Relationships among atmosphere-cryosphere-biosphere in a transitional glacial catchment (Sabbione Lake, North-Western Italian Alps)

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ABSTRACT: The present study was carried out in the Sabbione Basin (North-Western Italian Alps, Piedmont). Climatological and geomorphological studies were conducted in order to understand the relationships among climate change and its effects on cryosphere and geosphere. Meteorological data (air temperature, rain and snow) recorded by two stations in the studied area (Formazza and Sabbione) were analyzed. Considering its importance in the cryosphere, particular attention to snow data (amount of snowfall, thickness and persistence of snow cover) was paid; moreover, some stratigraphic profiles of snow cover and snow density data (from A.I.N.E.V.A. and Meteomont, respectively interregional agency and military service for snow and avalanches) were examined. A detailed geomorphological map (scale 1:10000) was created from multitemporal photographic interpretation of aerial images and digital orthoimages. Moreover, field surveys were conducted with the aim to identify micromorphological evidences resulting from cryotic processes. In order to determine the potential presence/absence of permafrost in the area, the model PERMACLIM was implemented in a plug-in in open GIS (QuantumGIS software), and modelled meteorological data input (air temperature and, especially, snow thickness and distribution) were analyzed in detail through the comparison with ground measured data and satellite images. The geomorphological analysis results were compared with three permafrost distribution models, already available for the studied area (PERMAROCK mod., APMOD and Swiss Permafrost Map). Finally, floristic surveys were carried out in order to characterize the vegetation in the basin.

KEYWORDS: climate change, Alps, periglacial processes, glaciers, geomorphology, NW Italy

1 INTRODUCTION

According to the report of the Intergovernmental Panel on Climate Change in 2007 (IPCC, 2007), the global linear trend of air temperatures for the last 100 years (1906-2005) is 0.74±0.18°C, while in the Alps the minimum temperatures have increased (2°C) more than the maximum temperatures (Beniston, 2005). This increase is almost twice that of the global average value (Auer et al., 2007). Climate change also involves the precipitation (solid/liquid); for example, in North-Western Alps there has been a snowfall/snow depth reduction in the period between 1951 and 2010 (Terzago et al., 2013).

On high altitudes climate changes interact with glacial processes, influence the glacial dynamics and cause important modifications on the geomorphological characteristics of alpine landscapes. These changes lead to a gradual evolution of the cryosphere and biosphere with implications also on human activities.

The regression of glaciers allows the formation of the periglacial environment conditions in deglaciated areas. The periglacial environment, which is characterized by frost action and cryotic morphogenetic processes (Péwé, 1969), and permafrost, defined as “soil and/or rock that has remained below 0°C for more than two years” (Brown and Péwé, 1973), are also affected by climate warming, according to some studies that confirm the increase in ground temperature during the last century (Osterkamp and Romanovsky, 1999). This increase has been accelerating during recent years (Harris et al., 2003) with a high interannual variability which depends mainly on the thickness/persistence of snow cover and the distribution of air temperature (Hoelzle and Gruber, 2008).

In the present work the data extracted from meteorological stations located in the basin were analyzed in order to characterize the climate of the study area, to verify the existence of climatic conditions for the development of cryotic processes and to investigate the morpho-climatic evolution of the basin, considering the transition from glacial to proglacial/paraglacial and periglacial environments. A detailed geomorphological map was achieved in order to understand the evolution of the recently deglaciated areas. To determine the potential

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distribution of permafrost the model PERMACLIM (Guglielmin et al., 2003) was implemented in QuantumGIS. Furthermore, other models already available for the studied area (PERMAROCK mod., Guglielmin, 2009; APMOD, Boeckli et al., 2012; Swiss Permafrost Map 1:50000, BAFU, 2005) were compared; the models results were integrated by BTS measurements (Bottom temperatures of snow cover) (Haeberli, 1973), performed within the basin by Arpa Piemonte in the late winter 2011. Finally, vegetation samples on grassland and by transect were carried out to identify the main habitats in the basin.

