

ACCELERATING CLIMATE CHANGE IMPACTS ON ALPINE GLACIER FOREFIELD ECOSYSTEMS IN THE EUROPEAN ALPS

NICOLETTA CANNONE,^{1,4} GUGLIELMINA DIOLAIUTI,² MAURO GUGLIELMIN,³ AND CLAUDIO SMIRAGLIA²

¹University of Ferrara, Department of Biology and Evolution, Ferrara, Italy

²University of Milan, "A. Desio" Department of Earth Sciences, Milan, Italy

³University of Insubria, Department of Structural and Functional Biology, Varese, Italy

Abstract. In the European Alps the increase in air temperature was more than twice the increase in global mean temperature over the last 50 years. The abiotic (glacial) and the biotic components (plants and vegetation) of the mountain environment are showing ample evidence of climate change impacts. In the Alps most small glaciers (80% of total glacial coverage and an important contribution to water resources) could disappear in the next decades.

Recently climate change was demonstrated to affect higher levels of ecological systems, with vegetation exhibiting surface area changes, indicating that alpine and nival vegetation may be able to respond in a fast and flexible way in response to 1–2°C warming.

We analyzed the glacier evolution (terminus fluctuations, mass balances, surface area variations), local climate, and vegetation succession on the forefield of Sforzellina Glacier (Upper Valtellina, central Italian Alps) over the past three decades. We aimed to quantify the impacts of climate change on coupled biotic and abiotic components of high alpine ecosystems, to verify if an acceleration was occurring on them during the last decade (i.e., 1996–2006) and to assess whether new specific strategies were adopted for plant colonization and development.

All the glaciological data indicate that a glacial retreat and shrinkage occurred and was much stronger after 2002 than during the last 35 years. Vegetation started to colonize surfaces deglaciated for only one year, with a rate at least four times greater than that reported in the literature for the establishment of scattered individuals and about two times greater for the well-established discontinuous early-successional community. The colonization strategy changed: the first colonizers are early-successional, scree slopes, and perennial clonal species with high phenotypic plasticity rather than pioneer and snowbed species.

This impressive acceleration coincided with only slight local summer warming (approximately +0.5°C) and a poorly documented local decrease in the snow cover depth and duration. Are we facing accelerated ecological responses to climatic changes and/or did we go beyond a threshold over which major ecosystem changes may occur in response to even minor climatic variations?

Key words: alpine glaciers; climate warming; clonal plants; colonization strategies; Italian Alps; mountain ecosystems; Sforzellina Glacier; vegetation.

INTRODUCTION

The increasing recession of the cryosphere in the Alps is probably related to important changes occurring in mid-tropospheric conditions, such as the widely recognized rapid increase in temperature during recent decades (IPCC 2001). The worldwide retreat of glaciers, from alpine areas (Haeberli and Beniston 1998) to Antarctica (Rott et al. 1996, Cook et al. 2005), in the course of the last few decades, is frequently mentioned as a clear and unambiguous sign of global warming (Oerlemans 2005). Compared with other climate indicators like tree rings, glacial systems react in a relatively simple way to climate change: the transfer function does not change in time and geometric effects can be

addressed. Likewise, as many glaciers are found at high elevations, a climate signal reflected in glacier fluctuations can be studied as a function of height (Oerlemans 2005).

In the Alps atmospheric warming was found to increase more than double over the same period (Böhm et al. 2001), with a significant summer warming, which was particularly severe since 1970 (Casty et al. 2005). As a result of this rapid climate evolution, many small glaciers (i.e., glaciers with surface area <1 km²) located at mid-elevation could disappear in the next few decades. These small glaciers are common in the Alps, where they represent 80% of total glacial coverage and make an important contribution to water resources (Oerlemans and Fortuin 1992).

The rapid "disintegration" of alpine glaciers has already been pointed out in an analysis of the Swiss Glacier Inventory 2000 by Paul et al. (2004). Among the

Manuscript received 19 July 2007; accepted 16 November 2007. Corresponding Editor: H. P. Schmid.

⁴ E-mail: nicoletta.cannone@unife.it

others, smaller glaciers were found to show both a wider scatter of variation with respect to the larger ones, and to contribute more than proportionally to the area they represent. In fact, 44% of the area loss between 1973 and 1998/1999 refers to glaciers of lengths of <1 km and covering only 18% of the total area in 1973 (Paul et al. 2004). Thus small glaciers are showing higher sensitivity than larger ones due to their very fast reaction time (*sensu* Haerberli and Hoelzle 1995) and are, hence, suitable sites for assessment and monitoring of climate change impacts (Dyurgerov and Meier 2000). Moreover, at high elevations temperature, moisture, and pressure trends and anomalies are clearer than at lower levels, where the large-scale climate signals tend to be dampened (Beniston 2000, 2003). Also soil characteristics of the glacier forefield were used as climate change indicators (*i.e.*, Egli et al. 2006).

Not only the abiotic (glacial) but also the biotic components (plants and vegetation) of the mountain environment are showing ample evidence of climate change impacts (*e.g.*, Grabherr et al. 1994, Beniston et al. 1997, Beniston 2003, Walther et al. 2005, Cannone et al. 2007). According to quantitative estimates of the biological impacts of the climate change “fingerprint,” a greater amplitude is expected at high latitudes and altitudes (Root et al. 2003). In the Alps, the shifts in the altitudinal range margins of plant species and bioclimatic zones in the last 50 years, with upward migration of alpine and nival-plant species at a rate of 8–10 m per decade (Grabherr et al. 1994, Walther et al. 2005), and changes in community composition (Keller et al. 2000) provide the first evidence of the sensitivity of mountain habitats to climatic change.

Surface area changes of the vegetation in a high alpine site of the European Alps between 1953 and 2003 demonstrated that climate change is able to affect higher levels of ecological systems and that even 1–2°C warming of air temperature may produce significant changes in vegetation community dynamics (Cannone et al. 2007). As these changes follow the sudden warming of summer and annual temperatures after 1980, these results suggest that alpine and nival vegetation may respond faster and more flexibly to climatic change than previously believed (Pauli et al. 1999, Walther et al. 2005).

Glacier forefields are suitable environments to investigate the processes of vegetation colonization and development and, because of the age control of the surfaces, to calculate the speed of primary succession and to understand their mechanisms (*e.g.*, Whittaker 1993, Chapin et al. 1994). In the European Alps several authors have investigated glacial chronosequences and described different stages of vegetation succession from pioneer to climax communities in relation to site age (*e.g.*, Pirola and Credaro 1993, 1994, Burga 1999, Caccianiga and Andreis 2004, Raffl and Erschbamer 2004) and to the mechanisms of seedling establishment (*e.g.*, Stöcklin and Bäumler 1996, Niederfriniger Schlag and Erschbamer 2000). Moreover, in high mountain areas, most glacial forefields

provide environments subject only to natural dynamics, without direct anthropogenic impacts, where it is possible to compare the responses of related environmental components (glaciers and vegetation) to the same climatic inputs and to quantify their variations in response to climate changes.

The aim of our research was to quantify the biotic and abiotic impacts of climate change over the past three decades in an alpine glacier area without direct anthropogenic impacts, to verify if an acceleration has been occurring on them during the last decade (*i.e.*, 1996–2006), and to assess whether new specific strategies were adopted for plant colonization and development.

For this purpose we analyzed the patterns and rate of glacier evolution (abiotic component) and vegetation succession (biotic component) on the forefield of Sforzellina Glacier (Upper Valtellina, central Italian Alps).

