Published in "Geophysical Research Letters 36: L23501, 2009"
which should be cited to refer to this work.

Strong Alpine glacier melt in the 1940s due to enhanced solar radiation

M. Huss,[1,2] M. Funk,[1] and A. Ohmura[3]

[1] A 94-year time series of annual glacier melt at four high elevation sites in the European Alps is used to investigate the effect of global dimming and brightening of solar radiation on glacier mass balance. Snow and ice melt was stronger in the 1940s than in recent years, in spite of significantly higher air temperatures in the present decade. An inner Alpine radiation record shows that in the 1940s global shortwave radiation over the summer months was 8% above the long-term average and significantly higher than today, favoring rapid glacier mass loss. Dimming of solar radiation from the 1950s until the 1980s is in line with reduced melt rates and advancing glaciers. **Citation:** Huss, M., M. Funk, and A. Ohmura (2009), Strong Alpine glacier melt in the 1940s due to enhanced solar radiation,

1. Introduction

[2] Changes in climatic forcing are directly reflected by the mass budget of snow and ice surfaces (see *von Hann* [1897] and *Hock* [2005] for a review). Understanding the impact of changing climate conditions on glacier melt is a prerequisite for projections of glacier volume, changes in mountain hydrology, natural hazard frequency and sea level rise. For the last decades a rapid mass loss of mountain glaciers in response to climate warming has been reported for high and low latitudes all over the planet [*Kaser et al.*, 2006]. Glacier wastage in the 20th century was mainly attributed to changes in air temperature [e.g., *Haeberli and Beniston*, 1998; *Braithwaite and Zhang*, 1999]. Global solar radiation at the earth's surface shows significant variations over the last century profoundly affecting the climate system [*Ohmura and Lang*, 1989; *Wild et al.*, 2004, 2005]. Changes in solar radiation were rarely considered to explain cryospheric variability on decadal time scales [*Ohmura et al.*, 2007]. This is due to the scarcity of both long-term radiation measurements and unbiased time series of glacier melt.

[3] Here, we interpret a 94-year time series of annual snow and ice melt at four high elevation sites in the European Alps derived from the longest direct observations of glacier surface mass balance worldwide [*Huss and Bauder*, 2009]. We investigate possible drivers of multi-decadal changes in the glacier mass budget by putting into context the impact of variations in solar radiation given by a 73-year radiation record. Based on the presented data sets we discuss the limitations of the empirical temperature-index approach for projections of glacier melt.

2. Data and Methods

[4] The surface mass balance of alpine glaciers is mainly determined by the sum of solid precipitation and melt throughout one year. Long-term measurements of the seasonal mass balance have been carried out since 1914 at four point locations in the accumulation area of different Swiss glaciers [*Müller and Kappenberger*, 1991; *Huss and Bauder*, 2009]. Winter snow accumulation and the summer ablation, respectively, were observed almost every year. Two stakes on Claridenfirn, and one stake each on Aletschgletscher and Silvrettagletscher are surveyed (Figure 1). The sites are located between 2700 and 3350 m a.s.l.

[5] Methods of field data homogenization and analysis are described in detail by *Huss and Bauder* [2009] and are summarized hereafter. The 94-year seasonal field measurements are evaluated using a temperature-index melt model based on daily meteorological data (Figure 1). Using the model (i) field data are homogenized, and (ii) mass balance components – accumulation and melt – are separated. Daily melt rates M are calculated using air temperature $T > 0$°C as [*Hock*, 1999]

$$M = \left(f_{\mathrm{M}} + r_{\mathrm{snow/firn}} I\right) \cdot T. \quad (1)$$

f_{M} is a melt factor and $r_{\mathrm{snow/firn}}$ are radiation factors for snow and firn surfaces; the three factors are assumed to be proportional to each other [*Huss and Bauder*, 2009]. Our formulation includes the variation of potential direct clear-sky radiation I in the course of the year, the evolution of the snow cover determining the surface type and different albedo over snow and firn surfaces (equation (1)). Snow accumulation is calculated as solid precipitation corrected using a dimensionless multiplier c_{prec} and separated from the liquid state by a threshold of 1.5°C [*Hock*, 1999]. Measured daily mean air temperature and precipitation are extrapolated to the study sites assuming constant altitudinal gradients. The melt factors (f_{M}, $r_{\mathrm{snow/firn}}$) and c_{prec} are diagnosed based on the seasonal field data. This is done for each year individually, so that both the measurement of winter accumulation and summer ablation are matched by the calculated cumulative daily mass balance curve, providing annually varying parameter values for the melt factors and c_{prec} (Table S1 of the auxiliary material) [*Huss and Bauder*, 2009].[4]

[1]Laboratory of Hydraulics, Hydrology and Glaciology, ETH Zurich, Zurich, Switzerland.
[2]Department of Geosciences, University of Fribourg, Fribourg, Switzerland.
[3]Institute for Atmospheric and Climate Science, ETH Zurich, Zurich, Switzerland.