2 STUDY AREA

The Sabbione basin is located in Formazza Valley (Lepontine Alps, Northern Piedmont, Italy, 46° 41' N; 8° 34' E), forming the upper basin of the Toce River and the boundary line with Switzerland (Figure 1). The major peaks of the basin are (numerical references in Figure 1): 1) Blinnenhorn (3374 m), 2) Corno di Ban (3027 m), 3) Gemelli di Ban (2946 m), 4) Punta d'Arbola (3235 m) and 5) Hohsandhorn (3182 m).

From geological point of view, the Formazza Valley lies in the Lower Penninic nappes characterized by orthogneiss in the southern sectors and mesozoic carbonate rocks/calcschist in the northern sectors; amphibolites and prasinites are also diffused in marginal zones of the study area (Rivella et al., 2012).

A storage pond of 1.23 km^2 (about 26 million m^3) is located in the basin, which gathers the ablation waters of the glaciers situated within the area; the main glaciers are the Northern Sabbione Glacier and the Southern Sabbione Glacier (ca. 3.8 km^2 of total covered area in the 2007). The major glaciers lie in the north-western sector of the basin, between Punta d'Arbola and Blinnenhorn (Figure 1).

3 MATERIALS AND METHODS

3.1 Climate

The data derived from meteorological stations “Formazza” (automatic, 2453 m; period 1988÷2012) and “Sabbione” (manned, 2470 m; period 1950÷2012) (respectively 6 and 7 in Figure 1) were statistically analyzed. A data quality control with the RClimDex software (Zhang and Yang, 2007) was performed before the analysis of air temperature, liquid and solid precipitation time series, and data series with

