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Supporting Information for

Common climatic signal from glaciers in the Alps over the last 50 years

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Introduction

Our study uses the longest and most continuous annual mass balance series for six glaciers covering all climatic regions of the Alps and for which the point annual mass balance and coordinates were available for each measurement. Indeed, unlike previous studies related to mass balance analysis over the entire European Alps, our study requires the positions of each measurement. For this purpose, a major effort was required to extract the coordinates and annual mass balances going back to 1962 for each stake from the original notebooks. However, the point measurements were not performed exactly at the same location for the life time of the stakes (1-5 years) due to the movement of the ice. In some cases (Hintereisferner and Vernagtferner), the ablation stakes were replaced at the end-locations of the previous stakes, meaning that the stakes follow the flowline. For all these reasons, it is not possible to extract a surface mass balance at a fixed location for each year on the basis of the field measurements. Consequently, the analysis requires the locations of each stake for each year and a multivariate statistical analysis as explained in Text S1 below.

Figure S1 shows the maps of the six glaciers selected for our study: Hintereisferner, Vernagtferner (AU), Silvretta, Gries (CH), Sarennes and Saint Sorlin glaciers (FR), along with the perimeters selected for the statistical analysis in the ablation areas. The selection criterion for these limiting perimeters was the availability of a sufficient number of point annual mass balance measurements over the common period of measurements (1962-2013). Note that point mass balances of Vernagtferner are available since only 1967.

Figure S2 shows the centered point mass balances calculated from stakes located in the ablation zone over the period 1962-2013 for a) two neighboring zones on Saint Sorlin glacier (blue squares in Fig. S1) and b) two clusters of stakes on Griesgletscher. This figure shows that the common variance for point mass balances measured in two neighboring areas on the same glacier is very high. We could not perform this test on each glacier because of insufficient data. For Saint Sorlin glacier and Griesgletscher, we found a common variance of 97% and 92% respectively for point mass balances in two neighboring areas located on these glaciers.

Figure S3 displays the averaged differences between centered point mass balances calculated from each pair of glaciers. This figure reveals that three years show large differences in centered mass balances between the eastern and western parts of the Alps: 1976, 1989 and 2009.

Table S1 shows the altitude range, overall surface area and dominant aspect for each investigated glacier.

Table S2 shows the common variance between a) the glacier-wide mass balances and b) the centered point mass balances.

Text S1 Methodology.

Our analysis uses a multivariate statistical analysis as proposed by Lliboutry [1974]. The model assumes that the mass balance can be decomposed into two independent spatial (α_i) and temporal (β_t) variation terms, giving:

$$b_{i,t} = \alpha_i + \beta_t + \varepsilon_{i,t} \qquad (1)$$

where $b_{i,t}$ is the mass balance recorded at site *i* for year *t*, α_i the spatial effects at location *i* (i.e. the average balance at the site over the whole study period) and β_t the annual deviation from this average balance(therefore $\Sigma\beta_t = 0$). The spatio-temporal decomposition implies that β_t is the same for each location for any given year *t* and has a glacier-wide significance.

The cross-terms that account for non-linear effects that deviate from separating the time and space variable are neglected here [Lliboutry, 1974; Thibert and Vincent, 2009]. The $\varepsilon_{i,t}$ term represents residuals corresponding to both measurement errors and discrepancies between the model and data (unexplained variance). The temporal control factors and residuals are assumed to be identically normally distributed with means equal to zero. To account for lost stakes, changes in stake position or inconsistencies over the years, instead of treating each stake as an observation site [Lliboutry, 1974], the surface of the glacier is here divided into 0.2×0.2 km squares, within which the surface mass balance is assumed the same for a given year. From a detailed analysis conducted at Sarennes, missing values only slightly affect the β_t series uncertainty [Eckert et al., 2001], varying from ±0.13 m w.e. a^{-1} to ±0.27 m w.e. a^{-1} for none to three missing measurements out of five. The uncertainty around the annual temporal β_t therefore remains tenable even with up to 60% missing values in some years.

Moreover, the surface mass balances measured at each stake were corrected for changes in elevation before they were included in the model in order to take into account elevation changes over the last decades. Note that the elevation change ranges between about -20 m (Silvretta) and -77 m (Sarennes) over the studied 1962-2013 period in the investigated areas and has a large influence on point annual surface mass balances [Huss et al., 2012]. A vertical gradient of surface mass balance (0.007 m w.e. m^{-1} a^{-1}) [Rabatel et al., 2005] was therefore applied to each individual measurement in order to correct for elevation offsets from the original surface elevation. The elevation changes were assessed using the available DEMs (Table S1) leading to a systematic positive correction of the temporal term β_t. The effect is generally less than 0.3 m w.e. a^{-1}, close to the mean residual term $\varepsilon_{i,t}$, except for Sarennes where the difference in β_t reaches a maximum of 0.36 m w.e. a^{-1}. Note that an uncertainty in the elevation change of ±10 m leads to a maximum effect of ±0.15 m w.e. a^{-1} on the temporal term β_t. Note also that an uncertainty in the vertical gradient of ±0.002 m w.e. m^{-1} a^{-1} leads to a maximum difference of ±0.08 m w.e. a^{-1} in β_t. Although the ice surface elevation changes over time must be taken into account, the results are not very sensitive to their uncertainty.

