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WILFRIED HAEBERLI (*)

GLACIER FLUCTUATIONS AND CLIMATE CHANGE DETECTION

ABSTRACT: HAEBERLI W., *Glacier fluctuations and climate change detection.* (IT ISSN 0391-9838, 1995).

Observed glacier fluctuations contribute important information about rates of change in energy fluxes at the earth/atmosphere-interface, possible acceleration trends in the development and the range of pre-industrial variability. Both, the mass balance as the direct, undelayed signal as well as the cumulative length change as a clear but indirect, delayed, filtered and strongly enhanced signal, have a remarkable memory function and should be used in combination for worldwide glacier monitoring in view to climate change detection.

Mean annual mass losses measured for the period 1980-1993 on 35 glaciers in 11 mountain ranges of North America, Eurasia and Africa are close to three decimeters water equivalent. This amount reflects an additional energy flux of about 3 W/m² and roughly corresponds to the estimated man-induced radiative forcing. In the European Alps, the directly measured glacier mass balances during 1980-1990 were especially negative and comparison with holocene records of cumulative glacier length changes as reconstructed from moraine investigations indicates that the «warm» limit of the pre-industrial variability range is now reached at least with respect to the past about 5,000 years.

KEY WORDS: Glacier fluctuations, Climate change, Energy flux, Monitoring.

RIASSUNTO: HAEBERLI W., *Oscillazioni glaciali e rilevamento di cambiamenti climatici.* (IT ISSN 0391-9838, 1995).

Le oscillazioni glaciali osservate forniscono importanti informazioni sui tassi di cambiamento nei flussi di energia all'interfaccia terra/atmosfera e loro eventuale accelerazione sul tasso della variabilità prima dell'epoca dell'industria. Sia il bilancio di massa, che il cambiamento della lunghezza cumula hanno un'importante funzione di archivio e dovrebbero essere usati entrambi per la sorveglianza a livello mondiale dei ghiacciai, in un'ottica di rilevamento dei cambiamenti climatici. Il primo come segnale diretto, indelebile, il secondo come segnale chiaro ma indiretto, obliterabile, filtrato ed esagerato.

Le perdite di massa media annuali misurate per il periodo 1980-1993 in 35 ghiacciai di 11 catene montuose del Nord America, dell'Eurasia e dell'Africa sono prossime all'equivalente di tre decimetri d'acqua. Questa quantità riflette un flusso di energia addizionale di circa 3 W/m² e grosso modo corrisponde all'incremento radiattivo stimato indotto dall'uomo. Nelle Alpi Europee, i bilanci di massa dei ghiacciai direttamente misurati nel periodo 1980-1990 furono in particolar modo negativi, tanto che il confronto con i valori olocenici dei cambiamenti della lunghezza glaciale, ricostruita tramite studi su depositi morenici, indica che il limite «caldo» del tasso di variabilità pre-industriale è stato attualmente già raggiunto, almeno rispetto agli ultimi 5.000 anni circa.

TERMINI CHIAVE: Fluttuazioni glaciali, Variazioni climatiche, Flussi di energia, Monitoraggio.

INTRODUCTION

Central aspects connected with detection of climate change caused by anthropogenic greenhouse forcing include

a) secular rates of change in energy fluxes at the earth/atmosphere-interface,

b) natural (pre-industrial) variability in these energy fluxes, and

c) possible acceleration trends of ongoing and potential future changes.

Observed glacier fluctuations contribute important information about all three aspects. In fact, glacier fluctuations in cold mountain areas result from changes in the mass and energy balance at the earth's surface. Rates and ranges of such glacier changes can be determined quantitatively over various time intervals and expressed as corresponding energy fluxes with their long-term variability. This permits direct comparison with other effects of natural and estimated anthropogenic greenhouse forcing. In addition, glacier changes are linked to changing atmospheric conditions via important filters, such as pronounced memory and enhancement functions. As a consequence, glacier changes are among the clearest signals of ongoing warming trends existing in nature. Both, glacier mass balance as the direct/undelayed signal and glacier length change as an indirect/delayed signal (fig. 1), should be applied in combination for worldwide glacier and climate system monitoring (HAEBERLI & *alii*, 1989, WOOD, 1990). The following briefly explains the basic strategy for internationally

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(*) *Geographisches Institut, Universität Zürich, Winterthurerstrasse 190, CH-8057 Zürich.*