STUDY AREA

The Sforzellina Glacier is a southwest-facing cirque glacier extending from 2850 to 3100 m above sea level (*a.s.l.*; 46°20′55″ N, 10°30′50″ E), located in Valfurva Valley (Upper Valtellina), in the central Italian Alps. The glacial forefield extends between 2850 and 2700 m *a.s.l.*, and it is characterized by surfaces with different ages since deglaciation, ranging from one year to >80 years, while undisturbed by periglacial features such as sorted or unsorted polygons. Only a few not well-developed terracettes and solifluction lobes occur on the northeast-facing slope of the moraine ridge deposited at the beginning of the 20th century (1920–1925) on the southern border of the glacier.

Sforzellina Glacier represents a unique case of glaciological study in Italy because it has one of the older and more continuous records of terminus fluctuations (1925 to today) and mass balance (1987 to today). It is also one of the few glaciers of which there is relatively good knowledge of its thickness and geometry. On Sforzellina Glacier different geophysical surveys were applied in order to evaluate ice thickness and bedrock morphology. Geoelectrical survey (VES [vertical electrical sounding]; Resnati and Smiraglia 1989, Guglielmin et al. 1995) and seismic reflection (Pavan et al. 2000) gave a maximum ice thickness of 42 and 60 m, respectively. In 1999 a ground probing radar (GPR) survey was performed to obtain high-resolution topography of the glacier bed. The maximum ice thickness calculated was of ~60 m in the central area of the glacier and this value agrees with seismic data. In addition, geomorphological surveys were also performed (Rossi et al. 2003) to map the glacial landforms related to past glacial evolution.

The study area is included in the upper alpine belt (2600–2800 m *a.s.l.*) and in the nival belt (>2800 m *a.s.l.*). The vegetation is a mosaic of discontinuous alpine grasslands (including the climax communities dominated by *Carex curvula* and the initial grasslands dominated by *Poa alpina*), snowbed vegetation (with

Salix herbacea, *Veronica alpina*, *Sagina saginoides*, *Cerastium cerastioides*), pioneer and early-successional communities (with *Ranunculus glacialis*, *Geum reptans*, *Cerastium uniflorum*, *Oxyria digyna*, *Saxifraga bryoides*), and, at the higher altitudes, scattered individuals of vascular plants and cryptogams (see Plate 1). At the elevations of our site, the effects of anthropogenic land use change on vegetation are mostly negligible (Keller et al. 2005). Previous studies on the glacier forefield of the Sforzellina Glacier were carried out by Caccianiga and Andreis (2004) reporting the occurrence of a pioneer community (*Sieversio-Oxyrietum digynae*) with *Cerastium uniflorum*, *Geum reptans*, *Oxyria digyna*, *Ranunculus glacialis*, and *Poa laxa* on the 1980s morainic ridge and of the initial grassland dominated by *Poa laxa* and *Saxifraga bryoides* on the Little Ice Age moraine.

MATERIAL AND METHODS

Glacier monitoring

Recent (last three decades) glacial changes were reconstructed using all the available sources of data. Terminus fluctuations were analyzed from 1971 up to now, in order to evaluate the glacier's behavior (i.e., retreat vs. advance), and to calculate the rates of these changes. These data have been collected from benchmarks located on the glacier forefield without interruptions, providing a data set on the glacier's evolution for the last 35 years (CGI 1971–1977, 1978–2006). In 1991 the benchmark used for the terminus variation measurements changed and the new one was set at ~80 m (with an azimuth of 145° N) from the present (summer 2006) glacier limit.

Mass balances were evaluated from the authors (Catasta and Smiraglia 1993) from 1987 up to now using the standard glaciological method (Østrem and Brugman 1989, Kaser et al. 2003) based on a network of ablation stakes at different altitudes. Several differential global positioning system (DGPS) campaigns were performed with kinematic techniques aimed at obtaining digital elevation models (DEM) of the glacier surface and altimetry (in 1999, 2000, 2002) as well as to map the GPR profiles. The fast static technique was employed on DGPS surveys that focused on delimiting the glacier boundaries or on mapping moraine ridge positions (requiring fewer points, in 2002, 2003, 2006). DGPS surveys were also used to acquire the position of the benchmark used to measure the glacier terminus fluctuations from 1991 up to now and map the moraines of the 1920s and 1980s, which served to reconstruct the older and recent glacier advances, as well as to map supraglacial debris cover and the vegetation survey plots.

The DGPS surveys were always carried out at the end of the summer season, when the ablation zone is largest and no snow is present on the glacier snout. To obtain DEMs of the glacier surface and bedrock morphology (from GPR data), the field surveys were carried out using high density global positioning system (GPS) point data (i.e., 8000 points/km²) and interpolating the

data with the kriging algorithm. In addition, several nodes with known coordinates were positioned near the glaciers to improve the accuracy of the measurements taken by differential GPS with short bases according to Diolaiuti et al. (2004).

The glacier limits dating back to 2002, 2003, and 2006 were mapped on the field by DGPS surveys, and the 1920 and 1980 limits were reconstructed by the moraine ridge boundary marked on the field by DGPS as well. The glacier limits from 1991 to 2001 were reconstructed by a geographic information system (GIS) using the measured fluctuation data and the position of the 1991 benchmark used for measuring the distance from the glacier snout. Orthophotos dating back to 1999 and 2003 (Regione Lombardia 2004) were also used to map the glacier boundaries. GIS mapping was applied not only to past glacier limits but also to assign different ages to the land surfaces on the glacier forefield (1991–2001). All the vegetation plots were located by DGPS and included in the GIS mapping, allowing the vegetation covering of these areas to also be dated. Surface area changes were determined by GIS through the comparison of the historical glacier boundaries thus obtained. The final planar accuracy value was then evaluated according to Vögtle and Schilling (1999).

Vegetation survey

The vegetation of the glacier forefield was described, analyzing a total of 23 sampling plots of 1 × 1 m. Their positions were acquired through DGPS surveys as described previously and then mapped by GIS. The ages of the surfaces where the plots were sampled were obtained from the glacier analysis. Within every plot, total vegetation cover and the cover of each vascular species was estimated visually using indices to express the relative abundance of each species (+, <1%; 1, 1–5%; 2, 5–10%; 3, 10–15%; 4, 15–20%; 5, 20–25%; 6, 25–50%; 7, 50–75%; 8, >75%). Vascular plant species nomenclature is in accordance with Pignatti (1982). Cover estimates were also given for cryptogams, which were not identified as species but grouped into three broad categories: mosses, epilithic lichens, and ground lichens. Slope and aspect were recorded for each plot.

Climate

Local meteorological data were collected and processed to analyze recent climate behavior and evolution in the study area. The closest and highest automatic weather station (AWS), which was found to be running during the last three decades without significant interruptions, is located at Forni dam at 2180 m a.s.l., ~5 km northward from Sforzellina Glacier. Other AWSs, which have been working over the last 35 years, are located at Santa Caterina Valfurva (1730 m a.s.l.) and Uzza (1250 m a.s.l.), respectively. At these stations air temperature and liquid precipitation data were measured every hour and then recorded on the general database of the Geological Monitoring Service of ARPA