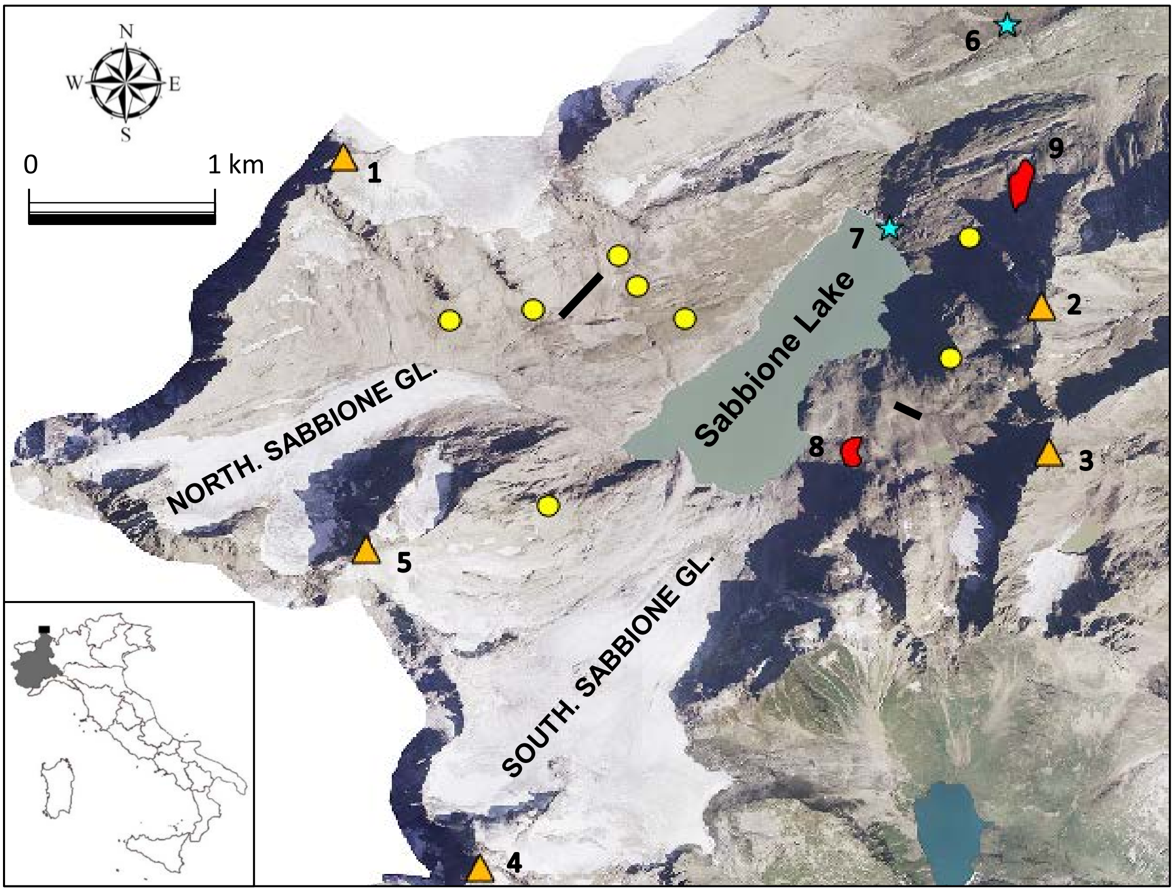

Figure 1. Digital orthoimage of the study area (orthoimage it 2000, year 2007, Blom CGR). Orange triangles: main peaks of the basin (see the names in the text); yellow circles: floristic surveys; red polygons: rock glaciers; blue stars: meteorological stations; black segments: vegetal transects. Details in the text (www.arpa.piemonte.it, wms service).

daily values less than 80% for each month were not considered (Sneyers, 1990). Statistical analysis of data was performed using Excel, RClimDex and AnClim softwares (Stèpànek, 2007). Values from both stations were aggregated on monthly and annual basis and trends were calculated for the main climatic parameters only for the longest time dataset of Sabbione station (maximum and minimum air temperatures, cumulated liquid precipitation, number of rainy days, cumulated fresh snow, snow depth, number of snowy days and period of absence of snow cover) using the non-parametric test of Mann-Kendall to verify the statistical significance (Sneyers, 1990; 1992).

3.2 Evolution of glaciers and geomorphology

Literature data review and historical maps were used to reconstruct the glaciers evolution since the end of the Little Ice Age (LIA).

The geomorphological analysis was conducted in order to describe the geomorhological characteristics of the basin and to understand the evolution of the recently deglaciated areas. The data, derived from photographic interpretation (aerial images of the years 1955, 1977, 1983, 1989, 1999, 2001 and digital orthoimages of the years 1988-1989, 1994-1998, 2000, 2007, 2009, 2010) and field surveys carried out in summer 2012, were digitized in GIS environment, using QuantumGIS and GRASS softwares. Through these data, detailed geomorphological maps (scale 1:10000 and details at 1:3000) and a map of glacial deposits (scale 1:25000) of the basin were realized.

3.3 Permafrost distribution

The physical model PERMACLIM (Guglielmin et al., 2003) was implemented in QuantumGIS to estimate the distribution of permafrost in the study area. The PERMACLIM is a process-oriented model which uses as input data a Digital Terrain Model (DTM) and climate data. Furthermore, qualitative and quantitative analyses of the input data were accomplished in order to apply the model within the basin.

3.4 Vegetation

During the summer seasons 2012 and 2013 vegetation samples were performed to identify the types of habitats existing in the basin. On the grassland 8 phytosociological surveys (Pignatti, 1995) were carried out (Figure 1, yellow circles); for each survey area of 100 m^2 GPS coordinates, altitude, slope and aspect were taken. Samples along transects were achieved (length 300 and 130 m) within 2 debris deposit areas where the vegetation was sporadic (Figure 1, black segments). Finally, the vegetation of two rock glaciers was sampled. Nomenclature of taxa follows Pignatti (1982).

4 RESULTS

4.1 Climate analysis

The analysis of the average annual results are the following:

- Formazza (period 1988÷2012):
  - Air temperature: -0.2°C;
  - Liquid precipitation: 995.1 mm;
  - Fresh snow: 696.2 cm;
  - Snow depth: 97.1 cm;
  - Snowy days: 60;
  - Wind speed: 2.5 m/s.
- Sabbione (period 1950÷2012):
  - Air temperature: -0.9°C;
  - Liquid precipitation: 1034.8 mm;
  - Fresh snow: 741.3 cm;
  - Snow depth: 128.3 cm;
  - Snowy days: 64;
  - Snow cover absence: 102 days.