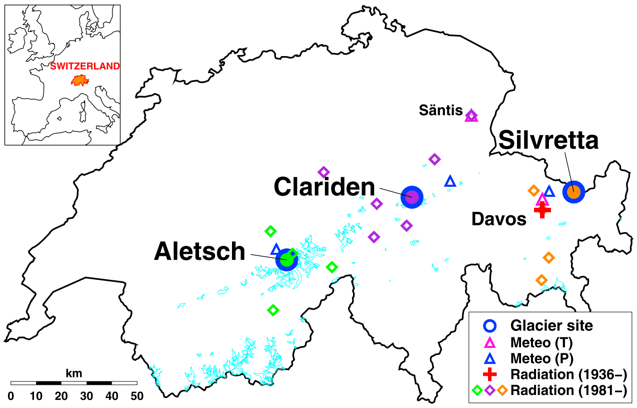

Figure 1. Location of the study sites in Switzerland. Relevant meteorological stations of MeteoSwiss for temperature (T) and precipitation (P), location of the radiation measurements at Davos and supplementary radiation stations are indicated. Radiation stations are colored according to three regions referring to the study sites (Table S2). The glacier distribution in the Swiss Alps is shown in light blue.

[6] Monthly means of global solar radiation since the late 1930s are available from the Global Energy Balance Archive (GEBA) [*Ohmura et al.*, 1989] for an inner Alpine station at Davos (Figure 1). The radiation data were checked for accuracy and homogeneity [*Ohmura et al.*, 1989]. Global radiation has also been continuously measured for almost three decades at 14 stations at elevations between 400-3600 m a.s.l. all located within 50 km of the three study sites (Figure 1 and Table S2). Radiation data in three regions are used to investigate the spatial representativity of the long-term measurements at Davos for the Alpine mountain range.

[7] The tendency towards relative homogeneity in global solar radiation increases with altitude and is higher in summer than in winter [*Marty et al.*, 2002]. This is favorable to the application of radiation data obtained at distant stations for interpreting melt rates on glaciers. We consider only the summer months as these are the most important for glacier melt. The regional mean summer (June, July, August) global solar radiation in the three regions, each representing one of the investigated glaciers, shows coherent temporal fluctuations (inset in Figure 2) with correlation coefficients $r^2 > 0.6$. Between 1981 and 2008 both the long-term mean and the temporal fluctuations ($r^2 = 0.60$) of summer radiation at Davos are matched by the average of the 14 time series distributed throughout the Alps (Figure 2). We therefore assume the variations in global summer radiation at Davos since 1936 to be representative at the scale of the Swiss Alps.

3. Results

[8] For each year i the relative anomaly n_i in annual snow and ice melt m_i inferred from the seasonal measurements is obtained with $n_i = (m_i/\overline{m}) - 1$, where $\overline{m}$ is the 94-year average of m at the study site. The relative fluctuations in the melt anomaly are similar for all four time series [*Huss and Bauder*, 2009]; the data confirm the small regional differences in climatic forcing over the European Alps reported by *Vincent et al.* [2004]. For further analysis the four time series of the relative melt anomaly n are averaged.

[9] Melting conditions have undergone strong temporal variations throughout the last century (Figure 3a). Three decadal periods of equal length are highlighted, accentuating the most significant snow and ice melt anomalies: During 1942–1952 and 1998–2008 melting was 17% and 13%, respectively, above average, while it was below average in 1971–1981 (−19%). According to the century-long data series, maximal melting at the study sites took place in 1947. Melt rates were substantially higher than in the summer of 2003, known for its extreme heat waves in Europe [*Schär et al.*, 2004]. Snow and ice melt at the four high elevation sites was stronger by 4% in the 1940s compared to the last decade. This is intriguing because air temperatures during the 20th century never were as high as today (see dashed line in Figure 3a). According to the non-parametric Mann-Kendall-Test, the 1914–2008 trend in air temperature is positive and statistically significant at the 99% level; there is no significant trend, however, in the annual melt rates. The observed multidecadal changes in snow and ice melt cannot be explained by temperature variations alone.