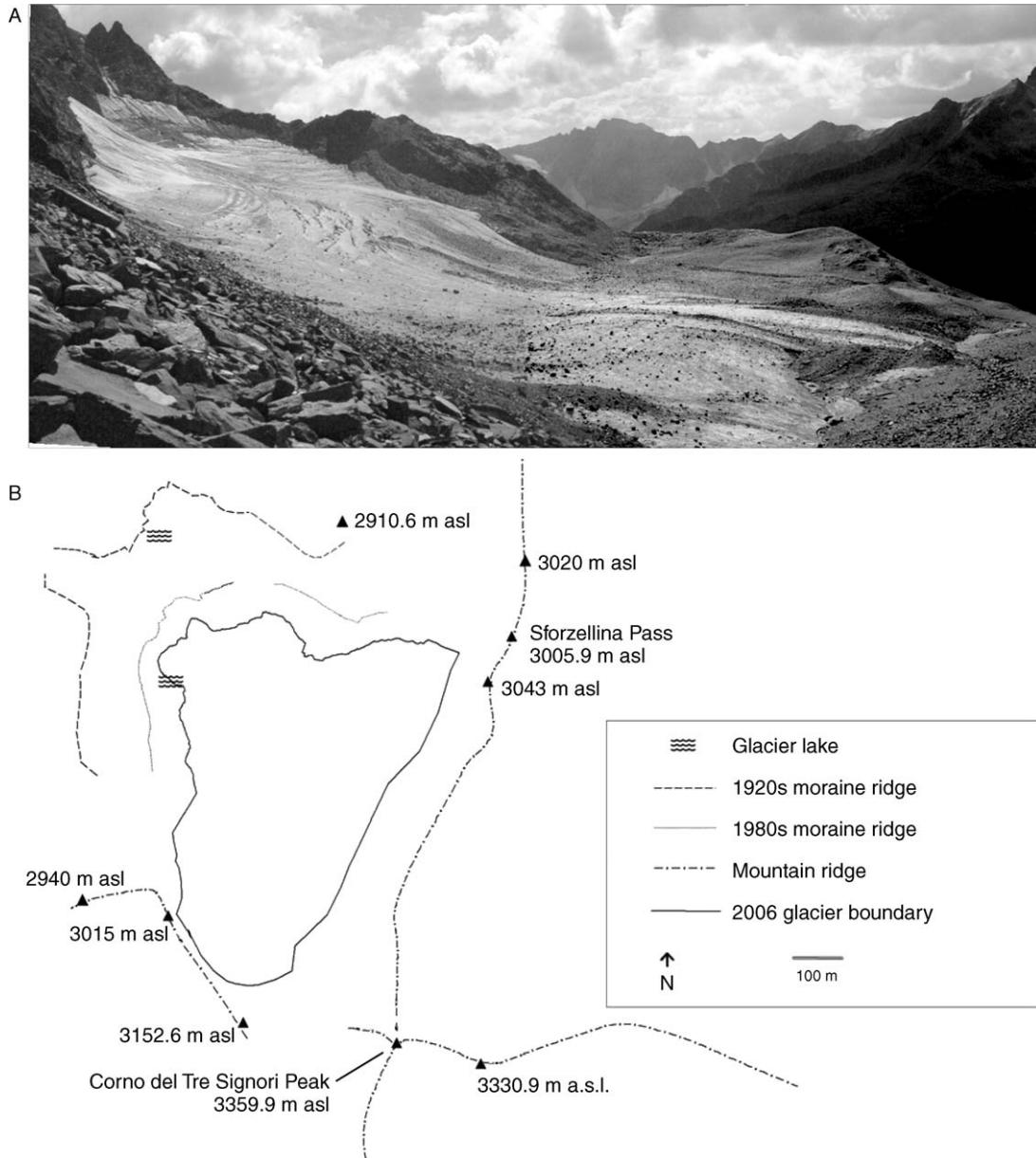


FIG. 1. (A) Sforzellina Glacier in summer 2006 (Photo credit G. Diolaiuti) with debris cover exceeding 40% of the whole glacier area. (B) Map showing the location of the 2006 glacier and moraine ridges of the 1920s and early 1980s in relation to the mountain ridges and peaks (height given in m a.s.l.).

Lombardia (Lombardy Regional Environmental Agency, Sondrio, Italy). Daily, monthly, annual, and seasonal averages of hourly air temperatures and monthly, annual, and seasonal cumulated liquid precipitation were computed for the climate analysis.

RESULTS

Glacier

During the last century Sforzellina Glacier suffered substantial reductions in its length and surface, as well as changes in its supraglacial conditions, with the

occurrence of debris cover that now exceeds 40% of the whole glacier area (Figs. 1 and 2). Two ice-contact lakes developed during the last 10 years, one of them is presently active (at the west side of the glacier; see map in Figs. 1 and 2) and calving phenomena occurred at the glacier water-contact area. Glacier volume was determined from the comparison of the DEMs processed from geophysical (bedrock topography by GPR) and topographical (glacier surface by GPS) data collected in 1999. The measured volume was $\sim 8.1 \times 10^6 \text{ m}^3$ of ice (i.e., $7.8 \times 10^6 \text{ m}^3$ water equivalent, w.e.).

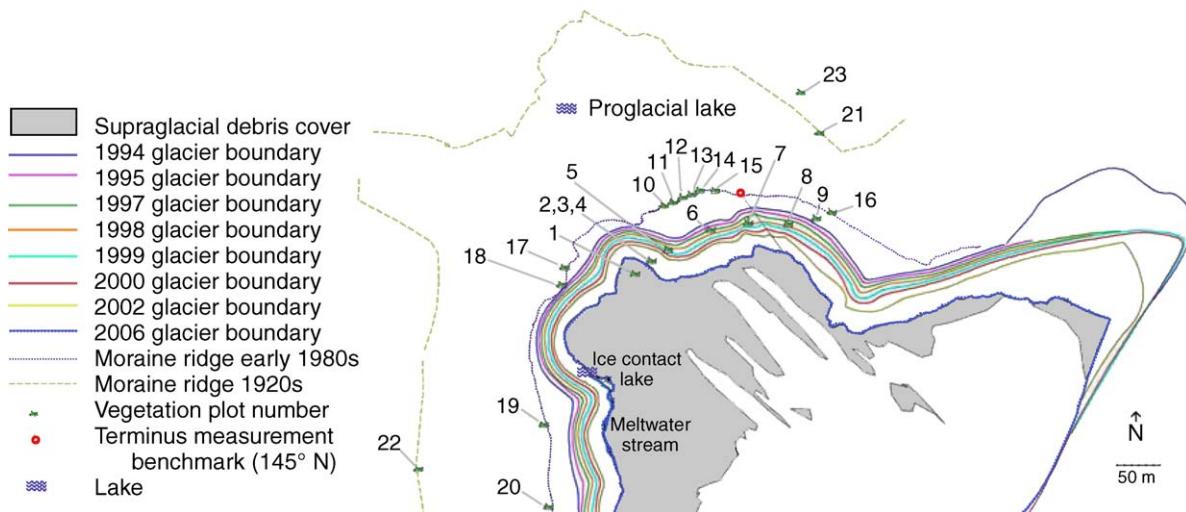


FIG. 2. Map showing the glacier boundary fluctuations between 1994 and 2006, the moraine ridges of the early 1920s and 1980s, and the location of the vegetation plots.

The analysis of the mass balance data collected on Sforzellina from the hydrological year 1986–1987 to present (Fig. 3) underlines that (with exception of the hydrological year 2000–2001) the glacier always lost in mass (yearly average of net specific balance = -1.1 m

w.e.). The whole loss by ablation processes thus exceeds 8×10^6 m³ (more than the remaining volume estimated in 1999). The rate of the glacier volume loss increased significantly from 0.30×10^6 m³/yr w.e. in the period 1986/1987–1999/2000 to 0.50×10^6 m³/yr w.e. in the