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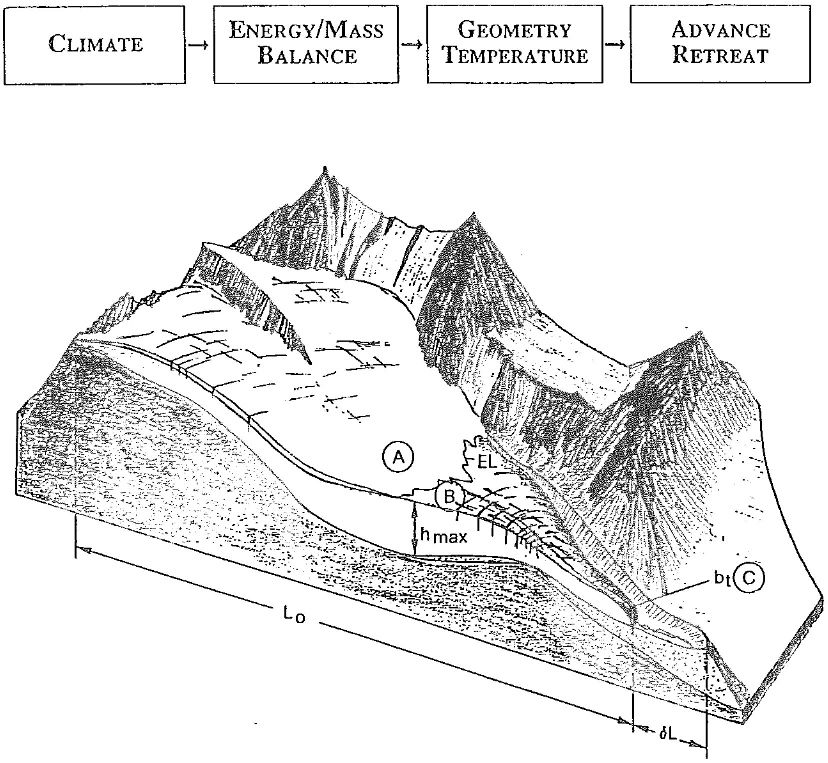

FIG. 1 - Schematic scheme of the processes linking climate and glaciers with the most important parameters used for quantifying long-term mass changes from cumulative length changes (advance/retreat of glacier tongues, cf. text for explanation of symbols; A, B, C = minimum array of stakes/pits for determination of specific mass balance with the linear balance model and repeated mapping).

TABLE 1 - Geodetically/photogrammetrically determined secular mass balances of Alpine glaciers

Glacier	observation period	coordinates	median elevation m.a.s.l.	surface area km²	b m/a w.e.
Rhone	1882-1987	4637/0824	2940	17.38	— 0.25
Vernagt	1889-1979	4653/1049	3228	09.55	— 0.19
Guslar	1889-1979	4651/1048	3143	03.01	— 0.26
N Schnee	1892-1979	4725/1059	2690	00.39	— 0.35
S Schnee	1892-1979	4724/1058	2604	00.18	— 0.57
Hintereis	1894-1979	4648/1046	3050	09.70	— 0.41

Sources: CHEN & FUNK (1990), FINSTERWALDER & RENTSCH (1990), IAHS (ICSI)/UNEP/UNESCO (1988).

coordinated observations and data analysis by mainly using the example of the well-documented Alpine glaciers for illustration (cf. HAEBERLI, 1994, 1995).

Worldwide collection of standardized observations on changes in mass, volume, area and length of glaciers with time (glacier fluctuations), as well as statistical information on the distribution of perennial surface ice in space (glacier inventories) is being coordinated by the World Glacier Monitoring Service (WGMS). The tasks of WGMS are

1) to continue collecting and publishing standardized data on glacier fluctuations at 5-yearly intervals,

2) to complete and continuously upgrade an inventory of the world's glaciers,

3) to publish results of mass balance measurements from selected reference glaciers at 2-yearly intervals,

4) to include satellite observations of remote glaciers in order to reach global coverage, and

5) to periodically assess ongoing changes.

This work is being carried out under the auspices of the International Commission on Snow and Ice (ICSI/IAHS), the Federation of Astronomical and Geophysical Data Analysis Services (FAGS/ICSU), the Global Environment Monitoring System (GEMS/UNEP) and the Division of Water Sciences of UNESCO. Data from WGMS are periodically published (for instance IAHS(ICSI)/UNEP/UNESCO, 1989, 1993a, 1993b, cf. also UNEP 1992) and flow into the World Data Center (WDC-A) for Glaciology (Boulder/Colorado) and the Global Resources Information Database (GRID of GEMS/UNEP).

GLACIER MASS BALANCE

In ablation areas and areas of temperate firn (which predominate at lower latitudes/altitudes and in regions with humid climatic conditions), atmospheric warming mainly causes changes in mass and geometry of glaciers. An assumed step change (δ) in equilibrium line altitude (ELA = the altitude on a glacier where the annual addition (accumulation) of mass is exactly compensated by the annual disappearance (ablation) of mass) induces an immediate step change in specific mass balance (b = total mass change divided by glacier area). The resulting change in specific mass balance (δb) is the product of the shift in equilibrium line altitude (δELA) and the gradient of mass balance with altitude (db/dH) as weighed by the distribution of glacier surface area with altitude (hypsometry). The hypsometry represents the local/individual or topographic part of the glacier sensitivity whereas the mass balance gradient mainly reflects the regional or climatic part (KUHN, 1990). As the mass balance gradient tends to increase with increasing humidity (KUHN, 1981), the sensitivity of glacier mass balance with respect to changes in equilibrium line altitude is generally much higher in areas with humid/maritime than with dry/continental climatic conditions (OERLEMANS, 1993a). Cumulative mass changes lead to ice thickness changes which, in turn, exert a positive feedback on mass balance and at the same time influence the dynamic redistribution of mass by glacier flow.

