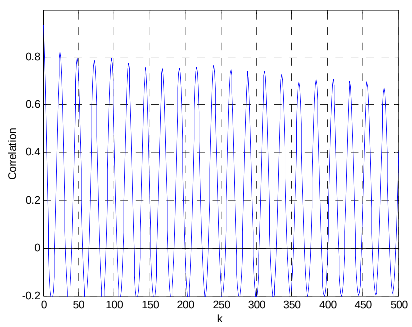
The cross-analysis between solar radiation and water level shows an important direct long-term correlation (Fig. 8c), which seems to be causal. There exists, as well, a time lag in this relation of about 15 days, which again confirms the regulatory character of the glacier. To study the short-term relation we have used the truncated time series (only the summer period) and there appears an important daily periodicity in the computed cross-correlogram (Fig. 8d).

4.7 Water conductivity – Water level relation

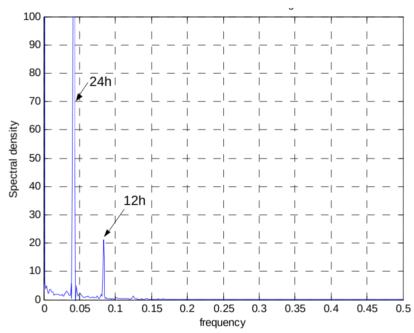
The glacier drainage can also be estimated with the water conductivity time series because high conductivities indicate sub-glacial drainage. Spectral analysis of the water conductivity series indicates the presence of several periodicities in the water mineralization (see Fig. 9a), which correspond respectively to 1.5 days, 3 days and 5 days. Otherwise, cross-correlation with the water level series indicates an overall inverse and negative relation (see Fig. 9b), which means the following: first, variations of water level (related with the discharge rate) determine variations of the water conductivity and, second: those variations are inversely related, i.e., an increase of the water level (and thus discharge rate) produces a decrease in the water conductivity. This fact can be explained as follows: if the water level increases, that means the discharge rate is higher and water flows quickly through the glacier basin, so there is less time for hydrolysis and dissolution processes and the water conductivity (related mainly with dissolved salts) decreases.

5 Conclusions

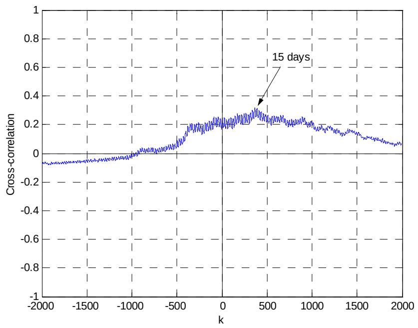
Time series and multi-scale analysis techniques have been applied to meteorological and hydrological data series coming from GLACE project. Behaviour of the different kind of series in terms of correlation and spectral analysis has been described. Daily periodicities have been found in the majority of the time series, but some more complex series as atmospheric pressure or water conductivity have shown other characteristic frequencies. A longer periodicity of 6 days has been discovered in several relations, and should be further analyzed to identify the physical processes causing it. Cross-correlation analysis has determined important relations, some of them possibly causal, as it is the case for the long-term relation between solar radiation and water level series, which along with the poor short-term precipitation – water level relation, explains the process of snow-like precipitations and posterior melting and drainage of melt snow.



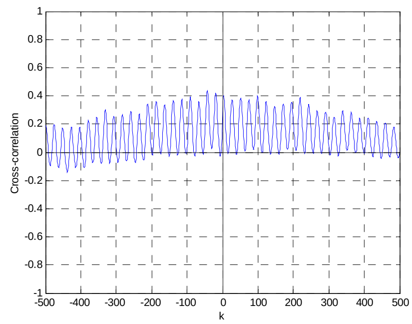
a. Autocorrelation of solar radiation time series.



b. Spectral density of solar radiation time series.

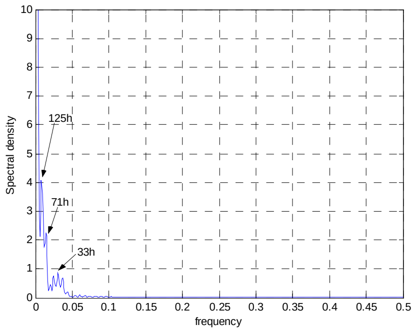


c. Cross-correlation of solar radiation - water level time series.

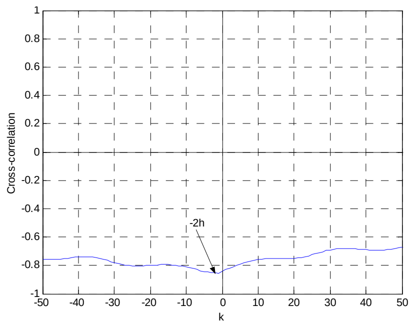


d. Cross-correlation of solar radiation - water level truncated time series.

Fig. 8. Cross-analysis for the relation between solar radiation and water level time series. Time period analyzed: (**a,b** and **c**) 20/1/02-31/12/02, (**d**) 20/1/02-30/04/02.



a. Spectral density of water conductivity time series.



b. Cross-correlation of water conductivity – water level truncated time series.

Fig. 9. Cross-analysis for the relation between water conductivity and water level time series. Time period analyzed: (**a**) 20/1/02-31/12/02, (**b**) 20/1/02-30/04/02.

Regulatory character of the glacier has been pointed out with the correlograms of air temperature and water level time series, as well as with the water conductivity – water level intercorrelation.

Correlation and spectral analysis has demonstrated to be useful to describe glacier discharge dynamics through the study of its meteorological and hydrological time series. Future work should focus on other multiscale techniques as well as in the study of longer time series to analyse the seasonal effects.

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