Geogr. Fis. Dinam. Quat.
30 (2007), 33-42, 6 figg., 4 tabb.

LUCA CARTURAN (*) & ROBERTO SEPPI (**)

RECENT MASS BALANCE RESULTS AND MORPHOLOGICAL EVOLUTION OF CARESER GLACIER (CENTRAL ALPS)

ABSTRACT: CARTURAN L. & SEPPI R., *Recent mass balance results and morphological evolution of Careser glacier (Central Alps)*. (IT ISSN 1724-4757, 2007).

This paper presents the 2002 to 2005 and historical mass balance series for Careser glacier. The mass balance evolution since 1967 has been compared with the meteorological data from the local weather stations. The most recent morphological changes of the ice body are also described. In the last four years the mass balance was extremely negative, with an average value of -2008 mm we and a minimum value of –3317 mm we. The current mass loss rate is nearly twice the average of the 1981 to 2001 (–1195 mm we), whereas between 1967 and 1980 the glacier was near equilibrium conditions. This behaviour seems to be strictly connected with the ablation season temperatures. By contrast, the relationship with the accumulation season precipitation amounts is less clear. The strongly negative mass balances result in huge morphological changes (surface lowering, bedrock emersion, rapid fragmentation) and positive feedbacks contribute to accelerate the deglaciation process. At the present-day climatic conditions, the complete extinction of the glacier has to be expected within few decades.

KEY WORDS: Glacier mass balance, Climatic forcing, Positive feedbacks, Morphological evolution, Careser glacier (Central Alps).

RIASSUNTO: CARTURAN L. & SEPPI R., *Recenti misure di bilancio di massa ed evoluzione morfologica del ghiacciaio del Careser (Alpi Centrali)*. (IT ISSN 1724-4757, 2007).

In questo lavoro vengono presentati i risultati delle misurazioni di bilancio di massa sul ghiacciaio del Careser dal 2002 al 2005 e la serie storica. L'evoluzione del bilancio di massa dal 1967 è stata messa a confronto con i dati registrati dalle vicine stazioni meteorologiche. Sono state inoltre descritte le variazioni morfologiche più recenti. Negli ultimi quattro anni il bilancio di massa è stato fortemente negativo, con un valore medio annuo pari a -2008 mm we e un valore minimo pari a –3317 mm we. L'attuale tasso di ablazione è quasi doppio rispetto alla media del periodo 1981-2001 (–1195 mm we), mentre tra il 1967 e il 1980 il ghiacciaio si trovava in condizioni prossime all'equilibrio. Questo comportamento appare fortemente influenzato dalle temperature della stagione di ablazione. Meno evidente è invece la correlazione con i cumuli di precipitazione della stagione di accumulo. Il continuo ripetersi di bilanci di massa annuali fortemente negativi sta producendo importanti variazioni morfologiche (abbassamento della superficie, affioramento del substrato roccioso, rapida frammentazione) e la presenza di effetti di reazione positiva contribuisce ad accelerare il processo di deglaciazione. Se le attuali condizioni climatiche permarranno anche in futuro, il ghiacciaio è destinato ad estinguersi completamente nell'arco di poche decine di anni.

TERMINI CHIAVE: Bilancio di massa glaciale, Forcing climatico, Feedback positivi, Evoluzione morfologica, Ghiacciaio del Careser (Alpi Centrali).

INTRODUCTION

Careser glacier is the residual accumulation area of a much wider glacier which, during the Little Ice Age (LIA), exhibited a well developed valley tongue that has completely melted away. It is located in the south-eastern sector of the Ortles-Cevedale massif (Central Italian Alps) and is set in a wide, south facing cirque surrounded by peaks ranging from 3162 m a.s.l. (Cima Lagolungo) to 3386 m a.s.l. (Cima Venezia) (fig. 1). Its gentle sloping surface of 2.83 km^2 extends from a minimum altitude of 2860 m a.s.l. to a maximum altitude of 3310 m a.s.l. The meltwaters were artificially dammed at 2600 m a.s.l. in the 1920's for hydropower production and since then the glacier has been intensely investigated.

Mass balance studies have gained increased attention because of their usefulness in detecting global climate change. Furthermore, glacier mass change is important for regional water supplies and power generation, and *in-situ* measurements of glaciological and meteorological quanti-

(*) *Comitato Glaciologico Trentino SAT, Trento & Università di Padova, Dipartimento Territorio e Sistemi Agro Forestali, Agripolis - Viale dell'Università, 16 - 35020 Legnaro PD, Italy.*

(**) *Comitato Glaciologico Trentino SAT, Trento & Museo Tridentino di Scienze Naturali, Via Calepina, 14 - 38100 Trento, Italy.*

Field data were collected by the Comitato Glaciologico Trentino SAT in collaboration with the Provincia Autonoma di Trento (Ufficio Previsioni e Organizzazione) and the University of Trento (Dipartimento di Ingegneria Civile e Ambientale). Meteorological data were provided by ENEL and by Provincia Autonoma di Trento (Ufficio Previsioni e Organizzazione). We would like to thank Prof. G. Dalla Fontana for suggestions and comments and S. Frisia for revising the English language. Finally, we would like to thank everybody who participated in the fieldwork and offered logistic support.

