Summary of Master's thesis:

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IMPACT OF THE REGIONAL CLIMATE CHANGE ON THE ENERGY AND MASS BALANCE OF THE ADAMELLO GLACIER

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INTRODUCTION

The Adamello glacier can be considered the largest of the Italian Alps, being 17.24 km² wide (as estimated through the analysis of an ASTER image dated 2003). It is located on the homonymous mountain range belonging to the Rhaetian Alps (Central Southern Alps). Ninety per cent of the glacier surface belongs to the province of Brescia (Regione Lombardia), while the remaining part belongs to the province of Trento (Regione Autonoma Trentino-Alto Adige/Südtirol).

In hydrological perspective, the situation is essentially reversed: water coming from the ice melt feeds both the Oglio River (Lombardia) and the Sarca River (Trentino-Alto Adige/Südtirol); due to an ice divide through Passo Adamè (Baroni & Carton, 1996), 13.38 km² (Mandrone Glacier: I-4L01011-15) of the total surface (Adamello Glacier) belong to the Sarca river basin (http://www.glaciologia.it/ghiacciai.html).

The purpose of the thesis was to simulate the glacier's response to possible future meteorological forcing, related to scenarios defined by the Intergovernmental Panel on Climate Change (IPCC, 2007) for the 21st century.

The response is evaluated on the basis of the glacier mass balance, already simulated in previous studies for the period 1995-2009 (see Ranzi et al., 2010), using PDSLIM - *Physically-based Distributed Snowmelt Land and Ice Model* (Ranzi & Rosso, 1991; Grossi & Falappi, 2003; Ranzi et al., 2010). For the hydrological simulations hourly time series of observations collected between 1995 and 2009 by a network of high-altitude weather stations placed close to the glacier were considered. The following variables were considered: air temperature and relative humidity, atmospheric pressure, total precipitation, global radiation, wind velocity.

Data time series were modified according to two future emission scenarios (in two different time periods), as simulated by the regional climate model COSMO-CLM (*COSMO model in CLimate Mode*), developed by DWD - Deutscher WetterDienst.

PDSLIM simulations were repeated using the modified meteorological data series, and the mass balance projected to different future climate scenarios and time windows was assessed; this makes a total of four different future configurations.

CLIMATE CHANGES IN THE PAST AND FUTURE SCENARIOS

In the first step of the analysis, the uncertainties related to climate modeling were considered, pointing out that the Earth's climate system is the result of the energy balance at the global level, depending on time-changeable factors. Many climatic oscillations occurred in the Earth's history on different time scales. On the other hand the global temperatures increase occurred over the last 150 years is ascribed, with a high degree of probability, to human activities and to the related greenhouse gases emissions in the atmosphere. Besides in the alpine area, temperatures were subject to a very marked increase during the last century (Auer et al., 2007, Brunetti et al., 2009), causing a constant retreat of most alpine glaciers since the end of the Little Ice Age. The Adamello glacier is subject to a strong retreat rate in recent years (Marchetti, 1978-1993, 1999-2004; Baroni & Carton, 1990; Baroni et al., 2004; Maragno et al, 2009).

IPCC, the international organization established by the United Nations Environment Programme and the World Meteorological Organization, is aimed at the study of the climate change, of its causes and its effects as well as to their probabilistic evaluation. Global circulation models and regional climate models are run by several research institutes supervised by IPCC in order to set future climate scenarios associated with a certain probability of occurrence, related to greenhouse gas emission levels expected during the century, as socio-economic analysis suggest.

THE COSMO-CLM CLIMATE MODEL

Taking into account IPCC scenarios, in terms of greenhouse gas emissions CLM model simulates an optimistic (B1) and a moderately pessimistic (A1B) configuration. COSMO-CLM is a non-hydrostatic regional climate model, derived from a dynamic downscaling of the ECHAM5/MPI-OM ocean-atmosphere coupled global circulation model, belonging to Deutsches Klimarechenzentrums (DKRZ). Access to data was provided, in NetCDF format and for research purposes, through the CERA WWW-Gateway standard.

The spatial resolution of the CLM model is about 20 km, with spatial coverage of the whole Europe. Eight adjacent grid cells around the location of the Adamello massif have been examined in this work, including the one (46.20 N - 10.20 E) overlaid to the Mandrone glacier and characterized by an average altitude of 2168 m asl.