Long-term mass balance measurements optimally combine the geodetic/photogrammetric with the direct glaciological method in order to determine changes in volume/mass of entire glaciers (repeated mapping) with high temporal resolution (annual measurements at stakes and pits). The primary goals of such systematic observations are usually to

1) determine the annual specific balance as a regional signal,

2) to understand in detail the processes of energy and mass exchange at glacier surfaces.

The annual specific balance as a *regional signal* can be obtained most economically using geodetic/photogrammetric volume change determinations repeated at time intervals of several years to a few decades (tab. 1) with or without annual observations on a minimum of three strategically selected index stakes (fig. 1): two stakes should be monitored near the equilibrium line where the surface area is most extended and one near the glacier front to determine ablation gradients and to quantitatively interpret length changes over extended time periods as explained below. Data interpretation can be made by applying a simplified version of the linear balance model (REYNAUD & *alii*, 1986) which assumes the mass balance variation at each point of the glacier to be proportional to the mass balance variation of the entire glacier. This concept is an important working tool building on the basic experience that the spatial distribution of mass balance often remains highly similar from year to year: the temporal variability in db/dh remains small close to the average equilibrium line altitude where surface area and, hence, the influence on the overall mass balance of a glacier is largest. The third stake recommended for a minimum stake network should be installed at the glacier terminus in order to keep control on the reliability of the linear balance model and to introduce adequate corrections if necessary (KUHN, 1984, OERLEMANS & HOOGENDORN, 1989).

Mass balance studies for improvement of the *process understanding* with respect to energy and mass fluxes at glacier surfaces require extensive stake networks to be maintained and seasonally observed at the end of both the (winter) accumulation as well as the (summer) ablation period. Even with high densities of stakes and pits, the absolute values of volume/mass change must be carefully calibrated by repeated geodetic/photogrammetric mapping, because the representativity of the monitored (stake/pit-) network with respect to the entire glacier can otherwise not easily be assessed: especially crevassed areas with their enlarged surfaces tend to escape the direct glaciological analysis. Process-oriented mass balance observations are, thus, expensive and time consuming. As a consequence, they should concentrate on characteristic effects of climatic variability. Mass balance gradients and their temporal changes under conditions of maritime/continental, tropical/polar climates etc., as well as their long-term evolution with potential climatic changes are of primary interest with respect to 2-dimensional considerations and models (OERLEMANS, 1993b). The 3-dimensional distribution of mass balance patterns as a function of energy balance components such as snowfall, snow redistribution, solar radiation, sensible heat flux etc. are nowadays investigated with digital terrain models and corresponding calculations of solar radiation, air temperature etc. (ESCHER-VETTER, 1985; FUNK, 1985). An ultimate goal of such investigations is to parameterize unmeasured glaciers and, thus, to better describe ongoing changes at a worldwide scale.

Secular mass balances have been measured for six glaciers in the European Alps by repeated precision mapping since the late 19th century (tab. 1). The average annual mass loss over the entire period varies between about 0.2 and 0.6m water equivalent. Such values reflect an additional energy flux towards the earth surface of a few W/m^2 and, hence, roughly correspond to the estimated anthropogenic greenhouse forcing (IPCC, 1992; UNEP, 1994). The overall loss in Alpine ice thickness since the end of the Little Ice Age is measured in tens of meters.

GLACIER LENGTH CHANGE

The complex chain of dynamic processes linking glacier mass balance and length changes is at present numerically simulated for only a few individual glaciers, which have