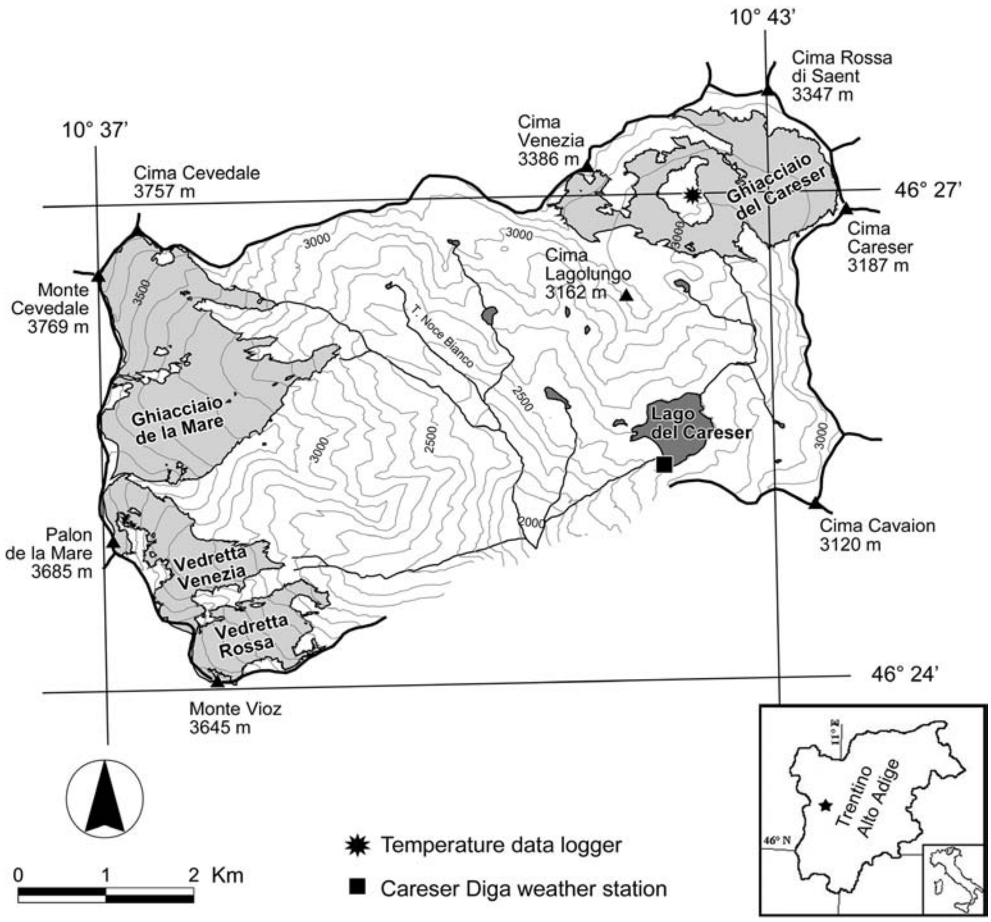

FIG. 1 - Geographical setting of the Careser glacier.

ties are useful for mass balance models development. (Fountain & *alii*, 1999; Oerlemans, 2001).

On Careser glacier, mass balance measurements have been carried out since 1967 and the data series, the longest for the Italian Alps, extends until present without interruption. Careser is part of the reference glaciers network taken into account by the World Glacier Monitoring Service on a global scale and the mass balance data are regularly published in the Glacier Mass Balance Bulletin and Fluctuations of Glaciers (IUGG (CCS)-UNEP-UNESCO-WMO, 2005). Measurements on Careser glacier were carried out from 1967 to 2001 by the Dipartimento di Geografia, University of Padova (Giada & Zanon, 1991; 1996; 2001; Zanon, 1970; 1992). Since 2002 the monitoring activity has been carried out by the Comitato Glaciologico Trentino (Società degli Alpinisti Tridentini). Since the beginning, the research activity has been promoted by the Comitato Glaciologico Italiano (CGI). In order to ensure the continuity and the homogeneity between the first (1967-2001) and the second (2002 - present day) series of mass balance data, we maintained the same monitoring network which had been used up to 2001. In addition, winter and summer balance measurements were resumed.

Here, we report the results of the last four years of mass balance measurements (2002-2005), compared with the historical data series. We also describe the rapid morphological changes affecting this glacier and attempt to relate its recent evolution with the climatic changes.

METHODS

Winter balance measurements were commonly carried out in the second half of May, just before melting started to become significant. Snow depth soundings were performed by aluminium probes along the contour lines at regular distances, increasing their density where needed (e.g. near the glacier edges). The whole glacier surface was covered with an average of 350 probing points whose position was determined by GPS.

The summer surface was always easily recognized, because it consisted of ice. Only rarely firn was found at the bottom of the winter snow pack. Sometimes, the presence of thick ice lenses in the snow pack lead to mistakes, but they were easily spotted in the winter balance map. The conversion to water equivalent was accomplished by density pit measurements, dug in several locations with different elevation and snow depth.

Two-meter long aluminium stakes, drilled into ice by means of a hand-driven auger, were used to measure ablation. In order to ensure the reliability of the measurements, stakes were re-drilled when less than 1 m was left in the ice. Net accumulation measurements were not needed in the last four years, because no residual snow was found on the whole glacier at the end of the ablation season.

The point measurements were then converted into distributed maps in GIS environment, by means of geostatistical inter- and extrapolation. GIS provide a useful tool for mass balance calculations, although computer plotting may have some limitations (Jansson, 1999; Kaser & *alii*, 2003; Ostrem & Brugman, 1991; Smith & Wessel, 1990). The case of Careser glacier is peculiar because of the relatively even distribution of accumulation and ablation, the density of the monitoring network and the lack of inaccessible areas. For these reasons, the glacier sectors where extrapolation was needed were significantly reduced.

Meteorological data where obtained from the local weather stations (Careser Diga, 2600 m a.s.l.; Peio, 1580 m a.s.l.; Cogolo Pont, 1200 m a.s.l.) and from a temperature data-logger installed on the central nunatak, at mean glacier elevation of 3060 m a.s.l.

The glacier topography was updated in 2003 by means of an aerial laser altimetry survey and the glacier boundaries were drawn on digital orthophotos of the same year. Additional observations on snow-cover, summer snowfalls and snow-line surveys with GPS were periodically conducted, to build-up an experimental basis that will be used to better understand the involved processes.

RESULTS

ANNUAL MASS BALANCES (2002-2005)

The spatial distribution of the 2002-2005 mean specific mass balance is shown in fig. 2 and the mass balance versus altitude for the same period in fig. 3. The figures show that the whole period was extremely negative with an average value of -2008 mm we and the average Equilibrium Line Altitude (ELA) was above the maximum glacier altitude.

In 2002 no winter balance measurements were carried out. However, from the Careser Diga weather station data, we infer that accumulation was poor in the 2001/02 winter season. The beginning of the summer season was warm and dry, in particular from June 12 to 24. By July 12, the lower half of the glacier was already snow-free and at the end of the month the snow cover had almost entirely disappeared.

In the following 2 months, unstable weather with below-average temperature and consistent snowfalls (on 10-11 August, 3 and 23-24 September) significantly reduced ablation. On the highest sectors of the glacier, a few decimetres of firn lowered the ablation in the period without snow cover, especially in the eastern accumulation basin. The mass balance has been quite negative (–1149 mm we), close to the average for the last 2 decades, and mass balance gradient rather high (6.4 mm we m^{-1}).