For each of the eight cells, the CLM output on a daily time scale for each of the six above mentioned variables was taken into account, aince this is the information needed for the evaluation of the glacier mass balance by applying the PDSLIM model.

The CLM_1979-1999 past years (control run) were considered and compared to CLM_2040-2060 and CLM_2079-2099 projections (referred to in the following by the intermediate year: 2050 and 2090), for both B1 and A1B scenarios.

The comparison between control and climate change scenarios was performed, for each variable and for each cell (sometimes through interpolation of the results of several cells), on the basis of the monthly twenty-years-averages. Then the ratio k between the respective monthly averages was computed. For the temperature only, the monthly average difference Δ was considered instead. The correction indices were evaluated for each variable and for each of the four scenarios considered: B1_2050, B1_2090, A1B_2050, A1B_2090. Besides indices for the summer semester were computed, as PDSLIM model simulates the melting season (April - September). Concerning total precipitations, an index, k_w, was also determined to evaluate the accumulation changes in the winter semester (October - March).

No change is essentially foreseen for surface pressure and wind velocity. The temperature increase is meaningful compared to 1979-1999 average, more pronounced for the A1B scenario, and still strong in both scenarios at the end of 21^{st} century. Rainfall is expected to slightly decrease in summer and to increase in winter, for three out of four scenarios. In particular B1_2050 scenario would see an increase of 35% of winter precipitation.

THE TRANSFORMATION OF DATA SERIES

Correction indices, Δ e k, were used to modify the 15-year time series of observations recorded by high-altitude weather stations, including those installed at Passo della Lobbia Alta (3020 m asl) and at Passo Adamè (3125 m asl). As aforementioned, the temperatures were adjusted by the additive term (Δ), the other variables by the multiplicative factor (k).

In this way the forcing of the hydrological model, in a modified climate scenario, is not the result of pure climate model simulations, but the outcome of transformations of actually recorded values. Beyond the average variation of each variable, all the features characterizing local meteorological conditions are considered: extreme cold or hot periods, very intense rainfall or drought, as well as intermediate states.

THE PDSLIM MODEL

PDSLIM model was developed from the original code (Ranzi & Rosso, 1991) aimed at the simulation of the snowpack dynamics. Over the years, many improvements and updates were implemented (Ranzi & Rosso, 1995; Grossi & Falappi, 2003). The integration of satellite imagery and Digital Elevation Models allowed model applications in specific cases, such as for studies on the Adamello glacier. Simulations are executed with hourly time step, so that most of the physical processes involved in the dynamics of snow cover and ice can be satisfactorily described.

For this study, the spatial domain encompasses the surface of the Mandrone glacier, and not the whole Adamello glacier. The parameter setting of the model was previously tested, both at the point and at the basin scale, comparing also simulated and observed runoff produced by the ablation of the glacier in the River Sarca watershed. The cell size of the computational spatial grid is 30m x 30m (equal to the cell size of the available DEM). For each cell the average altitude is known and the slope and the aspect maps can be easily computed.

The quantification of the melt rate is based on the energy balance at the interface between the atmosphere and the surface, eventually covered by snow, ice and debris. Runoff and percolation are represented through a multi-layer scheme: two snowpack layers, two ice layers, one debris layer.

The yearly mass balance (expressed as a specific volume of water equivalent and provided by the sum of the winter balance, 1^{st} October-31^{st} March, of the summer balance, 1^{st} April – 30^{th} September) is derived from the energy balance equation that for a unit area and finite depth layer of ice or snow superimposed over ice can be simply written:

$$H_m + H_c = Q_N + H_p + H_g + H_l + H_s$$

where each term stands for energy in unit time and unit area, respectively
H_m: energy available for melt;

Hc: internal energy of the ice or snow layer;
Q_N: net global radiation;
H_p: advective heat from precipitation;
H_g: conductive heat at the bottom surface of the ice or snow layer.
H_l: latent heat;
H_s: sensible heat;

Major uncertainties arise from the evaluation of the last two terms, since they represent very complex phenomena. In this study the mixing length theory was adopted.