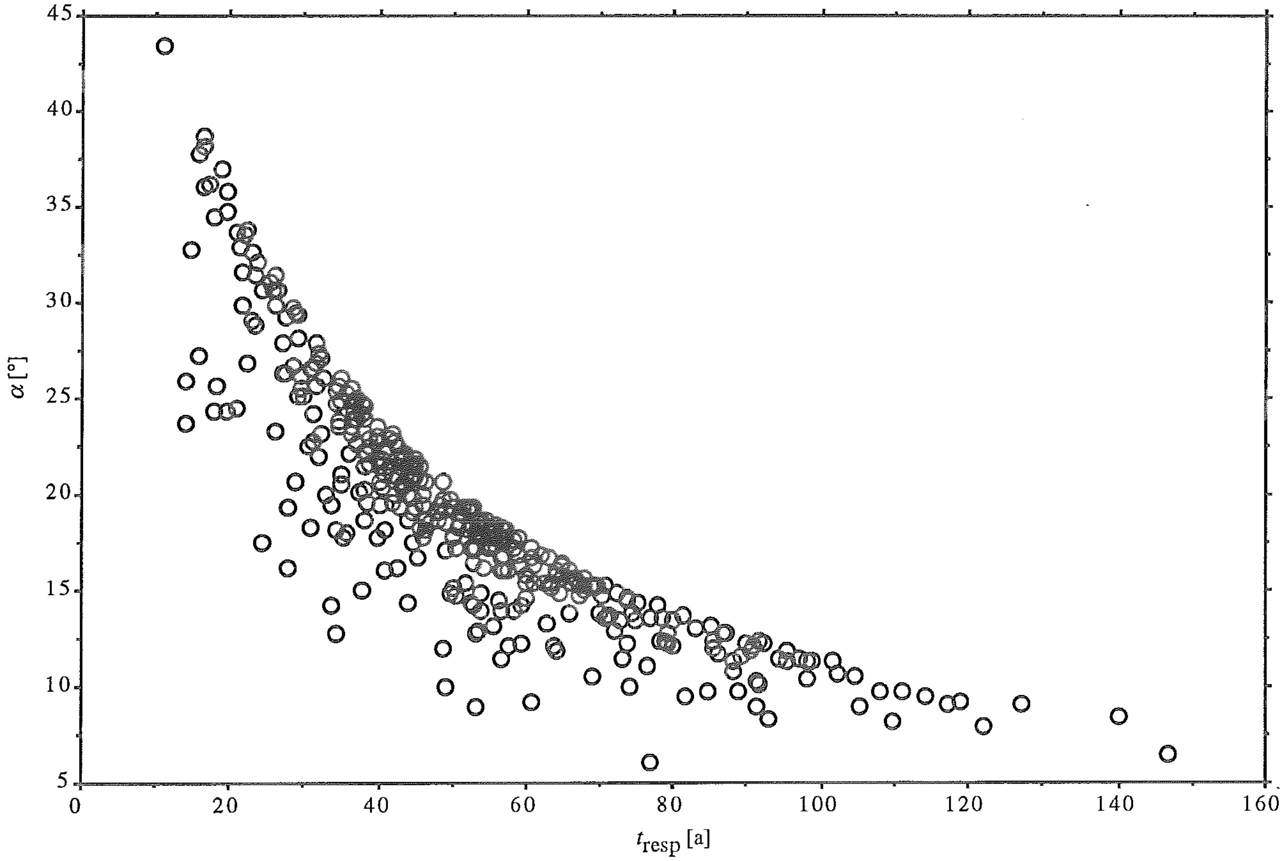

FIG. 2 - Response times t_{resp} as a function of average surface slope α for Alpine glaciers longer than 2 km (from HAEBERLI & HOELZLE 1995).

been studied in great detail (cf., for instance, KRUSS, 1983, OERLEMANS, 1988, OERLEMANS & FORTUIN, 1992, GREUELL, 1992). Most complications, however, disappear if the time intervals analyzed are sufficiently long. After a certain reaction time (t_r) following a change in mass balance, the length of a glacier (L_o) will start changing and finally reach a new equilibrium ($L_o + \delta L$) after the response time (t_a). After full response, continuity requires that (NYE 1960).

$$\delta L = Lo * \delta b / b_t \qquad (1)$$

with b_t = (annual) ablation at the glacier terminus. This means that, for a given change in mass balance, the length change is a function of the original length of a glacier and that the change in mass balance of a glacier can be quantitatively inferred from the easily observed length change and from estimates of b_t as a function of ELA and db/dH. The response time, t_{resp}, of a glacier is related to the ratio between its maximum thickness (h_{max}) and its annual ablation at the terminus (JOHANNESSON & *alii*, 1989).

$$t_{resp} = h_{max} / b_t \qquad (2)$$

Corresponding values for Alpine glaciers are typically several decades (fig. 2). During the response time, the mass balance b will adjust to zero again so that the average mass balance <b> is 1/2*δb for a linear development. Secular glacier mass changes estimated in this way can be directly compared with the few measured long-term mass balance series existing in the Alps (tab. 2) - cumulative glacier length change clearly is a key phenomenon for assessing the representativity in space and time of the few measured glacier mass balances.

The remarkable signal characteristics of glacier length changes immediately appear by looking at cumulative values and different size categories (fig. 3):

1) the smallest, somewhat static, low-shear-stress glaciers (cirque glaciers, «glaciers réservoirs») reflect yearly changes in climate and mass balance almost without any delay;

2) larger, dynamic, high-stress glaciers (mountain glaciers, «glaciers évacuateurs») dynamically react to decadal variations in climatic and mass balance forcing with an enhanced amplitude after a delay of several years;

3) the largest valley glaciers give strong and most efficiently smoothed signals of secular trends with a delay of several decades.