The 2002/03 winter balance was slightly higher than average (1021 mm we). By contrast, the summer was very warm and dry and hot waves were extreme both in intensity and duration. For instance, the data-logger at 3060 m

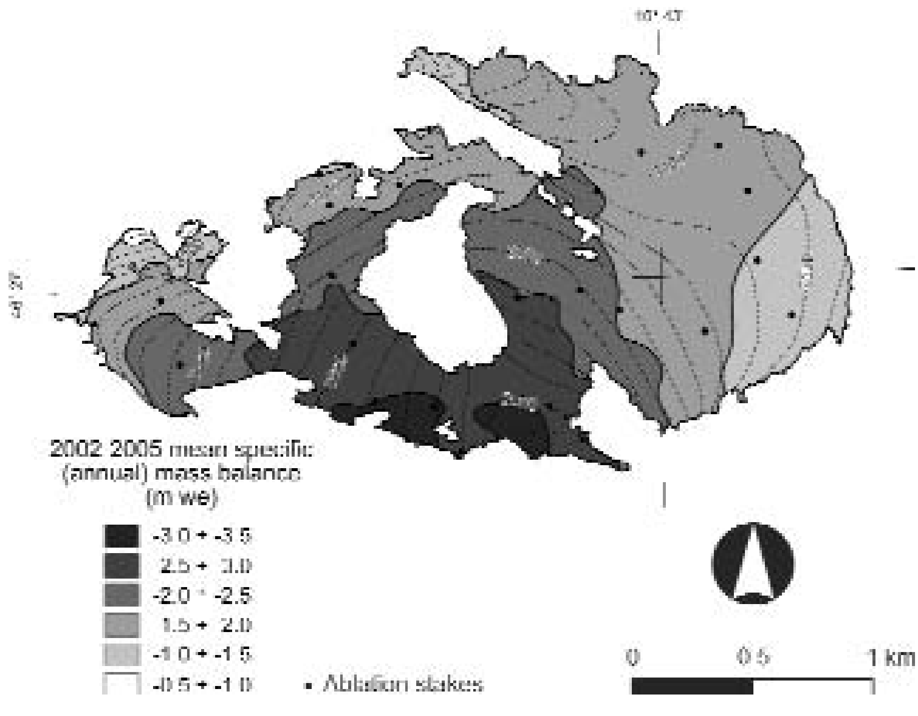

FIG. 2 - Mean 2002-2005 specific mass balance (m we) and ablation stakes location.

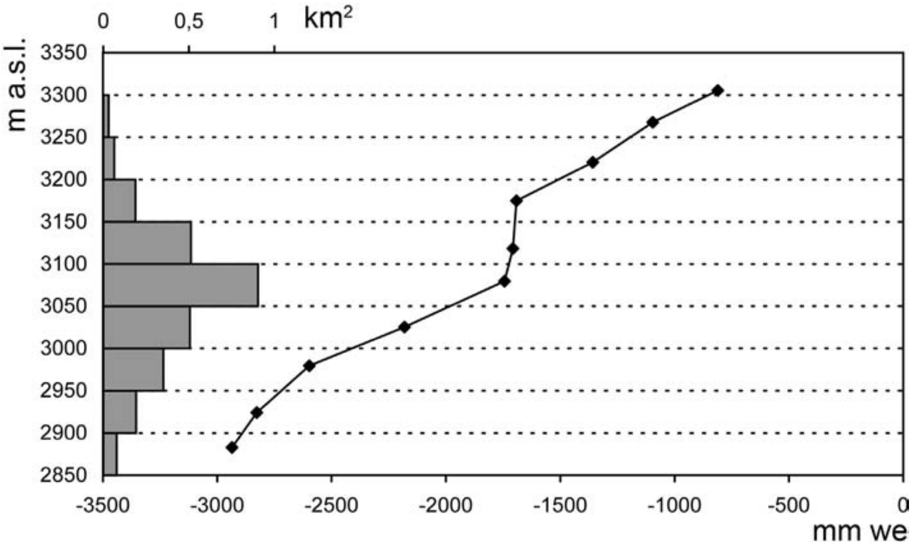

FIG. 3 - Mean 2002-2005 specific mass balance distribution versus altitude (mm we) and glacier hypsometry in 2003.

a.s.l. registered a maximum value of 14.7°C on 12 August. Summer snowfalls were restricted to two weak events occurred in early July and early September, and the snow quickly melted a few days later. By the end of June the glacier was completely snow-free and the following strong ablation caused large ice loss, ranging from 5 m in the lower sector to 2.5 m in the eastern accumulation basin. The glacier lost 9382135 m^3, with a mean specific mass balance of –3317 mm we, which represents the most negative of the entire series and the worst of the WGMS sample for 2003 (IUGG-UNEP-UNESCO-WMO, 2005). A comparison with the mass balance of 8 Austrian glaciers (tab. 1) clearly highlights the exceptionality of this hydrological year (Hydrographischer Dienst in Österreich, 2006). The ELA was above maximum glacier elevation and its calculated altitude was ca. 3700 m. The balance gradient was particularly reduced, with a mean value of 4.3 mm we m^{-1}.

In 2003/04 accumulation was 10% higher than average, but once again late summer temperatures exceeded the long-term average. In June and July warm and cool periods alternated, with two important snowfall events on 20 June (nearly 50 cm on the glacier) and on 11 July (20 cm, followed by some days of dry and cool weather). Consequently, at the end of July the glacier was still covered by residual snow. By contrast, August and September were warmer than average, and snowfalls consisted in only a few, weak events. Ablation continued until the first decade of October, and no remnants of snow were left below 3300 m. Late summer ablation lead to another negative mass balance on Careser glacier (–1562 mm we), with an ELA at 3430 m and a very low mass balance gradient (3.6 mm we m^{-1}).

The winter balance of 2004/05 was below average (–15%) and strong heat waves alternated with short periods of cool temperatures in the first part of the summer season, without significant snowfall. Snow cover disappeared early and more than 1 m of glacier ice was lost at the snout by mid July. August was cooler than average, with little snowfalls above 3100-3200 m. The strongest snowfall occurred from 21 to 23 August, with 20-30 cm on the glacier. September was warm at the beginning, but from the 13th colder weather conditions followed, with fresh snow that persisted until the end of the month. The early disappearance of the snow cover and the high temperatures in the first half of summer caused a strong mass loss (–2005 mm we), which was the 3rd most negative value after 2003 and 1998. The balance gradient was higher than average and equal to that observed in 2001/02 (6.4 mm we m^{-1}). The calculated ELA was located at 3391 m.

THE MASS BALANCE SERIES

Table 2 shows the complete mass balance series. Winter and summer balances from 1967 to 1982 and from 2003 to 2005 were directly measured, whereas those marked with asterisks («index» values), were obtained by few sample points. Two distinctive phases can be recognized in the mass balance series (tab 3 and fig. 4). The first, from 1967 to 1980, was characterized by near-equilibrium conditions. The second, from 1980 to present-day, by strong mass loss and lack of positive balances. Deglaciation rate seems to have accelerated and the last four-year period was the most negative of the entire Careser glacier mass balance series, with a cumulative value of –8033 mm we and an annual average of –2008 mm we. This value is strongly influenced by the 2002/03 balance, which was 50% more negative than any previous observed value. The cumulative mass balance since the beginning of observations (1967-2005) reaches about –35 m we, corresponding to –38.9 m of ice depth (fig. 4).