PDSLIM inputs are provided through matrices representing the spatial distribution of the following elements: the elevation; the albedo; the hillslope aspect; the terrain view factor; the land use; the Leaf Area Index (if a vegetation cover exists); the sub-basins, used by the model to estimate the average values of each energy and mass balance component, the height of the debris cover (zero for the Adamello case study). Other 2D input data concern the the initial condition of the snow cover (1^{st} April): the snowpack height, the snow density in the top layer (≤10cm) and in the bottom layer, the temperature and liquid water content in each of the two layers.

RESULTS

When the initial and boundary conditions are set and the meteorological time series prepared, PDSLIM can be used to simulate the energy and mass balance for both control and future scenarios and for each cell.

First feature deserving attention is that, in each scenario, winter gross gain in water equivalent is lower, in absolute value, than summer melt loss, as observed in the past 1995-2009 years, even if less evident (figure 1).

Only the B1_2050 scenario shows both in April and in May the same condition observed in the past 15 years observed, with a void or positive balance. However in an average year, even an increase of more than 30% in winter precipitation and accumulation for the B1_2050 scenario, would not succeed in reducing ice and snow melting between April and September, although a limited rise in summer temperatures (+0.9°C) is noticeable.

This result is in agreement with other studies, reporting that for most glaciers the increase in precipitation needed to cancel the effect of a 1°C-warming is expected to be between 40 and 50% (Alley, 2003).

All the remaining scenarios provide an early melting season. Starting from June, the mass deficit of climate projections is continuously increasing over the control simulation.

The behaviors of two peculiar years, 2001 and 2003, is reflected into the future projections. In 2001 snowfall was exceptionally high: this was an exceptional year with a slightly positive simulated mass balance. Summer 2003 was the hottest ever registered in the last century. Of course the observed mass balance was strongly negative (as also PDSLIM output confirms); future projections of this loss would be even more dramatic, namely doubled for scenario A1B_2090, the most pessimistic one for the end of the century. Summer 2008 and 2009 led to negative mass balances as well.