[10] The long-term radiation records at Davos show significant changes in global summer (JJA) radiation throughout the 20th century (Figure 3b). The time series reflect the trend towards a dimming of global radiation between 1950 and 1980 [*Ohmura*, 2009] and brightening during the last two decades, both recognizable on a global scale and related to the aerosol content of the atmosphere [*Wild et al.*, 2005]. Top of the atmosphere radiation variations are in the order of 1 W m^{-2} and thus small compared to changes observed at the earth's surface. At the inner Alpine station of Davos, maximal global radiation was recorded during the 1940s (Figure 3b). Summer radiation was 8% above the long-term average and 18 W m^{-2} higher than over the last decade. The positive summer radiation anomalies between 1940 and 1960 provide evidence that the

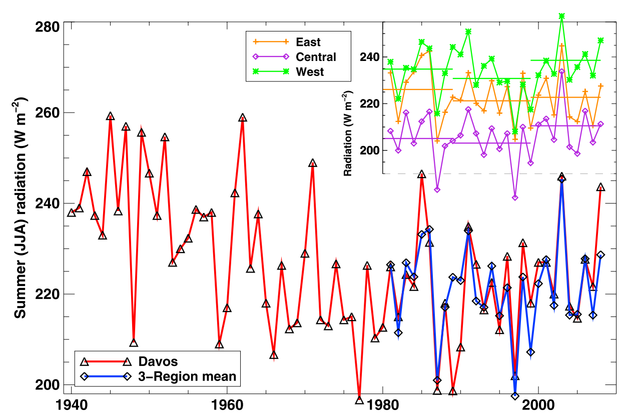

Figure 2. Comparison of regionally distributed summer (JJA) radiation as a mean of three regions in the Swiss Alps (Figure 1) to the long-term series at Davos. The inset shows average global radiation in individual regions; decadal means are indicated with horizontal lines.

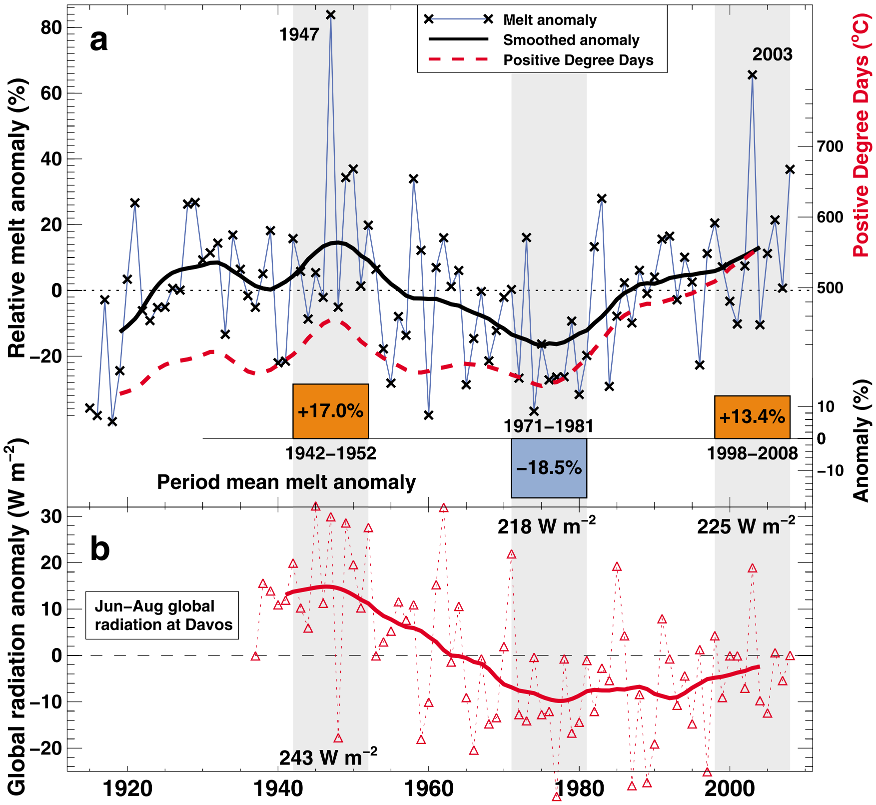

Figure 3. (a) Four-site average of annual melt anomaly n (see text) and sum of daily air temperatures above 0°C over the year at the study sites (dashed), low-pass filtered using 11-year running means. Melt anomalies for extreme decadal periods are shown by bars. (b) JJA anomaly in measured global radiation at Davos. Period means are given.

extreme melt rates in the 1940s were favored by radiation and only to a lesser extent by high air temperatures.