For the latter two size categories, the high-frequency (interannual) «noise» is filtered out but the «memory» of all major perennial ice bodies enables cumulation of effects for decades to centuries. Moreover, the secular thickness change of a few tens of meters is «amplified» into a length change measured in hundreds to thousands of meters. The extreme

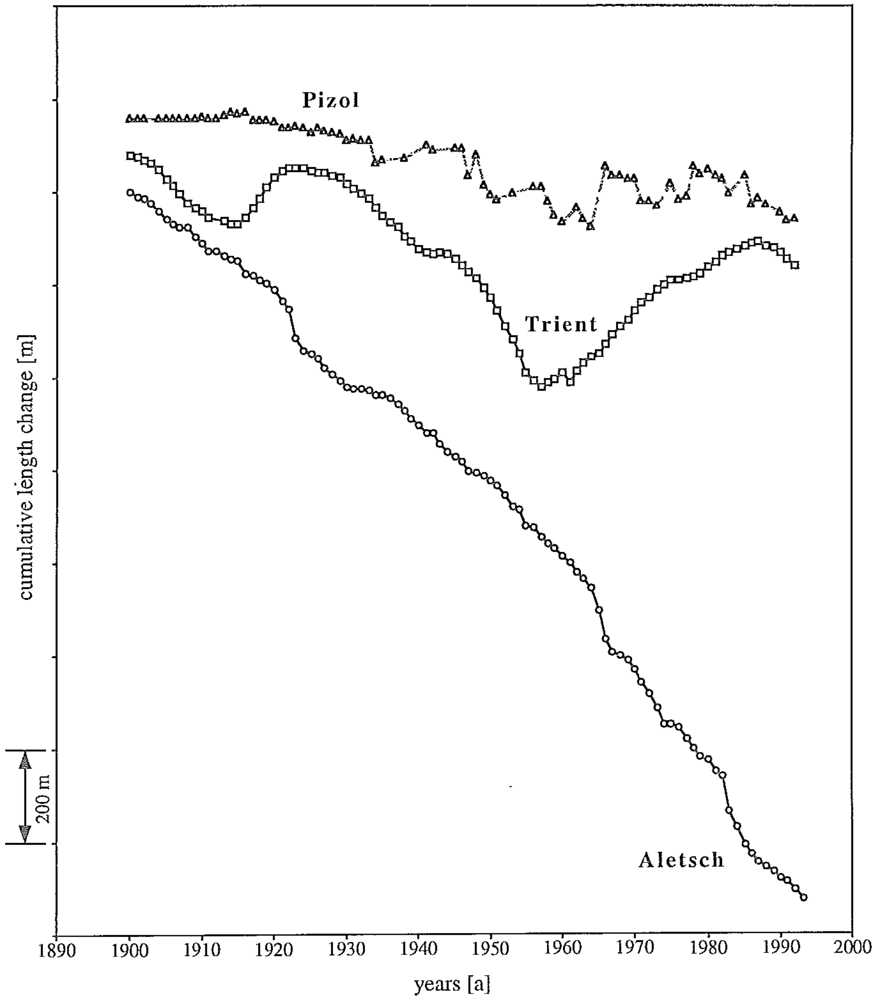

FIG. 3 - Cumulative length changes since 1900 of 3 characteristic glacier types in the Swiss Alps. Small cirque glaciers such as Pizol Glacier have low basal shear stresses and directly respond to annual mass balance and snowline variability through deposition/melting of snow/firn at the glacier margin. Medium-size mountain glaciers such as Trient Glacier flow under high basal shear stresses and dynamically react to decadal mass balance variations in a delayed and strongly smoothed manner. Large valley glaciers such Aletsch Glacier may be too long to dynamically react to decadal mass balance variations but exhibit strong signals of secular developments. Considering the whole spectrum of glacier response characteristics gives the best information on secular, decadal and annual developments. Source: KASSER & *alii*, 1986; IAHS (ICSI)/UNEP/UNESCO, 1988, 1993; AELLEN & HERREN, 1994; AELLEN, written communication).

clarity of this signal makes it possible to apply very simple observational methods such as, for instance, repeated tape-line readings. This, in turn, enables the cooperation of numerous non-specialists with long-term measurements at several hundreds of glacier snouts all over the world. The so-collected quantitative and qualitative observations of secular glacier retreat in mountain ranges, especially at low latitudes, leave no doubt about the fact that climate change causing glacier mass loss is, indeed, fast and a global phenomenon.

GLACIER INVENTORIES

An extensive data basis on topographic glacier parameters is being built up in regional glacier inventories (IAHS(ICSI)/UNEP/UNESCO 1989). Repetition of such glacier inventory work is planned at time intervals which are comparable to characteristic dynamic response times of mountain glaciers (a few decades). This should help with analyzing changes at a regional scale and with assessing the representativity of continuous measurements which can only be carried out on a few selected glaciers. In addition, glacier inventory data also serve as a statistical basis for extrapolating the results of observations or model calculations concerning individual glaciers (OERLEMANS, 1993b, 1994) and to simulate regional aspects of past and potential future climate change effects. This latter application requires the introduction of a parameterization scheme using the four main geometric parameters contained in detailed inventories (length; maximum and minimum altitude along the central flowline; surface area) and using correspondingly simple algorithms for deriving such parameters as overall slope, mean and maximum thickness, equilibrium line altitude, mass balance at the glacier terminus, response time etc. (fig. 2).