The mass balance distribution map (fig. 2) shows an asymmetrical pattern, with more negative values in the E and SE with respect to the W and SW facing sectors, located at the same altitude. This behaviour was already

FIG. 4 - The Careser glacier mass balance series from 1967 to 2005.

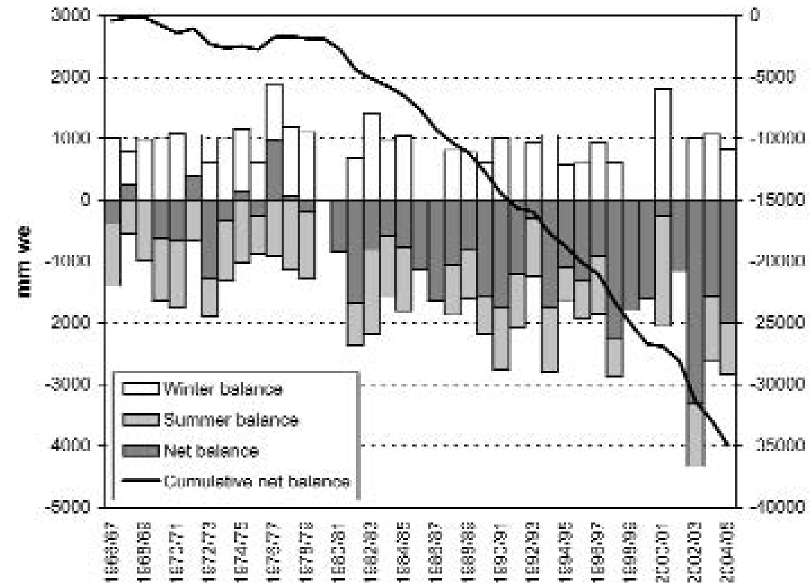

TABLE 1 - Comparison between the mass balance data of the record year 2002/2003 and the historical series of measurements, for Careser and 8 nearby Austrian glaciers. (A_c = accumulation area; B_c = accumulation; A_a = ablation area; B_a = ablation; A = total area; B = mass balance; b = mean specific mass balance; Δb = difference from 1991-2000 decade; ELA = Equilibrium Line Altitude; AAR = Accumulation Area Ratio)

Glacier	A_c (km^2)	B_c ($10^6\ m^3$)	A_a (km^2)	B_a ($10^6\ m^3$)	A (km^2)	B ($10^6\ m^3$)	B (mm)	Δb (mm)	ELA (m a.s.l)	AAR
Hintereisferner										
2002/2003	0.26	0.03	7.55	14.22	7.82	-14.19	-1814	-941	>3750	0.03
1970/71 - 79/80	5.58	3.89	3.44	4.98	9.02	-1.09	-120		2960	0.62
1980/81 - 89/90	3.83	1.56	5.22	7.49	9.05	-5.93	-656		3075	0.42
1990/91 - 1999/2000	3.23	1.25	5.37	8.77	8.60	-7.52	-873		3115	0.38
Kesselwandferner										
2002/2003	0.00	0.00	3.94	6.09	3.94	-6.09	-1546	-1286	>3500	0.00
1970/71 - 79/80	3.41	2.38	0.84	1.41	4.25	0.97	229		3080	0.80
1980/81 - 89/90	2.81	1.15	1.64	1.99	4.44	-0.84	-189		3130	0.63
1990/91 - 1999/2000	2.35	0.91	2.38	2.44	4.26	-1.14	-260		3195	0.56
Vernagtferner										
2002/2003	0.00	0.00	8.53	18.20	8.53	-18.20	-2133	-1510	>3600	0.00
1970/71 - 79/80	6.77	2.60	2.63	2.07	9.40	0.53	56		3050	0.72
1980/81 - 89/90	4.16	1.01	5.13	4.72	9.29	-3.71	-400		3210	0.45
1990/91 - 1999/2000	3.02	1.13	5.98	6.37	9.00	-5.15	-623		3295	0.34
Stubacher Sonnblickkees										
2002/2003	0.01	0.00	1.39	4.03	1.40	-4.02	-2870	-2192	(3800)	0.01
1970/71 - 79/80	1.24	0.80	0.50	0.43	1.74	0.37	210		2690	0.71
1980/81 - 89/90	0.74	0.36	1.00	1.11	1.74	-0.75	-432		2815	0.42
1990/91 - 1999/2000	0.55	0.24	0.97	1.28	1.52	-1.04	-678		2840	0.37
Jamtalferner										
2002/2003	0.00	0.00	3.46	7.71	3.46	-7.71	-2229	-1585	*****	0.00
1990/91 - 1999/2000	1.32	0.39	2.48	2.85	3.80	-2.46	-644		2835	0.35
Wurtenkees										
2002/2003	0.03	0.01	0.94	2.12	0.97	-2.12	-2177	-1316	3070	0.03
1990/91 - 1999/2000	0.18	0.06	0.85	1.02	1.03	-0.90	-861		3000	0.18
Goldsbergkees										
2002/2003	0.01	0.00	1.48	2.70	1.49	-2.70	-1806		>3100	0.01
Kleines Fleißkees										
2002/2003	0.00	0.00	0.94	1.52	0.94	-1.52	-1604		>3100	0.00
Careser										
2002/2003	0.00	0.00	2.83	9.39	2.83	-9.39	-3317	-1922	3700	0.00
1970/71 - 79/80	2.12		2.60		4.72	-0.51	-107		3094	0.45
1980/81 - 89/90	0.04		3.80		3.84	-4.18	-1089		3372	0.01
1990/91 - 1999/2000	0.06		2.77		2.83	-3.95	-1395		3429	0.02

TABLE 2 - Careser glacier mass balance series from 1967 to 2005. Values with asterisks are «index» values