[11] Our results indicate a prolongation of the melting season (number of days with melt >1 kg m^{-2}) at high elevations by almost one month since the 1970s (Figure 4a). Simultaneously, the calculated fraction of snowfall relative to the total annual precipitation has decreased by 12% on average at the study sites (Figure 4b). These processes have the potential to considerably accelerate future glacier wastage, have strong impacts on the hydrological cycle and could offset the effect of currently lower solar radiation compared to the 1940s. Lower surface albedo due to earlier melting of the winter snow and dust deposition on glacier tongues [*Oerlemans et al.*, 2009] may further enhance glacier melt. This feedback, however, has not yet been reflected at the study sites situated in the accumulation area in most years.

4. Discussion

[12] Dimming and brightening of solar radiation can be explained with changes in cloudiness and atmospheric transmission [*Wild et al.*, 2005; *Ohmura*, 2009]. Increased aerosol concentration until the 1980s, related to air pollution [*Ramanathan et al.*, 2001], leads to lower transmissivity of the cloud-free atmosphere [*Wild et al.*, 2005], and also promotes cloud formation [*Krüger and Graßl*, 2002]. Between 1960 and 1980 high cloudiness, low global radiation and low air temperatures in the European Alps [*Auer et al.*, 2007] are in line with strongly reduced glacier melt rates (Figure 3), resulting in a short period of balanced mass budget of mountain glaciers worldwide [*Kaser et al.*, 2006]. The enhanced greenhouse effect of terrestrial radiation and the brightening of solar radiation since the early 1980s induced higher air temperatures [*Wild et al.*, 2004; *Philipona et al.*, 2009] and increasing snow and ice melt over the last decades approaching the maximum of the 1940s (Figure 3a).

[13] Temperature-index models (TIMs) are widely applied in glaciology and hydrology due to their simplicity and limited field data requirements [*Hock*, 2005]. The so called degree-day factors (DDFs) empirically relate air temperature to melt, integrating all components of the energy balance. TIMs are known to perform well in reproducing observed melt rates for various reasons [*Ohmura*, 2001; *Sicart et al.*, 2008]. Variations in the DDF over the year due to short-term changes in the radiation budget are broadly acknowledged [e.g., *Braithwaite*, 1995; *Hock*, 2005]. The stability of DDFs over decadal periods, however, has been rarely discussed in literature.

[14] Based on equation (1) we define the degree-day factor for snow as $DDF_{snow} = (f_M + r_{snow}\,\bar{I})$, with $\bar{I}$ the annual mean of potential direct radiation. Annual diagnosis of DDF_{snow} using the seasonal mass balance measurements allows us to quantify the long-term changes in the relation