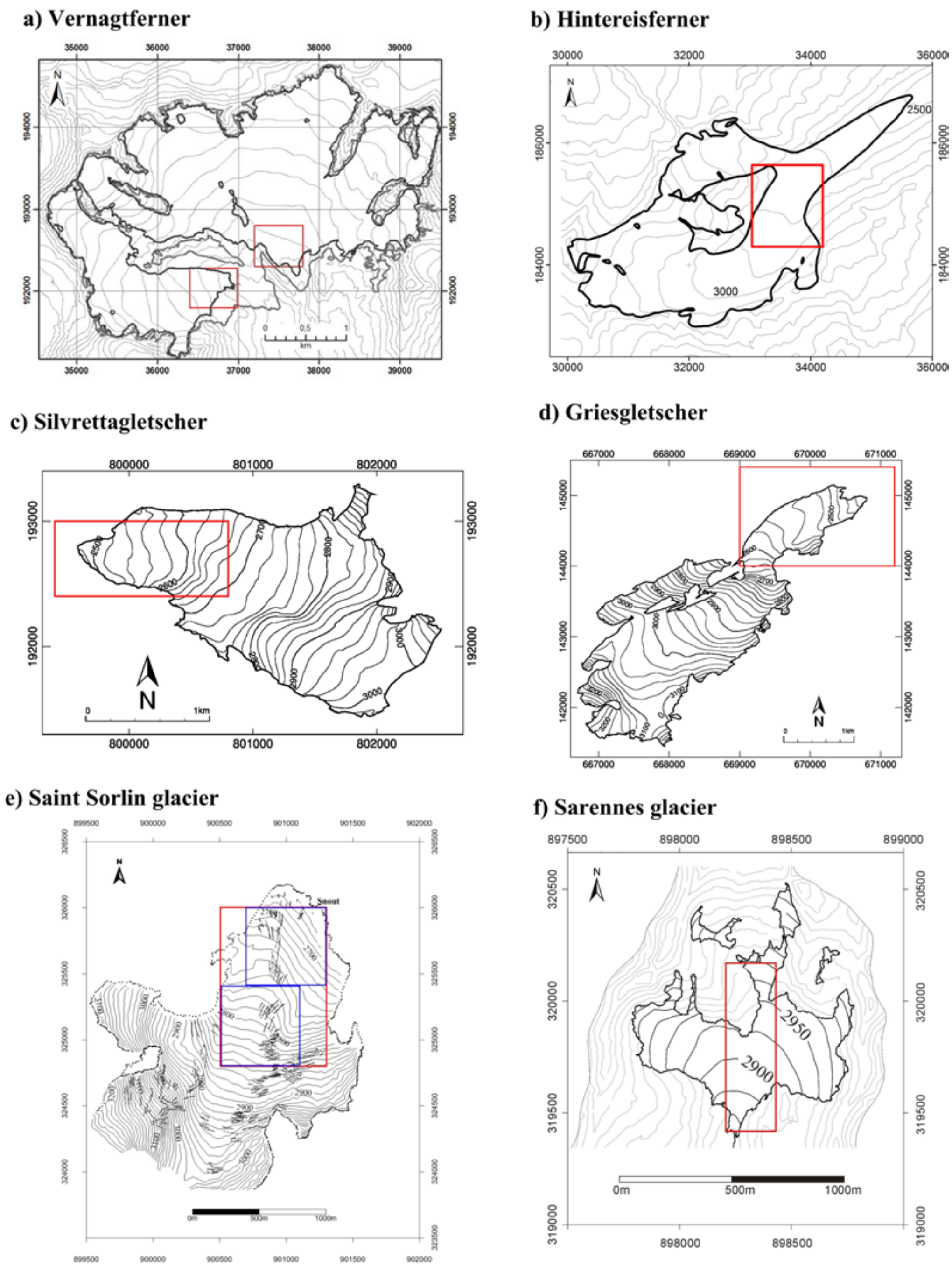


Figure S1. Maps of the six glaciers selected in this study: Hintereisferner, Vernagtferner (AU), Silvretta, Gries (CH), Sarennes and Saint Sorlin glaciers (FR). The point annual mass balances are obtained from stakes inserted in the ice in the ablation area and from drilled cores or snow pits in the accumulation zone. The squares in each map show the selected perimeters in the ablation areas used for our statistical analysis. For Saint Sorlin glacier, the blue squares show the two neighboring zones in which the statistical analysis was performed independently (Fig. S2). The years of maps are mentioned in Table S1 (third column).