The climatic trends of Sabbione are the following (period 1951÷2011, Figures 2 and 3):

- Maximum air temperature: significant increase of 0.03±0.01°C/year;
- Minimum air temperature: significant increase of 0.04±0.01°C/year;

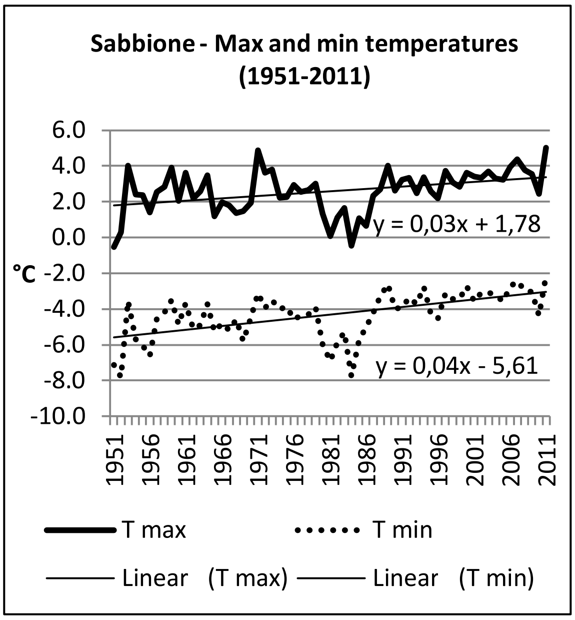

Figure 2. Annual maximum and minimum air temperature trends of Sabbione station (1951÷2011).

- Liquid precipitation: non-significant increase of 1.15±1.9 mm/year;
- Fresh snow (Hn): significant decrease of -3.17±1.35 cm/year;
- Snow depth (Hs): significant decrease of -0.82±0.27 cm/year;

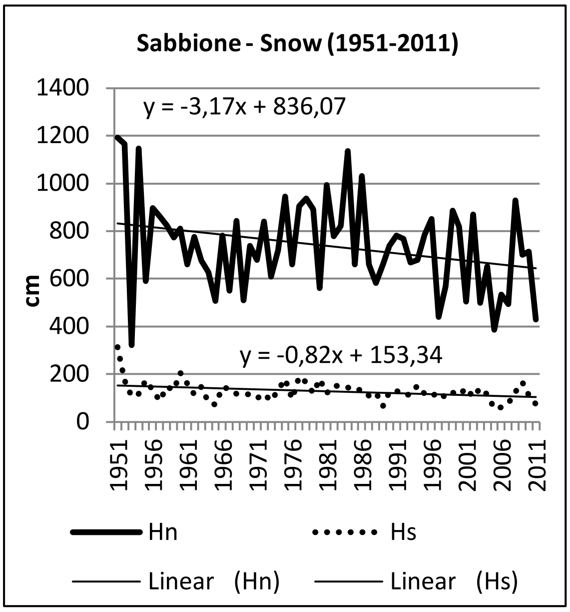

Figure 3. Fresh snow and snow depth trends of Sabbione station (1951÷2011).

- Snowy days: non-significant decrease of -0.06±0.09 days/year;
- Snow cover absence: non-significant increase of 0.08±0.1 days/year.

4.2 Geomorphological analysis

The analysis of the evolution of glaciers shows that the ice coverage of the basin has suffered of important reduction since the second half of the 19th century. Southern Sabbione Glacier retreated by 1,600 m in the period 1885÷1987 (average frontal retirement ca. 16 m/year) (Mazza and Mercalli, 1992). This rate increased in the period 1991÷2004 (ca. 23 m/year) (Mazza, 2007). The Northern Sabbione Glacier suffered of significant volumetric shrinkage (period 1885÷1991), estimated more than 50% (ca. 150 million m^3), and areal reduction, 40% (ca. 1.2 km^2) (Mazza, 1993).

A large amount of glacial deposits (3.2 km^2) has outcropped after the glaciers retirement and disappearance. The geomorphological analyses show the presence of periglacial landforms (such as rock glaciers, patterned ground, etc.) within these deposits, mainly characterized by coarse grain size. Specially, in the Gemelli di Ban area (8 in Figure 1) an active debris rock glacier was identified in deglaciated site by the 50s of 20th century, in which a gradual emphasizing of its morphological expression was observed since the 80s. The elevation of the front is 2505 m, maxima width and length are respectively 170 m and 95 m, covering a total area of 15,965 m^2; the slope is between 13° (depression located in the higher sector of rock glacier body) and 34° (terminus). Its evolution derived from the degradation of a LIA moraine (moraine rock glacier), perhaps due to partial melting of the inside ice core (ice-cored rock glacier).