Year	Specific winter balance (mm we)	Specific summer balance (mm we)	Specific net balance (mm we)	Equilibrium Line Altitude (m a.s.l.)	Accumulation Area Ratio	Cumulative net balance (mm we)
1966/67	1016	-1402	-386	3165	15	-386
1967/68	788	-541	247	3045	70	-139
1968/69	989	-994	-5	3084	53	-144
1969/70	995	-1626	-631	3155	17	-775
1970/71	1083	-1733	-650	3159	17	-1425
1971/72	1065	-665	400	3014	82	-1025
1972/73	602	-1878	-1276	3251	2	-2301
1973/74	995	-1314	-319	3137	25	-2620
1974/75	1152	-1007	145	3053	67	-2475
1975/76	611	-879	-268	3200	8	-2743
1976/77	1894	-906	988	2857	98	-1755
1977/78	1204	-1125	79	3060	63	-1676
1978/79	1103	-1285	-182	3125	32	-1858
1979/80			12	3083	53	-1846
1980/81			-839	3395	0	-2685
1981/82	684	-2362	-1678	3450	0	-4363
1982/83	1400*	-2187*	-787	3357	0	-5150
1983/84	990*	-1581*	-591	3273	3	-5741
1984/85	1045*	-1803*	-758	3279	3	-6499
1985/86			-1138	3383	0	-7637
1986/87			-1645	3485	0	-9282
1987/88	813*	-1869*	-1056	3398	0	-10338
1988/89	777*	-1594*	-817	3275	2	-11155
1989/90	610*	-2188*	-1578	3420	0	-12733
1990/91	1020*	-2754*	-1734	3463	0	-14467
1991/92	884*	-2083*	-1199	3315	0	-15666
1992/93	941*	-1244*	-303	3148	14	-15969
1993/94	1065*	-2808*	-1743	3380	0	-17712
1994/95	571*	-1652*	-1081	3469	0	-18793
1995/96	598*	-1918*	-1320	3463	0	-20113
1996/97	927*	-1847*	-920	3264	2	-21033
1997/98	624*	-2864*	-2240	3651	0	-23273
1998/99			-1800	3398	0	-25073
1999/00			-1610	3740	0	-26683
2000/01	1800*	-2050*	-250	3170	12	-26933
2001/02			-1149	3250	1	-28082
2002/03	1021	-4338	-3317	3700	0	-31399
2003/04	1069	-2631	-1562	3430	0	-32961
2004/05	826	-2831	-2005	3391	0	-34966

TABLE 3 - Summarized mass balance data: averages values for three main evolution phases of the Careser glacier are shown

	1967 - 1980	1981 - 2001	2002 - 2005
Mean specific net balance (mm we)	-132	-1195	-2008
Maximum value (mm we)	988	-250	-1149
Minimum value (mm we)	-1276	-2240	-3317
Positive balances	43%	0%	0%

observed at the beginning of the mass balance measurements and also in previous volume and altitude variations estimated by Giada & Zanon (1990; 1996) using aerial photogrammetry.

In the last 25 years, the ELA was normally above the highest elevation of the glacier, with a few exceptions. Consequently, the Accumulation Area Ratio (AAR) was always zero or near-zero from 1981 to 2005 (maximum value 0.14 in 1993) and at present Careser glacier has no accumulation areas.

METEOROLOGICAL OBSERVATIONS

The meteorological data of the weather stations of Peio valley have been recently processed (Bassan, 2006). The temperature and precipitation series were validated and successively used to determine the vertical thermo-pluviometric gradients and the fraction of solid precipitation; particular

TABLE 4 - Summarized meteorological data of the Careser Diga weather station. Average values for the three mass balance phases are shown. Meteorological data were provided by ENEL and by Provincia Autonoma di Trento - Ufficio Previsioni e Organizzazione

Period	October-May precipitation (mm we)	June-September temperature (°C)
1967-1980	728	5.4
1981-2001	816	6.4
2002-2005	757	7.3

care was devoted to the calculation of a proper Snow Correction Factor (SCF) that was used to correct the solid precipitation undercatch of the gauges. In particular, the Careser Diga weather station was quite useful because of its proximity to the Careser glacier, the length of the series and the availability of high altitude direct observations.

Table 4 shows the mean June-September temperature and the mean October-May precipitation amount for the three main phases that characterized the recent evolution of the Careser glacier. Ablation season temperatures increased by 1°C from 1967 to 1980 and 1981 to 2001 periods, while precipitation increased by near 10%. The last four summers were even warmer, exceeding by 1°C the 1981 to 2001 period. In particular, the 2003 ablation season was the warmest of the entire series back to 1933, but also 2002, 2004 and 2005 were above the 1981 to 2001 mean, with mean temperatures of 6.5, 6.9 e 6.8°C respectively. Apparently, the increase in precipitation was not sufficient to counterbalance the warmer summer periods, even if uncertainties about SCF remains and further investigations are needed. Furthermore, the use of Peio and Cogolo weather stations yielded contrasting results, and similar observations have been reported on an annual basis for other stations of Trentino (Bellin & Zardi, 2004). Also in the 2001 IPCC report for the period 1977-1999, there are not clear indications for the Trentino region.

By contrast, a temporal redistribution of precipitation inputs is clearer, with a winter-time decrease and an autumn increase, as observed elsewhere in the south-central Alps (Auer, 2003; Bellin & Zardi, 2004, Mitchell & *alii*, 2004). This redistribution, associated with an increase of temperatures and a corresponding decrease in the fraction of solid precipitation, could explain the recent reduction of snowfall in mid- and low-altitude stations or in glaciers at lower elevations (Valt & *alii*, 2005; Cagnati & *alii*, 2002). At the Careser glacier mean elevation, instead, the october-may snowfall amount doesn't show any tendency, whereas a decrease of solid precipitation in the ablation season is evident.

RECENT CHANGES IN GLACIER MORPHOLOGY AND GEOMETRY

The dramatic mass loss experienced by the Careser glacier during the last years resulted in huge morphological changes. The presence of separating septa can be inferred by the widespread emersion of bedrock, and the fragmentation of the glacier into at least 3 portions is to be expected in the next years. In Summer 2005, the separation of the western accumulation basin from the main glacier occurred. Consequently, this western portion can be now regarded as a separate glacier (fig. 5). This is located into a