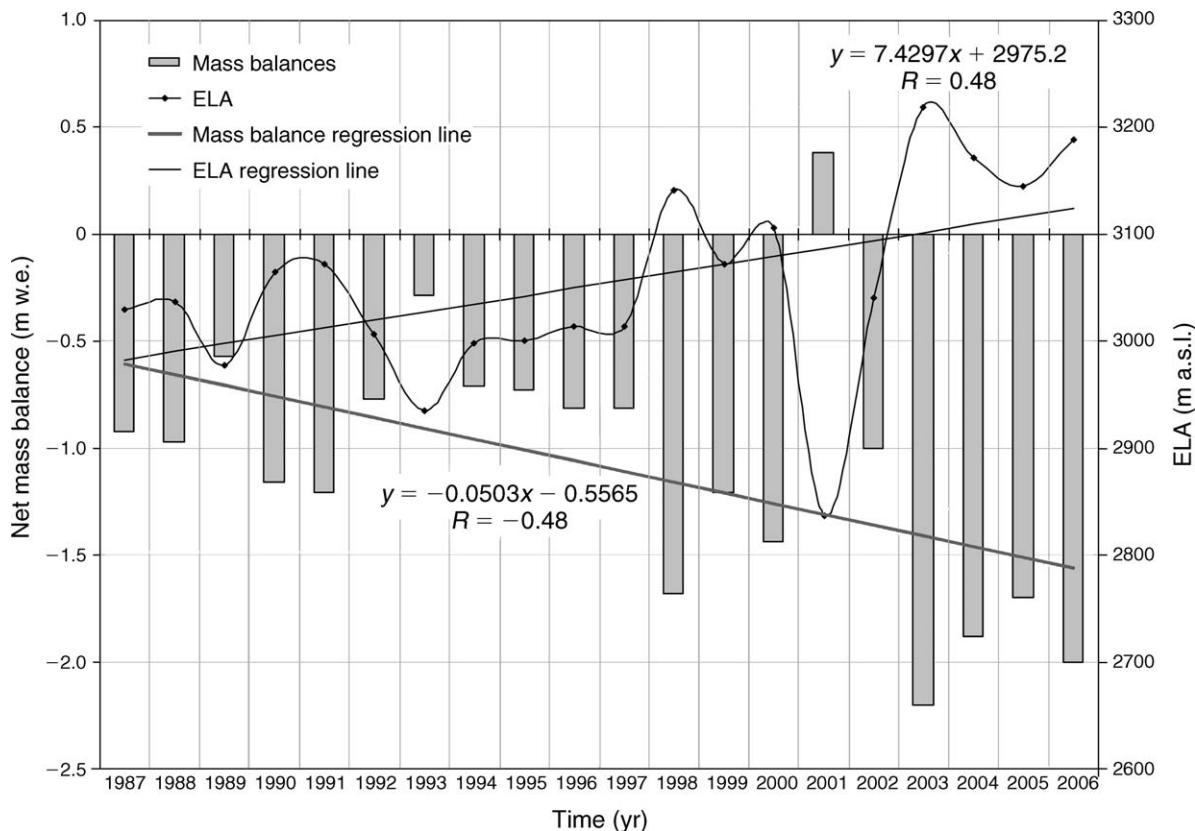


FIG. 3. Sforzellina Glacier net specific balance data (gray columns, values in m water equivalent, w.e.) and trends (thick gray line), and the ELA (equilibrium line altitude) yearly value (curve, in m a.s.l.) and trends (thin black line).

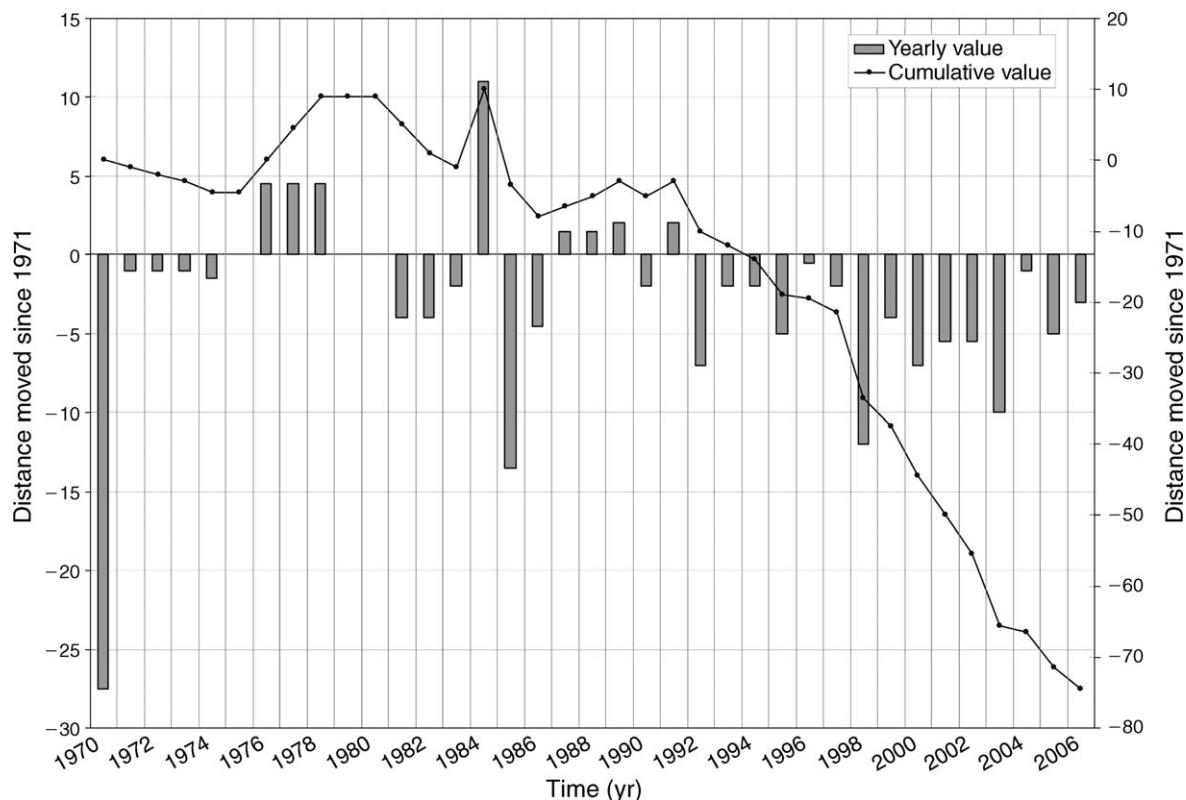


FIG. 4. Glacier terminus fluctuations from 1971 to 2006. The bars indicate yearly values, the line the cumulative value. When the glacier terminus was found to be stationary (change = 0), no bars are reported.

following six years. The accumulation area decreased as the equilibrium line altitude (ELA), calculated from yearly mass balance profile analysis, shifted at higher elevations (from 3029 m a.s.l. in the hydrological year 1986–1987, to 3189 m a.s.l. in 2005–2006; Fig. 3), and presently almost the entire glacier area lies below the ELA. The terminus fluctuations (Fig. 4) of Sforzellina Glacier showed a general retreat over the past 35 years. During the 1971–2006 period, the snout of Sforzellina Glacier retreated by ~ 75 m. The reduction in length over the 35 years of surveys equals 9% of the 1971 glacier length. The glacier retreated 25 years out of the 35 years analyzed (equal to 71% of the time); the average retreat rate was approximately -2 m/yr over the whole period (1971–2006), was -2.6 m/yr considering only the shorter time span 1985–1995, and accelerated up to -5 m/yr in the last decade (1996–2006).

In spite of this reduction trend, the terminus fluctuations also showed a small glacier advance in the period 1975–1984 (+14.5 m equal to a rate of +1.5 m/yr). It was followed by a transition phase during which the glacier alternated retreats and small advances, then, starting from 1992, the glacier shrinkage proceeded. The advance led to the formation of small moraine ridges between 1977 and the early 1990s (Rossi et al. 2003). The glacier limits from 1991 to 2006 and the moraine ridges of 1920 and 1980 are reported in Figs. 1 and 2.

Corresponding to the terminus fluctuation, the glaciated area decreased from 0.383 ± 0.005 km² (mean \pm SE) in 1981 to 0.2381 ± 0.002 km² in 2006, with a reduction of $\sim 38\%$. The yearly rate of surface area loss (Table 1) remained almost constant (around -0.005 km²/yr) between 1981 and 2002, while it doubled (to -0.0097 km²/yr) in the period 2002–2006.

Vegetation

Vegetation occurs in all the proglacial area (Tables 2 and 3), showing different patterns in relation to the surface age (Fig. 1; fourth column of Table 2), which was assigned on the basis of the GIS analysis, and ranging from terrains deglaciated after one year to moraine deposits of the 1920s.