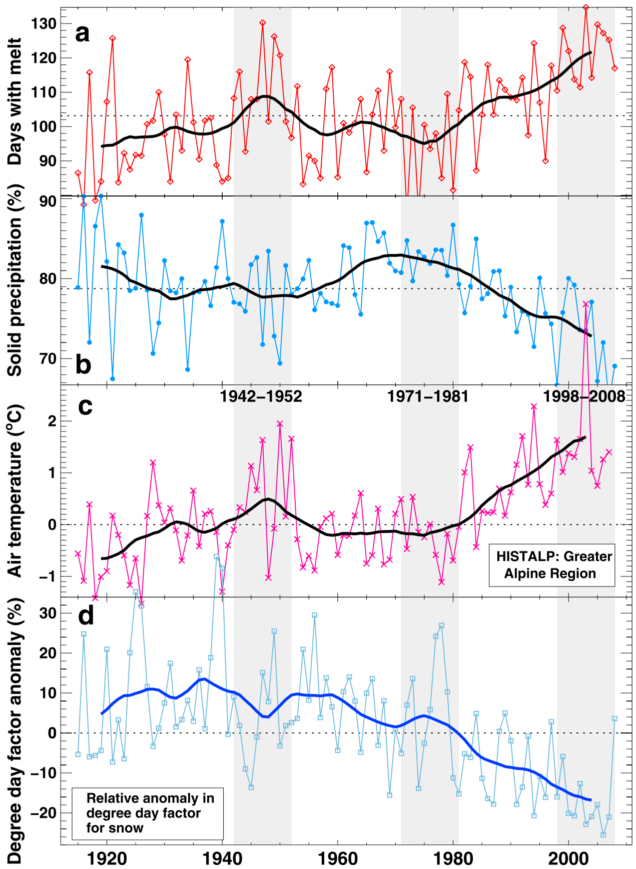

Figure 4. Four study sites average of (a) the length of the melting season inferred from field data and modelling, and (b) calculated mean annual fraction of solid precipitation. (c) Measured relative JJA anomaly in air temperature (Greater Alpine Region) from the HISTALP data set [*Auer et al.*, 2007]. (d) Relative anomaly in the degree-day factor for snow DDF_{snow} obtained from annual diagnosis based on seasonal field measurements. Annual series in all panels are low-pass filtered using 11-year running means (solid lines).

between positive air temperatures and melt. We find relatively stable DDFs until the mid-1970s followed by a negative trend of −7% per decade (Figure 4d). The drivers for these long-term variations cannot be detected based on the available data sets as they do not resolve all components of the energy balance. Higher air temperature dependent incoming longwave radiation (Figure 4c) plausibly explains part of the observed decrease in DDF_{snow} over the last decades, confirming an oversensitivity of temperature-index models to temperature change [*Pellicciotti et al.*, 2005]. DDFs are, however, also affected by variations in global shortwave radiation, and, to a lesser extent, by turbulent heat fluxes [*Braithwaite*, 1995; *Ohmura*, 2001]. We therefore caution against using classical temperature-index models calibrated in the past for projecting snow and ice melt in glaciological and hydrological studies and to calculate future sea level rise.

[15] Our data sets provide evidence that the extraordinary melt rates in the 1940s can be attributed to enhanced solar radiation in summertime. Models for past and future glacier changes should take into account the effect of decadal radiation variations as they significantly alter the relationship between glacier melt and air temperature.

[16] **Acknowledgments.** This study was funded by ETH Research grant TH-17 06-1. We are indebted to A. Bauder, H. Müller, G. Kappenberger and many previous researchers carrying out the field surveys. We thank MeteoSwiss and ZAMG for meteorological data. Radiation records were provided by the Global Energy Balance Archive (GEBA) of ETH Zürich.

References

Auer, I., et al. (2007), HISTALP—Historical instrumental climatological surface time series of the Greater Alpine Region, *Int. J. Climatol.*, *27*(1), 17–46.

Braithwaite, R. J. (1995), Positive degree-day factors for ablation on the Greenland ice sheet studied by energy-balance modeling, *J. Glaciol.*, *41*(137), 153–160.

Braithwaite, R. J., and Y. Zhang (1999), Modelling changes in glacier mass balance that may occur as a result of climate changes, *Geogr. Ann., Ser. A*, *81*(4), 489–496.

Haeberli, W., and M. Beniston (1998), Climate change and its impacts on glaciers and permafrost in the Alps, *Ambio*, *27*, 258–265.

Hock, R. (1999), A distributed temperature-index ice- and snowmelt model including potential direct solar radiation, *J. Glaciol.*, *45*(149), 101–111.

Hock, R. (2005), Glacier melt: A review of processes and their modelling, *Prog. Phys. Geogr.*, *29*(3), 362–391.

Huss, M., and A. Bauder (2009), 20th-century climate change inferred from four long-term point observations of seasonal mass balance, *Ann. Glaciol.*, *50*(50), 207–214.

Kaser, G., J. G. Cogley, M. B. Dyurgerov, M. F. Meier, and A. Ohmura (2006), Mass balance of glaciers and ice caps: Consensus estimates for 1961–2004, *Geophys. Res. Lett.*, *33*, L19501, doi:10.1029/2006GL027511.

Krüger, O., and H. Graßl (2002), The indirect aerosol effect over Europe, *Geophys. Res. Lett.*, *29*(19), 1925, doi:10.1029/2001GL014081.