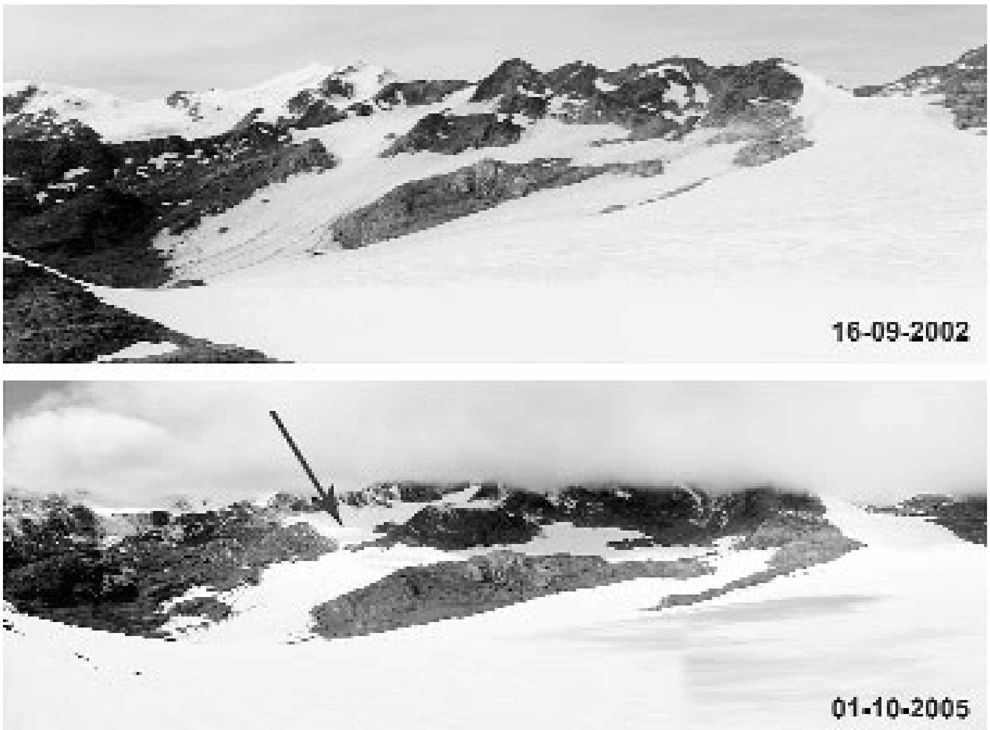

FIG. 5 - Photographic comparison between 2002 and 2005. The arrow indicates the recently detached portion, named «Ghiacciaio Occidentale del Careser».

gentle-sloping cirque facing SE, ranges from 3050 to 3310 m a.s.l., with a mean altitude of 3158 m a.s.l and has a surface of 34.4 ha. For this «new» glacier we here suggest the name «Ghiacciaio Occidentale del Careser». In the 2004-2005 hydrological year the mass balance calculated for this glaciological unit was –1689 mm we, while in the same period the mass balance of the whole glacier was –2005 mm we. This suggests that the Ghiacciaio Occidentale del Careser is still far from equilibrium.

The glacier snout is no longer in contact with the proglacial lakes and with the roches moutonnees located along the right flank of the frontal area. The collapse of some sub-glacial cavities in the frontal area is currently causing a strong, rapid withdraw of the snout, of some tens of meters per year. The glacier is currently unfed, and persists as a stagnant ice mass. The large snout retreat, therefore, should not be interpreted as a dynamic response.

The central nunatak has almost doubled its extension since 1990 and new, large portions of bedrock emerged in the eastern accumulation basin in 1998, indicating the presence of a rocky step at about 3050 m a.s.l. In the highest sector of the glacier, were ice thickness was lower, large portions completely disappeared in the last few years and now the connection with the neighbouring Serana glacier (Val Martello) is interrupted.

From the comparison of the hypsometric curves (fig. 6), the changes in glacier geometry since 1967 can be evaluated. The glacier lost 40% of its surface from 1967 to 2003, and by 2005 the reduction rises to 47%, with the detachment of the western accumulation basin. Even if little changes affected maximum and minimum elevations, the hypsographic distribution of area with altitude shows a remarkable variation. The progressive lowering of the surface and the loss of large sectors at the head of the glacier reduced both the average and the median altitudes, which dropped from 3080 m to 3060 m and from 3090 m to 3071 m, respectively. This behaviour is not consistent for a glacier that is dynamically adjusting its geometry to climate changes. Probably this has to be ascribed to the shape of the basin that allowed a thicker ice-depth to accumulate in the lower part of the accumulation basin, close to the LIA's mean ELA. Recent geophysical surveys confirm this hypothesis (Forieri & *alii*, 1999).

DISCUSSION

The quick deglaciation of the Careser basin seems to be related to a constant increase in the ablation season length and intensity. No clear trends can be observed in the October-May precipitation amount. However, accumulation rarely plays an important role in the annual mass balance, as observed in earlier studies (Zanon, 1982). Probably this has to be ascribed to the glacier hypsometry and to the geographic location near to the inner dry Alpine zone (Schwarb, 2000; Schwarb & *alii*, 2001), and main source of nourishment (directly accumulated and wind-drifted snow).

Since the 1980s ablation seasons have often been warmer and longer than in the first 13 years of mass balance observations, which exhibited near-equilibrium conditions. In many cases, ablation started early in May and was still active in the first decade of October. In addition, repeated and strong heat waves affected the Alps

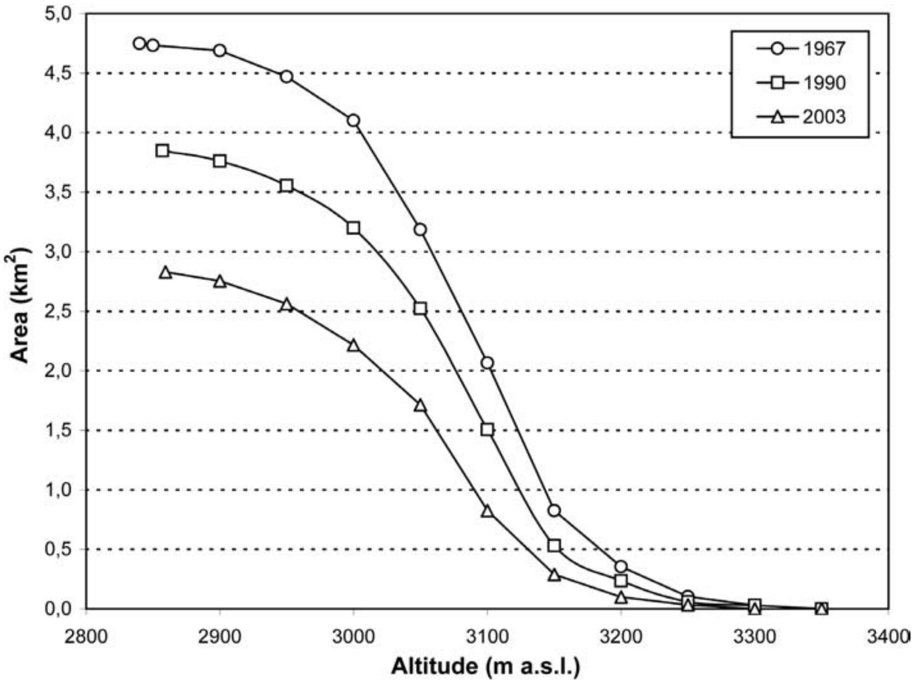

FIG. 6 - Hypsometric distribution of area versus altitude in 1967, 1990 and 2003.

from June to August, as a consequence of robust and persistent blocking high pressure systems (Beniston & Diaz, 2004; Schär & *alii*, 2004). Cool weather periods during summer were too short and lead by the rapid passage of cold fronts bringing intense but brief thunderstorms. Low pressure systems with cool weather were extremely infrequent. Heavy summer snowfalls, that could significantly reduce ablation or completely stop it at higher altitudes or on northward exposed surfaces (Kuhn & *alii*, 1999; Oerlemans & Klok, 2004; Arnold & *alii*, 1996), were also rare.