Colonization starts one year after deglaciation with generally very low coverage (although it reaches 14% in

TABLE 1. Yearly rate of surface area loss of Sforzellina Glacier, central Italian Alps.

Time frame	Yearly surface area change (km ² /yr)	\pm Accuracy (km ²)
1920–1981	-0.0029	0.009
1981–1985	-0.0053	0.008
1985–2002	-0.0050	0.006
2002–2006	-0.0097	0.005

TABLE 2. Features of investigated vegetation plots.

Plot no.	Total cover (%)	No. species	Age since deglaciation (yr)	Slope (°)
1	0	0	0	
2	1	6	1	0
3	1	2	1	0
4	14	7	1	0
5	0.1	6	6	
6	3	5	8	2
7	2	1	7	
8	35	6	7	4
9	7	5	11	2
10	22	7	25	2
11	45	8	25	
12	65	8	25	18
13	18	5	25	20
14	4	3	25	2
15	20	5	25	
16	10	4	25	
17	18	4	25	
18	38	4	25	
19	0.1	2	25	
20	15	2	25	
21	60	9	>80	
22	65	12	>80	
23	90	12	>80	

some sheltered sites). Vegetation is composed of scattered individuals of eight species of vascular plants and by mosses. It is remarkable that, instead of exclusively pioneer species (i.e., species that appear in the first stages of colonization but are not able to persist during succession), the first colonizers are mainly composed of early-successional species (i.e., species able

to persist during succession as well as to carry out the first stages of colonization) (Jochmisen 1970, Matthews 1992, Burga 1999). Moreover, these species belong to different stages of vegetation development and to different vegetation series. In particular *Geum reptans*, *Cerastium uniflorum*, and *Poa laxa* are characteristic species of the scree slopes vegetation, *Poa alpina* and *Saxifraga bryoides* are typical species of the initial alpine grassland, and *Sagina saginoides* is a snowbed species.

On surfaces deglaciated 6–11 years ago, the vegetation is still scattered with low coverage (2–3% as average although up to 35% in more favorable sites), composed of mosses and 12 species of vascular plants, and dominated by *Geum reptans* and *Cerastium uniflorum*. Here we observed a change in species composition with respect to the younger surface, with the disappearance of *Ranunculus glacialis*, and a slightly different pool of early-successional species (with the ingression of *Oxyria digyna*) and snowbed species (*Cerastium cerastioides*).

Vegetation coverage and species richness increases significantly on the 25-year-old surfaces, where closed patches of vegetation occur. The relatively high coverage of *Oxyria digyna*, similar to the values of *Geum reptans* and *Cerastium uniflorum*, indicates a further evolution of the vegetation development.

The initial grassland and the more mature grassland of the *Luzuletum spadiceae* occur on surfaces older than 80 years, where it is possible to observe a shift in community composition, with the dominance of *Poa alpina* and/or *Luzula spicata*, the ingression of *Salix*

TABLE 3. Relative abundance of species in vegetation plots.

Species	Relative abundance by plot																						
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23
<i>Ranunculus glacialis</i>		+		+						+	+	+							+			1	2
<i>Cerastium uniflorum</i>		+		1	+	1	2			2	1	7	1		1	1	1	2			1	4	
Mosses		+	+			1	1	1		1					1		1				2	1	2
<i>Poa laxa</i>		+						1			+	1			2								
<i>Geum reptans</i>			+	1	+	1	1	2	1	1	6	2	1	1	1	+	3	4	+	3			5
<i>Leucanthemopsis alpina</i>		+	1	+	1				2	+			2	1							3	3	
<i>Saxifraga bryoides</i>				1							1							1				1	1
<i>Poa alpina</i>				+		1															6	2	1
<i>Sagina saginoides</i>		+			+			1			+										1	+	
<i>Poa alpina vivipara</i>					+							1				1							
<i>Oxyria digyna</i>					+					1	1	1	1	1		1	2	3				1	
<i>Cerastium cerastioides</i>						+		3															1
<i>Cerastium pedunculatum</i>									1														
<i>Arabis caerulea</i>									+	+	+	1	+								1		
<i>Veronica alpina</i>												2									1		1
<i>Linaria alpina</i>													1										
<i>Epilobium anagallidifolium</i>																							
<i>Taraxacum alpinum</i>																						+	
<i>Sedum alpestre</i>																						1	+
<i>Salix herbacea</i>																					2	+	1
<i>Saxifraga oppositifolia</i>																						1	
<i>Armeria alpina</i>																						+	
<i>Luzula spicata</i>																							7
<i>Cardamine resedifolia</i>																							+
Ground lichens																							1
Epilithic lichens																							1

Note: Indices express the relative abundance of each species (+, <1%; 1, 1–5%; 2, 5–10%; 3, 10–15%; 4, 15–20%; 5, 20–25%; 6, 25–50%; 7, 50–75%; 8, >75%).

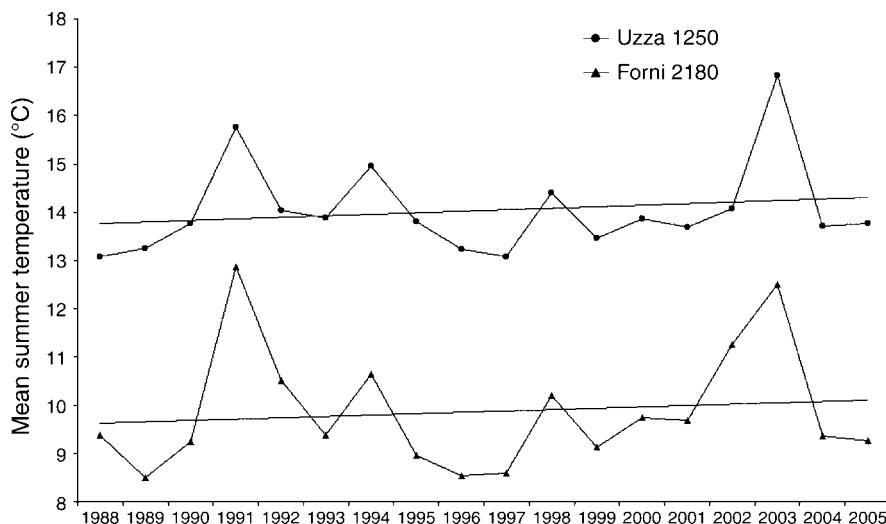


FIG. 5. Mean summer air temperatures (June–August) in the period 1988–2005 recorded at Uzza (solid dots) and Forni (solid triangles).

herbacea and *Sedum alpestre* (snowbed species also occurring frequently in the climax grassland), and the persistence of the early-successional *Geum reptans*, *Cerastium uniflorum*, and *Leucanthemopsis alpina*, and average total coverage up 90%. Only at this stage do lichens make their ingress as epilithic lichens growing on boulders as well as ground foliose lichens.

Climate

Despite the general strong warming found in the Alps (Beniston 2000), in Valfurva Valley during the period 1988–2006 the mean annual air temperatures show a very slight decrease (-0.2°C at 2180 m a.s.l.), while the mean summer (June–August) air temperatures are clearly increasing ($+0.5^{\circ}\text{C}$; Fig. 5). The precipitation pattern we evaluated only referred to liquid precipitation (as the closest AWS [Forni, 2180 m a.s.l.] only recorded water equivalent data); in the areas surrounding the glacier data for snow precipitation were not available, making it difficult to evaluate any change in snow depth and duration. In any case, a remarkable decrease in total precipitation (around -10% at 2180 m a.s.l.) has been recorded since 1988.

DISCUSSION

At a global scale, glaciers are very sensitive to climate change. In particular, the smaller ones seem to be consistent climate change indicators, given that they are showing faster reaction times (Dyrgerov and Meier 2000, Paul et al. 2004). On the other hand, previous studies suggest it would be inappropriate to use length changes of a single glacier as being representative of climate change (Chinn 1999).