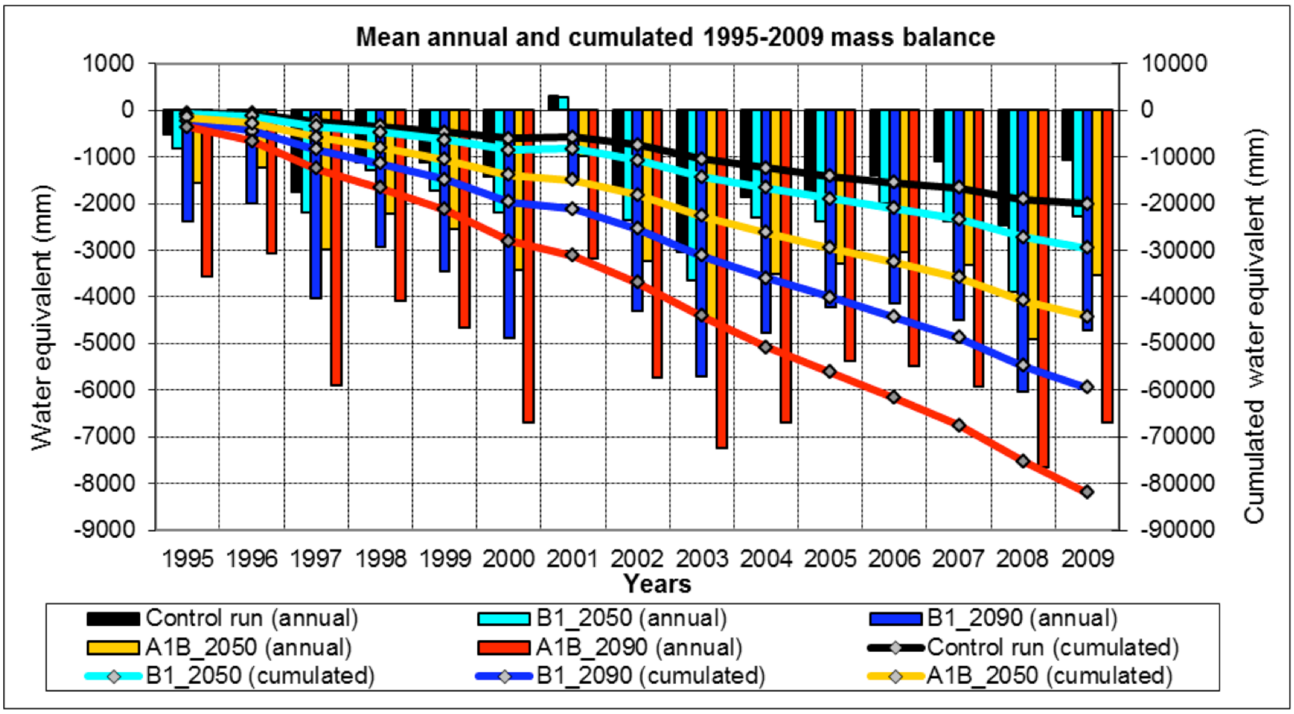

Figure 1: Mean annual and cumulated 1995-2009 mass balance for the Mandrone glacier (control and future scenarios)

As a result of this occurrence, a strong correlation between an increase in the air temperature and the acceleration in the melting process is evident. It is here worth to notice that CLM, compared to other regional climate models, provides pessimistic scenarios, as far as summer air temperature is concerned. Scenarios A1B and B1_2090 could then be hardly trusted for our future. On the other hand it is still not possible to completely eliminate the chance that the temperature will increase so much by the end of the 21st century.

The spatial distribution of the mass balance was also estimated for each scenario. If any of the future projections provided by CLM+PDSLIM simulations occurred, mean annual mass balances would be always negative, which is observed even currently for the Adamello glacier; moreover, every sub-unit of the glacier would be characterized by a mass deficit; even in the control scenario, only 2% of the whole area has a positive mass balance.

In both 2090-scenarios there would be no areas with an average annual deficit, in absolute value, lower than one meter in water equivalent, while A1B_2050 simulations show only a few small areas on the slopes of Monte Fumo and Dosson di Genova with limited mass losses.

B1_2050 scenario shows losses <1000 mm in water equivalent at various locations, along the edge of the glacier (Figure 2). This is probably due to the smaller angle of the solar radiation that reaches these sites.

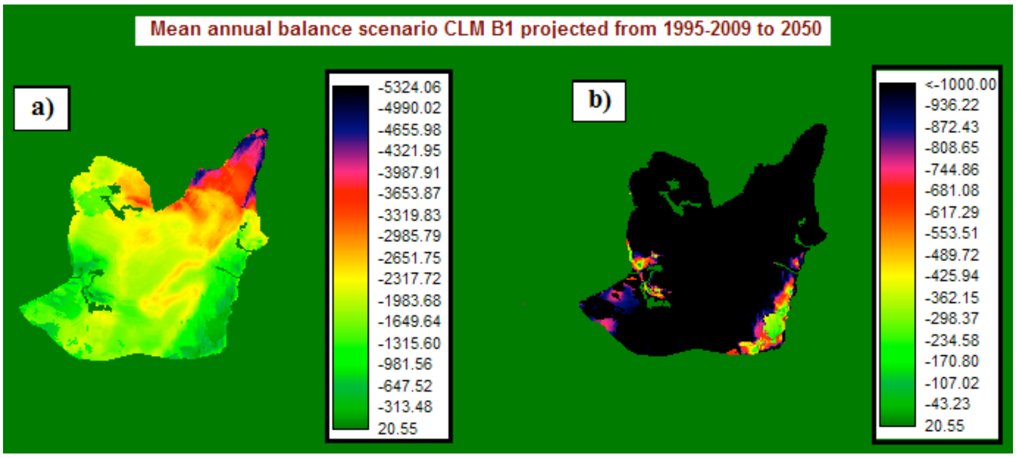

Figure 2: Mean annual mass balance (mm in water equivalent) projected to 2050: CLM_B1 scenario. Figure 2a shows the expected values of the mass balance; in the figure 2b, black cells are characterized by a mass deficit higher than 1000 mm in water equivalent.

Considering the obtained results, a simple subdivision of the glacierized surface was suggested, according to different levels of vulnerability due to foreseen climate changes (or also if the current temperature trend on the area continued). Most vulnerable areas would be the the Northern sector of the Mandrone glacier and the glacier tongue descending from Monte Venerocolo, both subjected to a quick retreat nowadays.

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