Marty, C., R. Philipona, C. Fröhlich, and A. Ohmura (2002), Altitude dependence of surface radiation fluxes and cloud forcing in the Alps: Results from the Alpine surface radiation budget network, *Theor. Appl. Climatol.*, *72*, 137–155.

Müller, H., and G. Kappenberger (1991), Claridenfirn-Messungen 1914–1984, *Zürcher Geogr. Schr. 40*, 79 pp., Geogr. Inst., ETH Zurich, Zurich, Switzerland.

Oerlemans, J., R. Giessen, and M. van den Broeke (2009), Retreating alpine glaciers: Increased melt rates due to accumulation of dust (Vadret da Morteratsch, Switzerland), *J. Glaciol.*, *55*(192), 729–736.

Ohmura, A. (2001), Physical basis for the temperature-based melt-index method, *J. Appl. Meteorol.*, *40*(4), 753–761.

Ohmura, A. (2009), Observed decadal variations in surface solar radiation and their causes, *J. Geophys. Res.*, *114*, D00D05, doi:10.1029/2008JD011290.

Ohmura, A., and H. Lang (1989), Secular variation of global radiation in Europe, in *Current Problems in Atmospheric Radiation*, edited by J. Lenoble and J.-F. Geleyn, pp. 298–301, A. Deepak, Hampton, Va.

Ohmura, A., H. Gilgen, and M. Wild (1989), Global Energy Balance Archive (GEBA), World Climate Programme—Water Project A7, *Zürcher Geogr. Schr. 34*, 62 pp., Geogr. Inst., ETH Zurich, Zurich, Switzerland.

Ohmura, A., A. Bauder, H. Müller, and G. Kappenberger (2007), Long-term change of mass balance and the role of radiation, *Ann. Glaciol.*, *46*(1), 367–374.

Pellicciotti, F., B. Brock, U. Strasser, P. Burlando, M. Funk, and J. Corripio (2005), An enhanced temperature-incex glacier melt model including the shortwave radiation balance: Development and testing for Haut Glacier d'Arolla, Switzerland, *J. Glaciol.*, *51*(175), 573–587.

Philipona, R., K. Behrens, and C. Ruckstuhl (2009), How declining aerosols and rising greenhouse gases forced rapid warming in Europe since the 1980s, *Geophys. Res. Lett.*, *36*, L02806, doi:10.1029/2008GL036350.

Ramanathan, V., P. J. Crutzen, J. T. Kiehl, and D. Rosenfeld (2001), Aerosols, climate, and the hydrological cycle, *Science*, *294*(5549), 2119–2124.

Schär, C., P. L. Vidale, D. Lüthi, C. Frei, C. Häberli, M. A. Liniger, and C. Appenzeller (2004), The role of increasing temperature variability in European summer heatwaves, *Nature*, *427*, 332–336.

Sicart, J. E., R. Hock, and D. Six (2008), Glacier melt, air temperature, and energy balance in different climates: The Bolivian Tropics, the French Alps, and northern Sweden, *J. Geophys. Res.*, *113*, D24113, doi:10.1029/2008JD010406.

Vincent, C., G. Kappenberger, F. Valla, A. Bauder, M. Funk, and E. Le Meur (2004), Ice ablation as evidence of climate change in the Alps over the 20th century, *J. Geophys. Res.*, *109*, D10104, doi:10.1029/2003JD003857.

von Hann, J. (1897), *Handbuch der Klimatologie*, J. Engelhorn, Stuttgart, Germany.

Wild, M., A. Ohmura, H. Gilgen, and D. Rosenfeld (2004), On the consistency of trends in radiation and temperature records and implications for the global hydrological cycle, *Geophys. Res. Lett.*, *31*, L11201, doi:10.1029/2003GL019188.

Wild, M., et al. (2005), From dimming to brightening: Decadal changes in solar radiation at Earth's surface, *Science*, *308*(5723), 847–850.

M. Funk, Laboratory of Hydraulics, Hydrology and Glaciology, Gloriastrasse 37-39, ETH Zurich, CH-8092 Zürich, Switzerland.

M. Huss, Department of Geosciences, University of Fribourg, Chemin du Musée 4, CH-1700 Fribourg, Switzerland. (matthias.huss@unifr.ch)

A. Ohmura, Institute for Atmospheric and Climate Science, ETH Zurich, Universitätsstrasse 16, CH-8092 Zürich, Switzerland.