In the Sabbione basin there is also an active talus rock glacier situated in the Corno di Ban zone (9 in Figure 1). The altitude of the front is 2475 m, maxima width and length are 120 m and 300 m respectively, for a total area of 27,717 m^2; the slope is between 14° (middle sector of the body) and 37° (terminus).

Periglacial landforms resulting from frost sorting and frost heaving processes, such as non-sorted circles and frost boils, were found within glacial deposits, in sectors with slopes ranging from 2° to 15°. Non-sorted stripes were also identified in till, which origin is related to the combination of cryotic and gravitative processes (frost sorting, frost heaving, frost creep and gelifluction). These forms were found on slopes with gradients mostly range from 5° to 15°.

4.3 PERMACLIM model implementation

The PERMACLIM plug-in was implemented in the open source QuantumGIS software, using the SEXTANTE platform and the Python language (in collaboration with Arpa Piemonte and Faunalia). The model calculates the Mean Annual Ground Surface Temperature (MAGST) for each point of the DTM including the snow buffering effect according to the heat conduction theory, which uses climate data and snow thermal characteristics.

Four IT calculation modules were created in order to perform the data processing:

- "Distribution of snow based on slope", which corrects the snow height according to the effects of the slope;
- "Ground Surface Temperature", that calculates surface temperatures for each cell of the DTM;
- "Mean band based on indexes" and "Monthly Mean", which perform mathematical and statistical analyses on model results.

The needed input data are: DTM, Snow cover thickness (h), Air temperature (Ta), Thermal conductivity of snow (K) and Sensible heat flux (Qs).

To apply the PERMACLIM in the study area, snow thickness/distribution (h) and air temperature (Ta) were derived from a hydrological model previously developed by Arpa Piemonte. An already available DTM 50m of Piedmont was also used. The thermal conductivity of snow (K) was calculated starting from density values extracted from stations of military service "Meteomont" (period 2000÷2010), integrated by data derived from 220 stratigraphic snowpack profiles of interregional institution for snow and avalanches

- AINEVA (period 1996÷2010). The mean values of K range from 0.16 Wm^{-1} $°C^{-1}$ in December-January-February to 0.22 Wm^{-1} $°C^{-1}$ in May. The sensible heat flux (Qs) was derived from studies conducted by Guglielmin et al. (2003) in Central Italian Alps and the value obtained is 0.86 Wm^{-2}.

Air temperature and snow thickness were compared with climatic data measured by meteorological station Formazza (period 2001÷2009). The results show an underestimation of the air and snow data modelled (average simulated snow height and air temperature lower than the measured values of ca. 50% and ca. 10% respectively). An additional analysis was conducted using Landsat satellite images to verify the quality of the simulated snow distribution, comparing with the remote sensing data. The results show a distributed model error of 40% and an overestimation of the snow model which simulates an average number of snow pixels higher than the satellite images (total error ca. 9%).

The validation of the IT application passed the testing phase, but the permafrost model was not applied in this study due to the low quality of the snow model. Nevertheless, using an open source software has allowed to create an open code tool, which can be freely used and developed by the scientific community.

4.4 Vegetation samples

The vegetation samples show the presence of the following types of habitat, according to the Habitat Directive 92/43/CE (Biondi and Blasi, 2009):

- 6150: Siliceous alpine and boreal grasslands, characterized by the presence of pioneer species *Carex curvula*;
- 6170: Alpine and subalpine calcareous grasslands, characterized by *Carex rosae*, *Sesleria caeruleae*, *Elyna myosuroides*;
- 8110: Siliceous scree of the montane to snow levels (*Androsacetalia*), characterized by *Achillea nana*, *Geum reptans*, *Saxifraga bryoides*, *Silene acaulis*;
- 8120: Calcareous and calcschist screes of the montane to alpine levels (*Thlaspietea rotundifolii*), characterized by *Artemisia genipi*, *Saxifraga biflora*, *Arabis alpina*;
- 8340: Permanent glaciers, devoid of seagrasses, possible to find algae (*Chlamydomonas nivalis*).