Our data show the trend of terminus fluctuations of Sforzellina Glacier to be in agreement with the general pattern of glaciers spread all over the Alps, which resulted in retreating from the end of the Little Ice Age

(LIA) up to now (Zemp et al. 2006) with a short interruption that occurred between the 1970s and the 1980s (Patzelt 1985, Wood 1988). In addition, the record of glacier mass balances, which are generally considered an unambiguous marker of climate change (Cogley and Adams 1998, Haeberli et al. 1999, Dyrgerov and Meier 2000, Oerlemans 2005), underlines a stronger volume reduction in the last decade (the average yearly value of the last 10 years was 66% larger with respect to the 1987–1996 average yearly value).

Moreover, the representativeness of Sforzellina Glacier as witness of the ongoing alpine glacier changes is further supported by the striking relationship between the Sforzellina mass balance (1986/1987–2002/2003) and those of the alpine glaciers reported in the Glacier Mass Balance Bulletins (IAHS (ICSI)-UNEP-UNESCO, 1988–2005; Bravais-Pearson correlation coefficient, $r = 0.84$). Furthermore, the ELAs of Sforzellina Glacier (1986/1987–2002/2003) compared with the mean alpine ELA (IAHS (ICSI)-UNEP-UNESCO, 1988–2005) also show a strong correlation ($r = 0.82$).

An accelerating surface area loss was also found for the period 2002–2006, and the glacier surface in 2006 resulted in a decreased of approximately -14% with respect to the 2002 glacier area.

The glacial reduction demonstrated by these findings (i.e., terminus fluctuations, mass balances, and surface area changes) is interpreted as a truthful impact of climate change. Indeed, as the transfer function among climate changes and glacier variations does not change in time (Oerlemans 2005), an acceleration in glacial changes is suggested.

Nevertheless, it is less easy to identify the climatic elements driving the glacier changes and, despite the many investigations on this topic (e.g., Hoelzle et al. 2003, Oerlemans 2005), the scientific debate is still open. Air temperature and precipitation, the two factors most



PLATE 1. *Androsace alpina* is a pioneer species colonizing the alpine and nival belts of the European Alps and is representative of the species actually suffering the highest impacts of climate change on high-elevation ecosystems. Photo credit: N. Cannone.

commonly correlated with glacier fluctuations, are only two elements of the complex chain of processes linking climate and glacier fluctuations (Haerberli 1995, Chinn 1999). Therefore, the glacier fluctuations indicate a complex combination of mass and energy exchange at the Earth's surface. The air temperature increase occurring in the alpine areas since the end of the LIA activated a positive feedback, with the consequent increase of both the downward sensible heat flux and the long-wave radiation balance (Oerlemans et al. 1998). Furthermore, during the last two decades, Sforzellina Glacier experienced a strong decrease of surface albedo (due to increasing debris coverage), which surely played a key role in increasing the glacier absorption of incoming energy fluxes, thus making larger the quantity of energy available for glacier melting.

To quantify the possible influence of temperature on the recent evolution of Sforzellina Glacier, neglecting the contribution due to changing precipitation, a simple approach was followed, according to Chinn (1999) and Oerlemans (2001). Analyzing all the ELAs of the period 1987–2006 (Fig. 3), the average difference between the estimated steady-state ELA and the calculated annual ELAs, gives a mean increase of ~ 150 m. This upward shift, obtained using a standard lapse rate of $-0.0065^{\circ}\text{C}/\text{m}$, represents a general warming of approximately $+0.6^{\circ}\text{C}$ since 1987. Therefore, considering that the summer warming that occurred in the same period is

$+0.5^{\circ}\text{C}$, the difference indicates that changes in precipitation also have to be considered.

In the context of vegetation succession, our data support recent evidence (Cannone et al. 2007) suggesting that the significant changes in vegetation community dynamics we found are consequences of an actual air temperature warming combined with the reduction of precipitation and the shortening of the snow season. Like the glacier reduction, all processes seem to be accelerated, including the vegetation dynamics.

The comparison of our data with glacial chronosequences described for the European Alps allows an assessment of the acceleration rate of these processes. In the alpine belt (>2200 m a.s.l.) the colonization of the recently deglaciated terrains is reported to start within 4–8 years after deglaciation (Stöcklin and Bäumler 1996, Burga 1999, Tscherko et al. 2005), with scattered early pioneer species. At least 10–25 years are required for the ingression of the early-successional species and the development of a well-established early-successional community (Pirola and Credaro 1993, Niederfriniger Schlag and Erschbamer 2000, Caccianiga and Andreis 2004, Raffl and Erschbamer 2004, Tscherko et al. 2005).

Our data provide evidence that these early stages of colonization suffered a dramatic acceleration: plant species are able to colonize the glacier forefield only one year after the glacier retreat. Considering the differences of colonization time between our data and the existing literature, the colonization speed increased

at least four times for the establishment of scattered individuals (one year in the Sforzellina area vs. 4–8 years reported by literature) and about two times for the well-established discontinuous early-successional community (6–11 years at Sforzellina vs. 10–25 years reported by the literature).

On the other hand, the following stages of vegetation development (>25 years) do not show remarkable differences with respect to the chronosequences described in the literature for the Alps (such as Pirola and Credaro 1993, Niederfriniger Schlag and Erschbamer 2000, Caccianiga and Andreis 2004, Raffl and Erschbamer 2004, Tscherko et al. 2005).

The ecological requirements of the species occurring on the one-year-old surface may explain the ability of these species to colonize such young substrata. In fact, most of them are species typical of the scree slopes or of rocks, with only one snowbed species (*Sagina saginoides*). The absence of snowbed species in a glacier forefield appears to be a paradox if we do not take into account the strong reduction of snow cover abundance and permanence documented for a site very close to the study area (Cannone et al. 2007). The shortening of the snow cover length supports the hypothesis by Galen and Stanton (1995) that climate change may induce interspecific differences in growth phenology of coexisting species and promote shifts in snowbed plant communities. Moreover, *Sagina saginoides* is a short-lived species with abundant seed production, and it is possible that the success of this species may be related to its efficient dispersal strategies.

The functional types of most of the species involved in the early stages of colonization may also provide some explanation for the accelerated rates of vegetation colonization. All these species are long-lived perennials adapted to the harsh environmental conditions of the alpine and nival belts and of the glacier forefield. Most of the early-successional species that are able to colonize the one-year-old terrains are clonal species, including clonal plants with widely spaced ramets (e.g., *Geum reptans*, *Saxifraga bryoides*, *Cerastium uniflorum*) as well as clonal plants with a clumped growth form (e.g., *Poa alpina*). Clonal growth is one of the most important adaptations to the severe climatic conditions and the nutrient shortage characteristic of the alpine environments (Stöcklin and Bäumler 1996, Pluess and Stöcklin 2005). Thus clonal reproduction increases with altitude both in closed grasslands and in pioneer communities (Stöcklin 1992). Clonal growth is a key factor for the successful establishment of the primary succession because it provides long-lived perennials with the ability to persist during succession (e.g., *Geum reptans*) with a large amount of phenotypic plasticity (Stöcklin and Bäumler 1996). Phenotypic plasticity is one of the most important mechanisms hypothesized allowing plants to persist in the environment modified by climatic change (Theurillat and Guisan 2001), thus avoiding migration and/or extinction. Therefore the preponderance of

clonal plants on the one-year-old surfaces demonstrates the correctness of this hypothesis and explains how colonization could occur with such fast rates at an elevation >2800 m a.s.l.

Acceleration of dynamics is evident only on recent vegetation; the fact that older stages of succession are quite similar to those described by other glacial chronosequences indicates that climate change impacts on these stages are not severe enough to induce significant changes and that older and more developed stages are probably more resistant to, and buffered from, climatic perturbation.