A test study with the European Alps (HAEBERLI & HOELZLE 1995) indicates a total Alpine glacier volume of some 130 km^3 at the mid-1970es. Total loss in Alpine surface ice mass from 1850 to the mid-1970es can be estimated at about half the original value. Most of this change took place during the second half of the 19th century and the first half of the 20th century (PATZELT & AELLEN 1990), i.e. in times of weak anthropogenic forcing. The short intervals of fast warming which occurred during this period

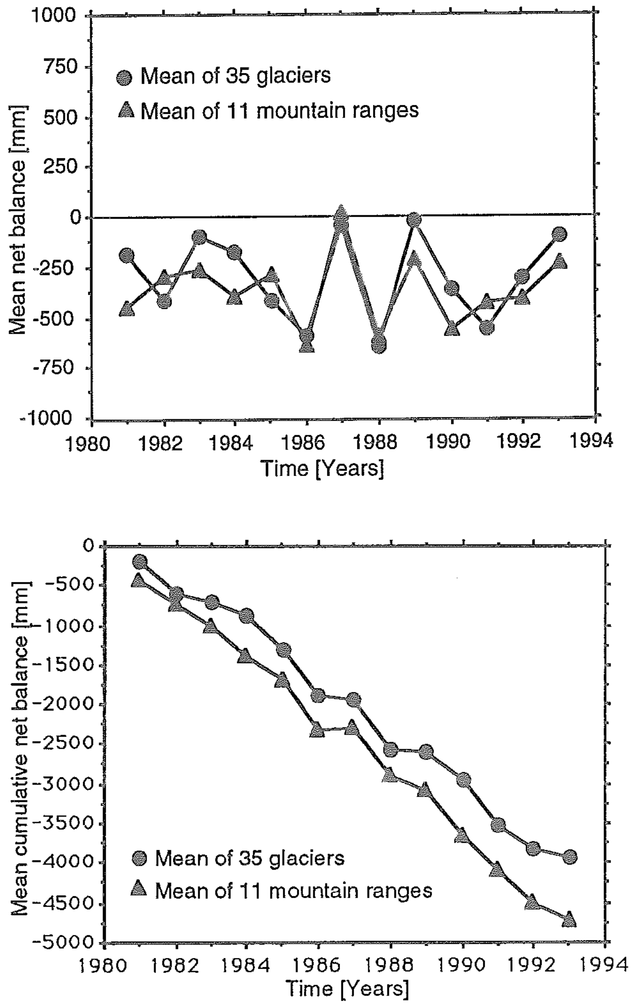

Fig. 4 - Mean net balance (top) and cumulative mean net balance (bottom) continuously measured for the period 1980 to 1993 on 35 glaciers in 11 mountain ranges (from Iahs (Icsi)/Unep/Unesco 1994).

may have been predominantly natural but could have included anthropogenic effects as well. An acceleration of this development with annual mass losses of around 1 meter per year or more as anticipated from Ipcc scenario A for the coming century could eliminate major parts of the presently existing Alpine ice volume within decades. The striking sensitivity of glacierization in cold mountain areas with respect to trends in atmospheric warming clearly appears.

DATA ANALYSIS AND MONITORING STRATEGY

Both, annual and cumulative long-term glacier mass balances can be statistically analyzed in a straightforward way. Continuous mass balance records for the period 1980-1993 are now available for 35 glaciers. The corresponding results of this sample from glaciers in North America, Eurasia and Africa is summarized in Table 3 and Fig. 4. The mean of all 35 glaciers is strongly influenced by the great number of Alpine and Scandinavian glaciers. A mean value is, therefore, also calculated using only one single (in some places averaged) value for each of the 11 mountain ranges involved. For the two years 1991/92 and 1992/93 together, the mean mass balance was negative by roughly two-tenths of a meter of water equivalent per year, a value which is about two-thirds of the decadal average 1980-1990. The proportion of positive mass balances was one-fourth of the sample. Glacier melt in the northern hemisphere, thus, continued during the two years reported but at a slightly reduced rate. It should be kept in mind, however, that the annual signal of the mean mass balance is smaller by far than the regional variability and must be improved by cumulating mass balance values over extended time periods. The mean specific net balance (-321 mm water equivalent) for the three years 1990/91-1992/93 is close to the decadal mean of 1980-1990 [-296] mm water equivalent). More detailed analyses reveal considerable spatio-temporal variability over short time periods. Decadal to secular trends, on the other hand, are comparable beyond the scale of individual mountain ranges with continentality of the climate being the main classifying factor (Letréguilly & Reynaud, 1990) besides individual hypsometric effects (Furbish & Andrews, 1984, Tangborn, & *alii*, 1990). Alpine glacier mass balances were strongly negative during the extremely warm decade 1980-1990. With an average value of -0.65 meters water equivalent (Haeberli, 1994), the Alpine ice cover may have lost about 10 to 20% of its volume as estimated for the 1970-es (Haeberli & Hoelzle, 1995). The decadal average is also markedly higher than the secular average of some 0.3 to 0.4 meters water equivalent and could possibly be an early indication of accelerating ice melt at non-polar latitudes. Extrapolating the above mentioned average secular melt rate to all glaciers and ice caps outside the large polar ice sheets of Antarctica and Greenland gives a sea level rise of some 5 to 6 cm during the 20th century (cf. Ipcc, 1992). The considerable uncertainty with such estimates is related to the problem of scaling a small number of observed values to large unmeasured areas. In firn of subzero temperatures which predominates at polar latitudes, in regions of continental climate and at very high altitudes, atmospheric warming does not directly lead to mass loss through melting/runoff but to warming of firn layers and thereby produces corresponding signals in firn/ice temperature profiles with depth (Blatter, 1987; Haeberli & Funk, 1991; Robin, 1983). On the other hand, important temperate meltwater producers such as the huge glaciers around the Gulf of Alaska or in Patagonia exist under very humid climatic conditions and, hence, react more sensitively to warming trends than the glaciers in the Alps with their transitional climate. Energy balance modelling is an important tool to develop adequate scaling (Oerlemans, 1993b). In addition to energy balance effects at stable surface altitudes, cumulative lowering of