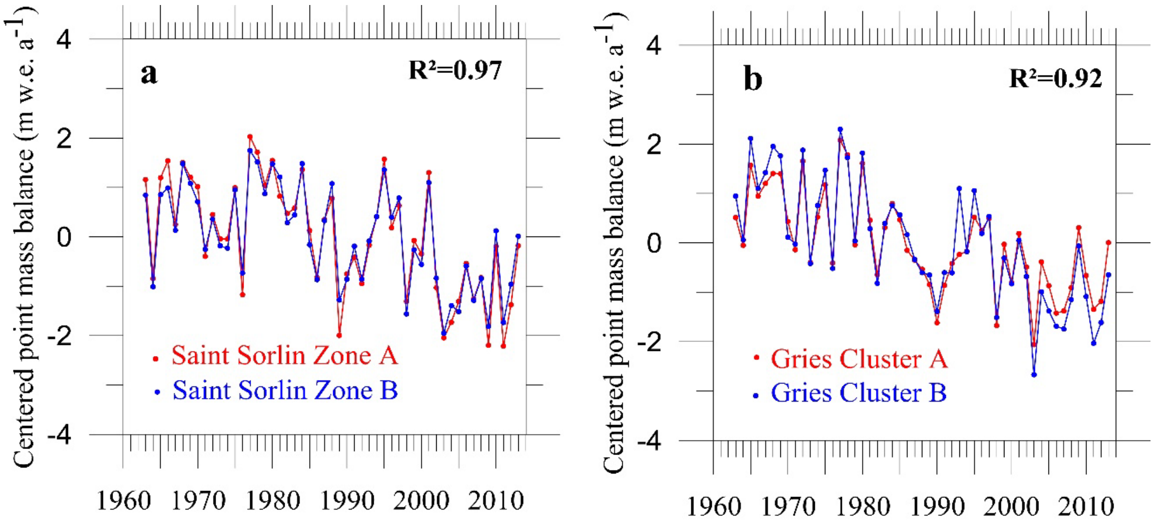


Figure S2. Centered point mass balances calculated from stakes located in the ablation zone over the period 1962-2013 for a) two neighboring zones on Saint Sorlin glacier (blue squares in Fig. S1) and b) two clusters of stakes on Gries glacier. The centered point mass balances have been calculated independently. In the case of Saint Sorlin glacier, we selected one zone close to the Equilibrium Line and another close to the snout. In the case of Gries glacier, we selected two different clusters of stakes in the red square shown in Fig. S1d.