Consequently, in the last years the winter snow cover completely disappeared early in the summer and, in the more extreme cases (e.g. summer 2003 and 2005), the vanishing of the snow has been observed at the end of June or in the first days of July. The bare ice was, therefore, frequently exposed to melt for two or three months, with melt rates often exceeding 5 cm day^{-1} and sometimes reaching 8-9 cm day^{-1} from late July to mid August.

The mass balance distribution (fig. 2) is typically altitude-dependent (average mass balance gradient: 5 mm we m^{-1}) and almost exclusively caused by ablation, since accumulation doesn't show a clear relationship with elevation. A marked asymmetry is noticeable between the eastern and western sectors and, at the same altitude, ablation is higher for SE exposed areas with respect to SW exposed ones. This behaviour is poorly related to accumulation and could be explained by taking into account the diurnal cloud cover cycle during summer, which has a typical morning minimum and a late-afternoon maximum. A preliminary application of a distributed snow- and ice-melt model that combines air temperature and potential clear sky solar radiation, already tested in a glacial environment (Cazorzi & *alii*, 2005), provided elements that would support this hypothesis.

The mass balance gradient is markedly variable from year to year. It reaches a maximum with significant summer snowfalls or firn-coverage at high altitudes, and a minimum with early disappearance of snow-cover, lack of summer snowfalls and high ablation rates in late summer.

Current winter accumulation is totally insufficient to counterbalance the increased ablation, which at present is 140% larger than accumulation. Since ice-melt rate is roughly 1.5 times that for snow (Braithwaite & Zhang, 2000), we can estimate that an increase of 90-100% in winter precipitations would be required to return to equilibrium conditions. In fact, in 2000/01, such an increase effectively lead to a near-zero mass balance.

The rate of deglaciation now appears to accelerate, and this is indicative of an accentuation of the climate forcing. Meteorological records support this trend even if some positive feedback effects increase the climate sensitivity of Careser glacier. These are mainly a reduced albedo, due to the lack of firn-covered areas, and the effects induced by the geometry changes. Careser glacier has always been extremely sensitive to ELA's fluctuations (Zanon, 1982) because of its area versus altitude distribution. Recent geometry changes (i.e. surface lowering, drop of mean altitude and large area losses at highest elevations) indicate that the glacier is no more able to adjust to the present-day climate conditions.

We calculated both the present-day and the 1967 ELA at equilibrium conditions (ELA_0), by taking into account the mass balance gradient and the hypsometry (Benn & Gemmel, 1997; Furbish & Andrews, 1984). To do this, we assumed a constant balance rate of 5 mm we m^{-1} both in accumulation and ablation area, according to earlier studies (Zanon, 1982) and our observations. We found that current AAR at equilibrium conditions (AAR_0) is 0.54, whereas 1967 AAR_0 was 0.49, as confirmed by the first 13 years of measurements. This indicates that, for the present-day glacier geometry, an ELA of 3063 m would be required to reach steady-state conditions. In 1967-1980 an ELA of 3090-3100 m was sufficient.

The trend of current climate change recorded by Careser glacier is surely accentuated by marked sensitivity and non-linear reactions, but is consistent with the signal provided by the W.G.M.S. sample of 30 glaciers in America and Eurasia, for which continuous mass balance records are available from 1980 to 2003 (IUGG-UNEP-UNESCO-WMO, 2005).

CONCLUSIONS

At present-day climate conditions, Careser glacier is expected to rapidly break up and completely vanish within a few decades. It still persists due to the huge amount of ice accumulated during the LIA. Since 1981, the glacier has no accumulation area, and the ELA is commonly located above the maximum altitude, with few exceptions. This rapid deglaciation can mainly be ascribed to the progressively longer and warmer ablation seasons and to the lack of summer snowfall. The winter accumulation rates seem to play a minor role.

The repeated, strongly negative mass balances are causing huge changes in the glacier geometry, which lead to a 20 m lowering of the mean glacier elevation from 1967 to 2003 and to the detachment of a 34.4 ha sector in 2005. Important effects emphasize the reactions to climate forcing, in particular albedo and hypsographic distribution of area with altitude, which determinate positive feedbacks with respect to radiative and turbulent heat fluxes. These non-linearities have to be taken into account if the entire mass balance series has to be considered. Positive and negative feedbacks are expected to become clearer in the next future, if the present-day climate forcing continues. Their observation would represent a useful tool, also for mass balance modelling.

A substantial adaptation of the monitoring network would be required if further morphological changes and fragmentation happen. Notwithstanding, we think that the monitoring activity must continue, because it represents a precious tool to observe and describe the rapid deglaciation process of a glacierized alpine catchment.

REFERENCES

ARNOLD N.S., WILLIS I.C., SHARP M.J., RICHARDS K.S. & LAWSON W.J. (1996) - *A distributed surface energy-balance model for a small valley glacier. I. Development and testing for Haut Glacier d'Arolla, Valais, Switzerland*. Journal of Glaciology, 42, 77-89.

AUER I. (2003) - *The instrumental period in the greater alpine region*. Public session of the ALP-IMP meeting, May 5th to 6th 2003, Vienna. http://www.zamg.ac.at/alpimp (last accessed 15 November 2006).

BASSAN D. (2006) - *Ricostruzione e analisi di serie termo-pluviometriche per la determinazione della frazione di precipitazione nevosa in Val di Peio (TN)*. Unpublished degree thesis, Fac. Sc. M.F.N., University of Padova, 185 pp.

BELLIN A. & ZARDI D. (2004) - *Analisi climatologica di serie storiche delle precipitazioni e temperature in Trentino*. Quaderni di Idronomia Montana, 23, 260 pp.

BENISTON M. & DIAZ H.F. (2004) - *The 2003 heat wave as an example of summers in a greenhouse climate? Observations and climate model simulations for Basel, Switzerland*. Global and Planetary Change, 44, 73-81.