Table 2a - Comparison of measured secular glacier mass changes (ca. 1890/1920-1980) with estimates from cumulative length change

Glacier	Rhone Glacier	Hintereisferner
measured average b (m w.e./a)	— 0.25	— 0.41
total length today (km)	10.0	7.7
estimated maximum thickness today (m)	500	400
ablation at snout (m w.e./a.)	5.5	5
estimated response time (a)	90	80
length change (km)	1.0	1.2
inferred balance change δb (m w.e./a)	— 0.55	— 0.78
inferred average b (m w.e./a)	— 0.28	— 0.39

Table 2b - Secular glacier mass loss of Great Aletsch Glacier estimated from cumulative length change

maximum thickness today (m)	900
ablation at snout (m w.e./a.)	12
estimated response time (a)	75
total length today (km)	24
length change (km, ca. 1915-1990)	1.5
inferred balance change δb (m w.e./a.)	— 0.75
inferred average b (m w.e./a.)	— 0.38

Sources: Aeellen (1979), Funk (1985), Haeberli & Hoelzle (1995), Iahs (Icsi)/Unep/Unesco (1988, 1991, 1993b), Iahs (Icsi)/Unesco (1985), and unpublished data of Vaw/Eth Zurich.

glacier surfaces usually predating the delayed retreat of glacier tongues, tends to reinforce mass losses through increased ablation. This mass-balance/altitude feed-back is especially important on large and flat glaciers which cannot dynamically adjust their length to climate change within decadal or even secular time intervals but rather waste down in place.

Analysis of short-term variations in glacier length, i.e. for time periods shorter than the involved response times, is delicate because of the complex dynamics involved. Only glaciers with comparable geometries (especially with respect to length and slope) can directly be compared (Ding & Haeberli, in press). Averaging annual length changes for glaciers with highly variable geometry, either as yearly percentages of advancing and retreating glaciers or as mean annual length changes, has been historically popular. This approach, however, mixes together information from glaciers with highly variable response characteristics and suppresses the long-term memory function of glacier fluctuations (Haeberli & *alii* 1989, Kuhn 1978).

Table 3 - Summary of continuous mass balance records measured on 35 glaciers in North America, Eurasia and Africa for the period 1980-1993

	1980-90	1991-92	1992-93
mean specific (annual) net balance:	— 296 mm	— 305 mm	— 99 mm
standard deviation:	± 485 mm	± 1156 mm	± 1045 mm
minimum value:	— 1085 mm	— 2798 mm	— 2342 mm
maximum value:	+ 683 mm	+ 2340 mm	+ 2180 mm
range:	1768 mm	4440 m	4522 mm
positive balances:	23%	20%	37%

Source: Iahs (Icsi)/Unep/Unesco (1994)