Within the well-documented increase of air temperature during the 20th century over the planet (IPCC 2001), the warming was significantly higher in the European Alps (Beniston 2000, Böhm et al. 2001). More recently Casty et al. (2005) in their temperature reconstruction for the Alps since 1500, found that 1994, 2000, 2002, and 2003 were the warmest years since 1500. Moreover, they found that summer warming was particularly severe after 1970, reaching, in 2003, the highest peak of summer temperature since 1500. Our data confirm the general summer warming of the last two decades, even if, at this site, very warm summers were recorded also in 1991 and 1998.

The temperature increase we found (+0.5°C in summer) has to be considered in the frame of the general post-1985 climate warming, which was accompanied by reduced precipitation on the Alps. Whereas the number of days with snow on the ground showed little evolution, the duration of continuous snow cover was clearly declining at all elevations. Although continuous snow cover tended to start earlier, it also melted much earlier (Beniston et al. 2003, Martin and Durand 2006). This general trend seems related to a positive North Atlantic Oscillation (NAO) index (Uppenbrink 1999) and to the summer warming. Our precipitation data indicate a general decrease (–10%) in agreement with the general trend (Brunetti et al. 2000). It is unfortunate that there are not any snow depth and duration data available for the Sforzellina Glacier forefield, but if we consider other local data recorded in another locality of the Upper Valtellina since 1978, we find they agree with the general patterns of the snow cover decrease (Cannone et al. 2007).

CONCLUSIONS

The stronger ice mass loss affecting the Sforzellina Glacier during the last decade (1996–2006) may be due to the local summer warming combined with reduced precipitation and the shortening of the snow season (Cannone et al. 2007). This abiotic evidence of climate change is correlated with changes in the vegetation of the glacier forefield, which indicated an acceleration of colonization rates in the same period. Here we show that there is a strong correspondence between the abiotic and biotic components of high altitude ecosystems and that, over the last decade (1996–2006) and, in particular since

2002, the impacts of climate change have undergone a dramatic acceleration, much stronger than any that occurred during the last 35 years. This acceleration occurred in tandem with a documented slight summer warming and a possible decrease in snow cover. Further in situ investigations are required to directly measure some of the influential parameters involved (e.g., snow cover, avalanche frequency) and to analyze species-specific responses to factors like snow cover reduction.

ACKNOWLEDGMENTS

We thank Christian Körner and Renato Gerdol for reviewing the paper before submission, Wilfried Haeberli and one anonymous referee whose comments and suggestions allowed us to improve the paper, and the Geological Monitoring Service of ARPA Lombardia (Lombardy Regional Environmental Agency) for the climatic data. This paper was funded by the project “Increasing rate of climate change impacts on high mountain areas: cryosphere shrinkage and environmental effects” (PRIN–MIUR 2005).

LITERATURE CITED

- Beniston, M. 2000. Environmental change in mountains and uplands. Arnold, London, UK.
- Beniston, M. 2003. Climatic change in mountain regions: a review of possible impacts. *Climatic Change* 59:5–31.
- Beniston, M., H. F. Diaz, and R. S. Bradley. 1997. Climatic change at high elevation sites: a review. *Climatic Change* 36: 233–251.
- Beniston, M., F. Keller, and A. Goyette. 2003. Estimates of snow accumulation and volume in the Swiss Alps under changing climatic conditions. *Theoretical and Applied Climatology* 76:125–140.
- Böhm, R., I. Auer, M. Brunetti, M. Maugeri, T. Nanni, and W. Schöner. 2001. Regional temperature variability in the European Alps: 1760–1998 from homogenized instrumental time series. *International Journal of Climatology* 21:1779–1801.
- Brunetti, M., M. Maugeri, and T. Nanni. 2000. Variations of temperature and precipitation in Italy from 1866 to 1995. *Theoretical and Applied Climatology* 65:165–174.
- Burga, C. A. 1999. Vegetation development on the glacier forefield Morteratsch (Switzerland). *Applied Vegetation Science* 2:17–24.
- Caccianiga, M., and C. Andreis. 2004. Pioneer herbaceous vegetation on glacier forefields in the Italian Alps. *Phytocoenologia* 34(1):55–89.
- Cannone, N., S. Sgorbati, and M. Guglielmin. 2007. Unexpected impacts of climatic change on alpine vegetation. *Frontiers in Ecology and the Environment* 7:360–364.
- Casty, C., H. Wanner, J. L. Luterbacher, J. Esper, and R. Böhm. 2005. Temperature and precipitation variability in the European Alps since 1500. *International Journal of Climatology* 25:1855–1880.
- Catata, G., and C. Smiraglia. 1993. The mass balance of a cirque glacier in the Italian Alps (Ghiacciaio della Sforzellina, Ortles-Cevedale Group). *Journal of Glaciology* 39:87–90.
- CGI (Comitato Glaciologico Italiano). 1971–1977. Campagne Glaciologiche (Glaciological surveys). *Bollettino del Comitato Glaciologico Italiano Serie I and II*:18–25.
- CGI (Comitato Glaciologico Italiano). 1978–2006. Campagne Glaciologiche (Glaciological surveys). *Geografia Fisica e Dinamica Quaternaria*:1–25.
- Chapin, F. S., L. R. Walker, C. L. Fastie, and L. C. Sharman. 1994. Mechanisms of primary succession following deglaciation at Glacier Bay, Alaska. *Ecological Monographs* 64: 149–175.
- Chinn, T. J. 1999. New Zealand glacier response to climate change of the past 2 decades. *Global and Planetary Change* 22:155–168.
- Cogley, J. G., and W. P. Adams. 1998. Mass balance of glaciers other than the ice sheets. *Journal of Glaciology* 44(147):315–325.
- Cook, A. J., A. J. Fox, D. G. Vaughan, and J. G. Ferrigno. 2005. Retreating glacier fronts on the Antarctic Peninsula over the past half-century. *Science* 308:541–544.
- Diolaiuti, G., C. Smiraglia, G. Vassena, and M. Motta. 2004. Dry calving processes at the ice cliff of Strandline Glacier, Northern Victoria Land, Antarctica. *Annals of Glaciology* 39:201–208.
- Dyurgerov, M. B., and M. F. Meier. 2000. Twentieth century climate change: evidence from small glaciers. *Proceedings of the National Academy of Sciences (USA)* 97:1407–1411.
- Egli, M., M. Wernli, C. Kneisel, and W. Haeberli. 2006. Melting glaciers and soil development in the proglacial area Morteratsch (Swiss Alps): I. Soil type chronosequence. *Arctic, Antarctic, and Alpine Research* 38:499–509.
- Galen, C., and M. N. Stanton. 1995. Responses of snowbed plant-species to changes in growing season length. *Ecology* 76:1546–1557.
- Grabherr, G., M. Gottfried, and H. Pauli. 1994. Climate effects on mountain plants. *Nature* 369:448.
- Guglielmin, M., A. Nardo, and C. Smiraglia. 1995. Lo spessore dei ghiacciai della Valfurva. *Misurazioni tramite Sondaggi Elettrici Verticali. Neve e Valanghe* 24:58–67.
- Haeberli, W. 1995. Glacier fluctuations and climate change detection—operational elements of a worldwide monitoring strategy. *World Meteorological Organisation Bulletin* 44:23–31.
- Haeberli, W., and M. Beniston. 1998. Climate change and its impacts on glaciers and permafrost in the Alps. *Ambio* 27: 258–265.
- Haeberli, W., R. Frauenfelder, M. Hoelzle, and M. Maisch. 1999. On rates and acceleration trends of global glacier mass changes. *Geografiska Annaler* 81A:585–591.
- Haeberli, W., and M. Hoelzle. 1995. Application of inventory data for estimating characteristics of and regional climate-change effects on mountain glaciers: a pilot study with the European Alps. *Annals of Glaciology* 21:206–212.
- Hoelzle, M., W. Haeberli, M. Dischl, and W. Peschke. 2003. Secular glacier mass balances derived from cumulative glacier length changes. *Global and Planetary Change* 36:295–306.
- IAHS (ICSU)-UNEP-UNESCO. 1988–2005. *Glacier Mass Balance Bulletins (GMBBs)*. Volumes 1–8. World Glacier Monitoring Service, Zurich, Switzerland.
- IPCC. 2001. *Third Assessment Report of the Intergovernmental Panel on Climate Change*. Cambridge University Press, Cambridge, UK.
- Jochmisen, M. 1970. Die Vegetationsentwicklung auf Moränenboden in Abhängigkeit von einigen Umweltfaktoren. *Verlag Universität Innsbruck* 46:1–22.
- Kaser, G., A. Fountain, and P. Jansson. 2003. *A manual for monitoring the mass balance of mountain glaciers*. IHP (International Hydrological Programme), Technical Documents in Hydrology, 59. UNESCO, Paris, France.
- Keller, F., S. Goyette, and M. Beniston. 2005. Sensitivity analysis of snow cover to climate change scenarios and their impact on plant habitats in alpine terrain. *Climatic Change* 72:299–319.
- Keller, F., F. Kienast, and M. Beniston. 2000. Evidence of response of vegetation to environmental change on high-elevation sites in the Swiss Alps. *Regional and Environmental Change* 1(2):70–77.
- Martin, E., and Y. Durand. 2006. *Precipitation and snow cover variability in the French Alps*. Lecture Notes in Earth Sciences. Volume 74. Springer, Berlin/Heidelberg, Germany.