BENN D.I. & GEMMELL A.M.D. (1997) - *Calculating equilibrium-line altitudes of former glaciers by the balance ratio method: a new computer spreadsheet.* Glacial Geology and Geomorphology, http://ggg.qub.ac.uk/ggg/ (last accessed 15 November 2006).

BRAITHWAITE R.J. & ZHANG Y. (2000) - *Sensitivity of mass balance of five Swiss glaciers to temperature changes assessed by tuning a degree-day model*. Journal of Glaciology, 46, 7-13.

CAGNATI A., VALT M. & TAURISANO A. (2002) - *Il monitoraggio dei ghiacciai dolomitici*. Neve e Valanghe, 45, 6-13.

CAZORZI F., CARTURAN L. & DALLA FONTANA G. (2005) - *Simulazione della fusione in ambiente glaciale con un modello distribuito ad indice morfoenergetico*. L'acqua, 3/2005, 23-32.

DYURGEROV M. (2002) - *Glacier mass balance and regime: data of measurements and analysis*. Mark Meier (INSTAAR) & Richard Armstrong (NSIDC) editors, 88 pp.

FORIERI A., PETTINICCHIO P., ROSSI G.C., TABACCO I., TOSI N., VERONESE L. & ZANON G. (1999) - *Modelling the evolution of the Careser glacier (Ortles-Cevedale Group) in 1970-1990*. European Journal of Environmental and Engineering Geophysics, 3, 245-264.

FOUNTAIN A.G., JANSSON P., KASER G. & DYURGEROV M. (1999) - *Summary of the workshop on methods of mass balance measurements and modelling, Tarfala, Sweden August 10-12, 1998*. Geografiska Annaler, 81A, 461-465.

FURBISH D.J. & ANDREWS J.T. (1984) - *The use of hypsometry to indicate long-term stability and response of valley glaciers to changes in mass transfer.* Journal of Glaciology, 30, 199-211.

GIADA M. & ZANON G. (1991) - *Variazioni di livello e volumetriche sulla vedretta del Careser (Gruppo Ortles-Cevedale) tra il 1980 e il 1990.* Geografia Fisica e Dinamica Quaternaria, 14, 221-227.

GIADA M. & ZANON G. (1996) - *Elevation and volume changes in the Careser glacier (Ortles-Cevedale group, Central Alps), 1967-1990.* Zeitschrift für Gletscherkunde und Glazialgeologie, 31, 143-147.

GIADA M. & ZANON G. (2001) - *Caratteri delle modificazioni areali, di livello e volumetriche per il Ghiacciaio del Caresèr (alto bacino del Noce-Adige, Gruppo Ortles-Cevedale) tra il 1990 e il 1997*. Geografia Fisica e Dinamica Quaternaria, Supplementi, 5, 129-146.

IPCC (2001) - *Climate Change 2001: The Scientific Basis. Contribution of Working Group I to the Third Assessment Report of the Intergovernmental Panel on Climate Change*. Cambridge University Press, Cambridge, 881 pp.

HYDROGRAPHISCHER DIENST IN ÖSTERREICH (2006) - *Hydrographisches Jahrbuch von Österreich 2003*. Band 111, 8-9.

IUGG (CCS)-UNEP-UNESCO-WMO (2005) - *Glacier Mass Balance Bulletin. Bulletin No. 8 (2002-2003)*. HAEBERLI W., NOETZLI J., ZEMP M., BAUMANN S. & FRAUENFELDER R. (editors), 100 pp.

JANSSON P. (1999) - *Effects of uncertainties in measured variables on the calculated mass balance of Storglaciaren*. Geografiska Annaler, 81 A, 633-642.

KASER G., FOUNTAIN A. & JANSSON P. (2003) - *A manual for monitoring the mass balance of mountain glaciers*. IHP-VI, 59, 107 pp.

KUHN M., DREISEITL E., HOFINGER S., MARKL G., SPAN N. & KASER G. (1999) - *Measurements and models of the mass balance of Hintereisferner*. Geografiska Annaler, 81 A, 659-670.

MITCHELL T.D., CARTER T.R., JONES P.H., HULME M. & NEW M. (2004) - *A comprehensive set of high-resolution grids of monthly climate for Europe and the globe: the observed record (1901-2000) and 16 scenarios (2001-2100)*. Tyndall Centre for Climate Change Research, Working Paper 55.

OERLEMANS J. (2001) - *Glaciers and climate change*. Balkema, Lisse, 148 pp.

OERLEMANS J. & KLOK E.J. (2004) - *Effect of a summer snowfall on glacier mass balance*. Annals of Glaciology, 38, 97-100.

OSTREM G. & BRUGMAN M. (1991) - *Glacier mass-balance measurements, a manual for field and office work*. N.H.R.I. Science Report, 4, 224 pp.

SCHÄR C., VIDALE P.L., LÜTHI D., FREI C., HÄBERLI C., LINIGER M.A. & APPENZELLER C. (2004) - *The role of increasing temperature variability in European summer heatwaves*. Nature, 427, 332-336.

SCHWARB M. (2000) - *The alpine precipitation climate. Evaluation of a high-resolution analysis scheme using comprehensive rain-gauge data*. Dissertation submitted to the Swiss Federal Institute of Technology Zurich, No. 13911, 131 pp.

SCHWARB M., DALY C., FREI C. & SCHÄR C. (2001) - *Mean annual precipitation throughout the European Alps 1971-1990*. In: *Hydrological Atlas of Switzerland*. Landeshydrologie, Bundesamt für Wasser und Geologie, Bern.

SMITH W.H.F. & WESSEL P. (1990) - *Gridding with continuous curve splines in tension*. Geophysics, 55, 293-305.

VALT M., CAGNATI A., CREPAZ A. & MARIGO G. (2005) - *Neve sulle Alpi italiane*. Neve e Valanghe, 56, 24-31.

ZANON G. (1970) - *Studi sul bilancio di massa del ghiacciaio del Careser (Alpi Centrali). Risultati per le annate 1966-67 e 1967-68*. Bollettino del Comitato Glaciologico Italiano, ser. 2, 18, 11-16.

ZANON G. (1982) - *Recent glaciological research in the Ortles-Cevedale region (Italian Alps)*. Geografia Fisica e Dinamica Quaternaria, 5, 75-81.

ZANON G. (1992) - *Venticinque anni di bilancio di massa del ghiacciaio del Careser, 1966-67/1990-91*. Geografia Fisica e Dinamica Quaternaria, 15, 215-220.

(Ms. received 15 December 2006; accepted 15 March 2007)