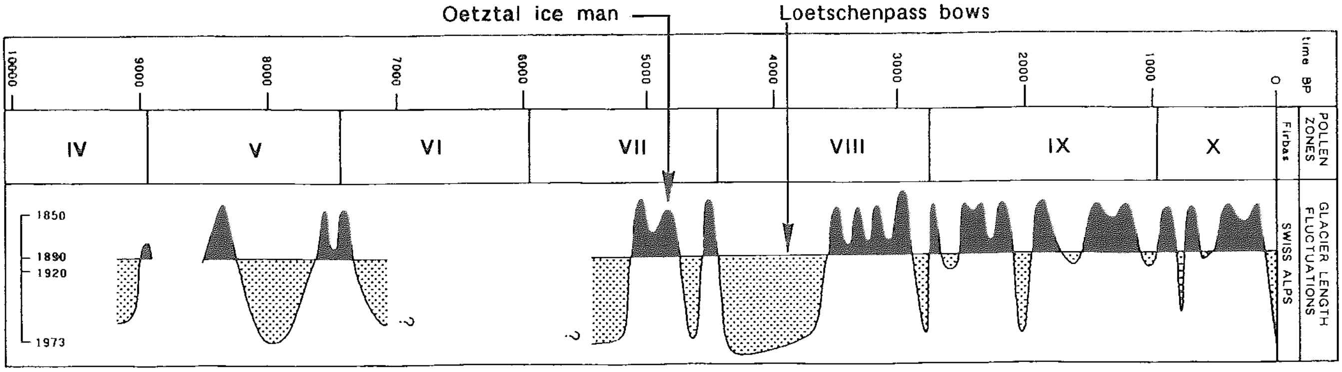

FIG. 5 - Holocene history of glacier length changes in the Alps and its relation to recent archaeological findings from melting ice in saddle configurazions (Oetztal ice man/Hauslabjoch, three bows/Lötschenpass). Modified from GAMPER & SUTER 1982) and ZUMBÜHL & HOLZHAUSER (1988). Time before present is in conventional ^{14}C years.

For time periods corresponding to the dynamic response time or to multiples of it, cumulative glacier length changes can be interpreted in terms of the average mass balance during the considered time interval. In the European Alps, for instance, such analyses confirm the representativity of the few secular glacier mass balances determined by repeated precision mapping (Table 2, cf. also HAEBERLI & HOELZLEL, 1995). The cumulative length change of glaciers, indeed, constitutes the key to global intercomparison of secular mass losses. Attempts are presently being made to collect and analyze data on maximum ice depth and ablation at the snouts of glaciers with long mass balance records in order to estimate dynamic response times and to derive long-term mass balances from cumulative length changes. It is hoped that the corresponding backward extension of mass balance records will be useful for investigating the question about secular rates of change and possible acceleration trends. Modern cumulative glacier length changes can also be compared to ranges of pre industrial and prehistoric variability which are quite well documented by moraines and other geomorphic traces. Reconstruction of past glacier length changes from direct measurements, old paintings, written sources, moraines, pollen analysis, tree-ring investigation, etc. indicates that already in earlier times glacier extent for periods had been reduced as much as today and that the rates of change observed during the 20th century were probably not uncommon for periods during the Holocene (ZUMBÜHL & HOLZHAUSER, 1988). On the other hand, Alpine glacier extent has varied over the past millennia within a range approximately defined by the extremes of the Little Ice Age maximum extent and today's reduced stage (GAMPER & SUTER, 1982, fig. 5). This means that the situation seems to be evolving towards or even beyond the «warm» limit of natural holocene variability.

Most recently, extraordinarily important evidence has also emerged from sites other than glacier snouts, i.e., from the top of glacier accumulation areas (VAW, 1993). Even at low altitudes, wind-exposed ice crests and firn/ice divides are not temperate but slightly cold and frozen to the underlying (permafrost) bedrock (HAEBERLI & FUNK, 1990). Such glaciological conditions (reduced heat flow through winter snow, no meltwather percolation, no basal sliding, low to zero basal shear stress at firn/ice divides) explain the perfect conservation of the «Oetztal ice man», whose body had been buried by snow/ice in a small topographic bedrock depression on such a crest/ saddle at Hauslabjoch (Austrian Alps; 3,200 m a.s.l.) more than 5,000 years ago and thereafter remained in place until it melted free in 1991. At an even lower altitude (2,700 m a.s.l.) but at a comparable site (Lötschenpass, Swiss Alps) three well-preserved wooden bows and a number of other archaeological objects were discovered as early as 1934 and 1944. Recent ^{14}C-AMS dating of the three bows gave dendro-chronologically corrected ages of around 4,000 years (BELLWALD, 1992). These remarkable findings confirm that warming periods comparable to the 20th century clearly have occurred before. The recent archaeological findings from melting ice in saddle configurations nevertheless confirm that the extent of glaciers and permafrost in the Alps may be more reduced today than ever before during the Upper Holocene.

The quantitative relation between mass and length changes of glaciers over secular time scales opens up the possibility for better worldwide coverage through the application of remote sensing techniques, ideally combined with energy balance models for more detailed quantitative analysis. Remote sensing could combine aerial photography, available in many regions since the 1950-es, with high-resolution satellite imagery such as Spot, Thematic Mapper, etc. The results of energy balance modelling could be applied to mass balance gradients and ablation at the terminus for quantifying retreat and mass loss of unmeasured glaciers. In this way, (semi-) secular mass balances could be estimated for remote areas and the global representativity of the few available direct measurements could be assessed. For this purpose, glaciers with optimal characteristics as «climate signals» must be selected, i.e. relatively clean glaciers with adequate response times (decades), clearly defined geometry (firn/ice divide) and stable dynamics (no avalanching, surge or calving instabilities). With accelerated warming, larger glaciers would continue downwasting rather than retreating. Repeated mapping or profiling with a combination of laser altimetry and kinematic Gps positioning would give important information in such cases, especially with regard to meltwater production and sea level rise. In fact, looking forward, systematic application of advanced remote sensing and modelling techniques appears to be the main challenge for worldwide glacier monitoring into the 21st century.

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