- Matthews, J. A. 1992. The ecology of recently deglaciated terrain. Cambridge University Press, Cambridge, UK.
- Niederfriniger Schlag, R., and B. Erschbamer. 2000. Germination and establishment of seedlings on a glacier foreland in the Central Alps, Austria. *Arctic, Antarctic, and Alpine Research* 32:270–277.
- Oerlemans, J. 2001. *Glaciers and climate change*. Balkema, Rotterdam, Netherlands.
- Oerlemans, J. 2005. Extracting a climate signal from 169 glacier records. *Science* 308:675–677.
- Oerlemans, J., B. Anderson, A. Hubbard, Ph. Huybrechts, T. Johannesson, W. H. Knap, M. Schmeits, A. P. Stroeven, R. S. W. van de Wal, J. Wallinga, and Z. Zuo. 1998. Modelling the response of glaciers to climate warming. *Climate Dynamics* 14:267–274.
- Oerlemans, J., and J. P. F. Fortuin. 1992. Sensitivity of glaciers and small ice caps to greenhouse warming. *Science* 258:115–117.
- Østrem, G., and M. Brugman. 1989. Glacier mass-balance measurements. National Hydrology Research Institute, Saskatoon, Saskatchewan, Canada.
- Patzelt, G. 1985. The period of glacier advances in the Alps, 1965 to 1980. *Zeitschrift für Gletscherkunde und Glazialgeologie* 21:403–407.
- Paul, F., A. Käab, M. Maisch, T. Kellenberger, and W. Haeberli. 2004. Rapid disintegration of Alpine glaciers observed with satellite data. *Geophysical Research Letters* 31:L21402 [doi: 10.1029/2004GL020816].
- Pauli, H., M. Gottfried, and G. Grabherr. 1999. Vascular plant distribution patterns at the low temperature limits of plant life—the Alpine-nival ecotone of Mount Schrankogel (Tyrol, Austria). *Phytocoenologia* 29:297–325.
- Pavan, M., G. Diolaiuti, V. Maggi, C. Smiraglia, and C. D'Agata. 2000. Prospezioni geofisiche sul Ghiacciaio della Sforzellina (Alpi Lombarde, Gruppo Ortles-Cevedale). Risultati preliminari. *Neve e Valanghe* 41:6–13.
- Pignatti, S. 1982. *Flora d'Italia*. Three volumes. Edagricole, Bologna, Italy.
- Pirola, A., and V. Credaro. 1993. Changes in the vegetation of a recent glacial moraine in the Bernina group. *Annali di Botanica LI*:145–153.
- Pirola, A., and V. Credaro. 1994. Osservazioni sul dinamismo della vegetazione di morena recente nel Gruppo del Bernina. *Fitosociologia* 27:139–149.
- Pluess, A. R., and J. Stöcklin. 2005. The importance of population origin and environment on clonal and sexual reproduction in the alpine plant *Geum reptans*. *Functional Ecology* 19:228–237.
- Raffl, C., and B. Erschbamer. 2004. Comparative vegetation analyses of two transects crossing a characteristic glacier valley in the Central Alps. *Phytocoenologia* 32:225–240.
- Regione Lombardia. 2004. Lombardy Glacier data base. (www.cartografia.regione.lombardia.it)
- Resnati, C., and C. Smiraglia. 1989. Ghiacciaio della Sforzellina. Misure dello spessore del ghiacciaio attraverso sondaggi geoelettrici. *Rivista Club Alpino Italiano* 110(6):70–75.
- Root, T. L., J. T. Price, K. R. Hall, S. H. Schneider, C. Rosenzweig, and A. J. Pounds. 2003. Fingerprints of global warming on wild animals and plants. *Nature* 421:57–60.
- Rossi, S., G. Diolaiuti, E. Forasacco, M. Pelfini, C. Smiraglia, and P. Spreafico. 2003. Evidenze geomorfologiche della più recente espansione glaciale correlabile all'episodio freddo degli anni '50–'70 del XX secolo sulle Alpi Lombarde. Pages 377–395 in M. Motta and A. Biancotti, editors. *Risposta dei processi geomorfologici alle variazioni ambientali*. Glauco Brigati, Genoa, Italy.
- Rott, H., P. Skvarca, and T. Nagler. 1996. Rapid collapse of northern Larsen Ice Shelf, Antarctica. *Science* 271:788–792.
- Stöcklin, J. 1992. Umwelt, Morphologie und Wachstumsmuster klonaler Pflanzen—eine Übersicht. *Botanica Helvetica* 102:3–21.
- Stöcklin, J., and E. Bäumler. 1996. Seed rain, seedling establishment and clonal growth strategies on a glacier foreland. *Journal of Vegetation Science* 7:45–56.
- Theurillat, J. P., and A. Guisan. 2001. Potential impact of climate change on vegetation in the European Alps: a review. *Climatic Change* 50:77–109.
- Tscherko, D., U. Hammesfahr, G. Zeltner, E. Kandeler, and R. Böcker. 2005. Plant succession and rhizosphere microbial communities in a recently deglaciated alpine terrain. *Basic and Applied Ecology* 6:367–383.
- Uppenbrink, J. 1999. The North Atlantic Oscillation. *Science* 283:948–949.
- Vögtle, T., and K. J. Schilling. 1999. Digitizing maps. Pages 201–216 in H.-P. Bähr and T. Vögtle, editors. *GIS for environmental monitoring*. Schweizerbart, Stuttgart, Germany.
- Walther, G. R., S. Beißner, and C. A. Burga. 2005. Trends in the upward shift of alpine plants. *Journal of Vegetation Science* 16:541–548.
- Whittaker, R. J. 1993. Plant population patterns in a glacier foreland succession: pioneer herbs and later-colonizing shrubs. *Ecography* 16:117–136.
- Wood, F. 1988. Global alpine glacier trends 1960s to 1980s. *Arctic, Antarctic, and Alpine Research* 20:404–413.
- Zemp, M., W. Haeberli, M. Hoelzle, and F. Paul. 2006. Alpine glaciers to disappear within decades? *Geophysical Research Letters* 33:L13504. [doi: 10.1029/2006GL026319]