The species most common on the rock glacier bodies are: Gemelli di Ban - *Saxifraga biflora*, *Saxifraga oppositifolia*, *Poa laxa* and *Arabis alpina*; Corno di Ban - *Saxifraga oppositifolia, Arabis alpina*, *Arabis caerulea* and *Saxifraga exarata*.

5 DISCUSSION AND CONCLUSIONS

According to the climate analysis and the definitions proposed by André (2003), Boelhouwers (2003), Guglielmin (2004) and French (2007), the Sabbione basin shows the presence of the periglacial s.l. domain (Mean Annual Air Temperature, MAAT<+3°C); furthermore, the climatic characteristics are typical of a permafrost context (MAAT<0°C and liquid/liquid-equivalent total precipitation<2000 mm/year).

The climatic evolution of the investigated area since the end of the LIA has caused a substantial decrease in glacial masses. In particular, the climatic trends of the past sixty years are the main cause of the pronounced glacial decline which is originated by ablation augmentation, due to the thermic increase in air temperatures, and by alimentation reduction caused by decrease in solid precipitation.

The regression of glacial bodies has allowed the outcropping of large amounts of till. The geomorphological analysis shows that in these glacial deposits the climatic conditions has led to the development of cryotic processes and conditions for permafrost aggradation.

Most landforms resulting from cryotic processes on deposits were observed in deglaciated areas before 50s/60s of the 20th century; therefore, it is evident that some decades are necessary for a sizeable development of cryotic processes, because of the temperate glaciers interfere significantly with the thermal conditions of the substrate (thermal inertia). In addition, favourable climatic and geomorphological conditions (altitude, distribution and thickness of snow cover, etc.) and a coarse grain size of the clasts are also needed.

The transition from glacial to paraglacial/periglacial environment is also reflected on the morpho-dynamic evolution of the study area. Considering the debris rock glacier, the relationship between glacial and periglacial processes appears even more evident. Indeed, this form, deriving from moraine degradation, represents the most evident demonstration of the transition from a glacial environment to an environment characterized by cryotic processes. In this case there is not only a coexistence of elements and processes, but the glaciers and their retreat are facilitating and fundamental factors for the creation of permafrost forms. The recent rapid development of this form could be related to the modification and/or to the partial melting of the ice core, due to the rising air temperatures showed in the climate analyses. In fact, generally rock glacier speed and movement are related to the climatic conditions and to the soil thermal regime; for this reason temperature changes can be considered a good indicator of rock glacier speed mutations; usually, to a temperature increase follows an increase in creep speed (Kääb et al., 2007).

To determine the potential permafrost distribution, the comparison of the models PERMAROCK mod., APMOD and Swiss Permafrost Map was conducted. The active rock glaciers, that are considered as indicators of permafrost presence (Barsch, 1996; Baroni et al., 2004), are located in sectors with permafrost probable. BTS measurements confirm a high probability of permafrost presence in the Corno di Ban rock glacier; temperatures (Ts)<-3°C, likely permafrost indicator (Hoelzle, 1992), were recorded in these soils. Instead, according to the models, a part of the identified cryotic forms is located in sectors with less likely permafrost presence. These forms are the result of high frequency/intensity seasonal freeze-thaw cycles in areas with sporadic or absent permafrost.

According to climatic considerations and actual trends, a further glacial retreat is expected in the next decades. Therefore, it is probable that extended areas of incoherent glacial deposits, which emerge with ice surface disappearance, will come to be affected by cryotic processes. At the same time there will be a gradual stabilization of the areas where the frost action will not be present because of the increase in air temperatures; in these areas vegetal species typical of more mature stages will supplant the pioneer species.

In the future we will carry out more detailed studies on the relationships between cryosphere and biosphere; in particular, we are investigating the phenological delay of *Artemisia genipi* individuals that grow on two rock glaciers bodies in the basin compared with those that grow in areas not affected by cryotic processes, in order to understand the influence of these processes on the vegetation development.

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