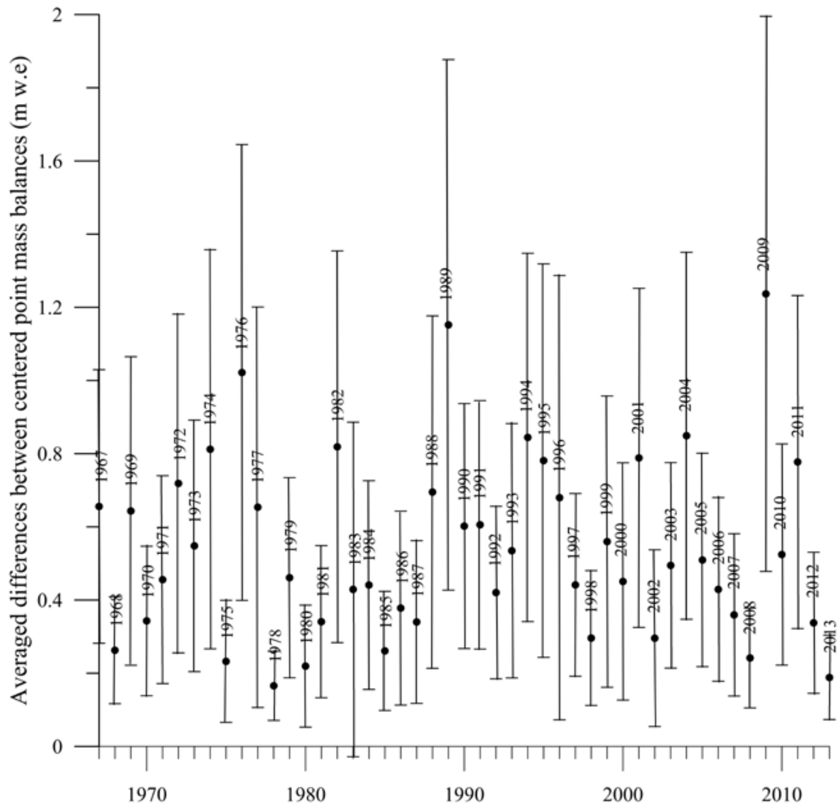


Figure S3. Averaged differences between centered point mass balances. The differences have been calculated using each pair of glaciers. Three years exceed three standard deviations: 1976, 1989 and 2009. The years 1976 and 1989 clearly reveal positive centered mass balances in the eastern Alps (Hintereisferner and Vernagtferner) and very negative values in the western Alps. The year 2009 shows a more complex pattern with annual mass balance close to the average at Gries, negative in the east and very negative in the western region of the Alps. These discrepancies are mainly related to the complex pattern of winter precipitation over the Alps for these specific years. For instance, the winter of 1976 was very dry in the western Alps (Sarennes and Saint Sorlin) while the winter accumulation was close to the average in Austria. In 1989, the winter accumulation was very low in the western Alps and normal in the eastern Alps. In 2009, the winter accumulation was low in the western Alps and higher than normal in Austria. Whatever the distance, some peculiar years show high common variance, among them 1975, 1978 and 1980, when glaciers encountered positive deviations in their mass budgets which were close to steady-state. On the other hand, high covariances are observed for 2013, 2008, 2002 and 1998, with strong negative budgets. Note that 2003, despite the occurrence of a central European extreme summer heatwave, does not show the largest common variance on account of the contrasted pattern of precipitations over the Alps in the winter of 2003.

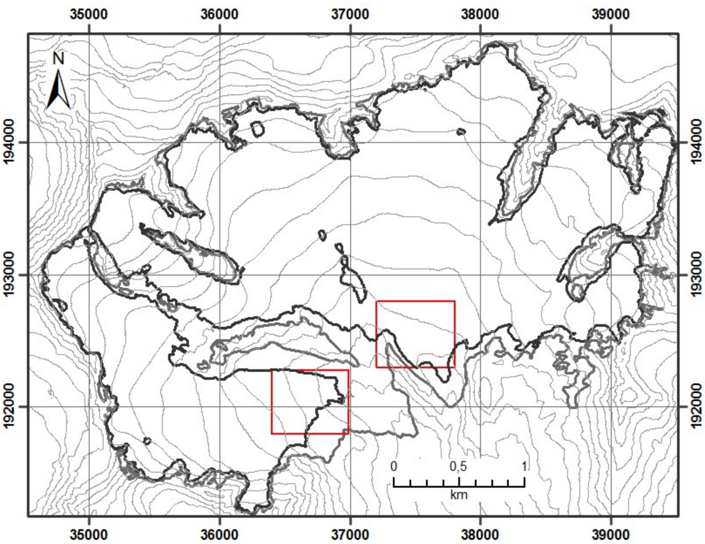
	Glacier			Studied area				
	Altitude range (m)	Surface area (km²) (year)	Aspect	Altitude range (m)	Number of stakes	Geodetic method for stake coordinates	Surface area (km²)	DEM years
Sarennes	2840-3050	0.4 (2003)	South	2840-3050	5-7	1949-2002: Theod. 2003-2013: DGPS	0.4	1952, 1981, 2003, 2009, 2011, 2014
Saint Sorlin	2700-3300	3 (2003)	North	2720-2850	5-15	1962-2000: Theod. 2000-2013: DGPS	0.8	1952, 1971,1998, 2003, 2008, 2014
Gries	2400-3306	4.8 (2012)	North-East	2450-2660	8-10	1959-2002: Theod. 2003 2013: DGPS	1.0	1961, 1967, 1979, 1986, 1991, 1998, 2003, 2007, 2012, then annual DEMs
Silvretta	2470-3070	2.7 (2012)	West	2530-2680	3-16	1959-2003: Theod. 2003 –2013: DGPS	0.6	1959, 1973, 1986, 1994, 2003, 2007, 2012, then annual DEMs
Hintereisferner	3600-2600	7.8 (1997)	North-East	2760-2815	3-8	1962-2000: Theod. 2007-2013: DGPS.	0.8	1893,1920,1939,1953, 1962, 1967,1969,1979, 1997, 2001 then annual DEMs
Vernagtferner	2920-3570	7.3 (2009)	South-East	2850-2950	2-6	Theodolite	0.5	1954,1969,1979,1990,1999,2003,2006, 2009

Table S1. Altitude range, overall surface area and dominant aspect for each investigated glacier. Various characteristics are also given for the studied area in the ablation zone of each glacier, including the number of stakes and the years with available digital elevation models. The stake coordinates were obtained from classical topographic measurements (theodolite surveys) until about the beginning of the 21st century and subsequently from differential global positioning systems (DGPS), depending on the glacier.

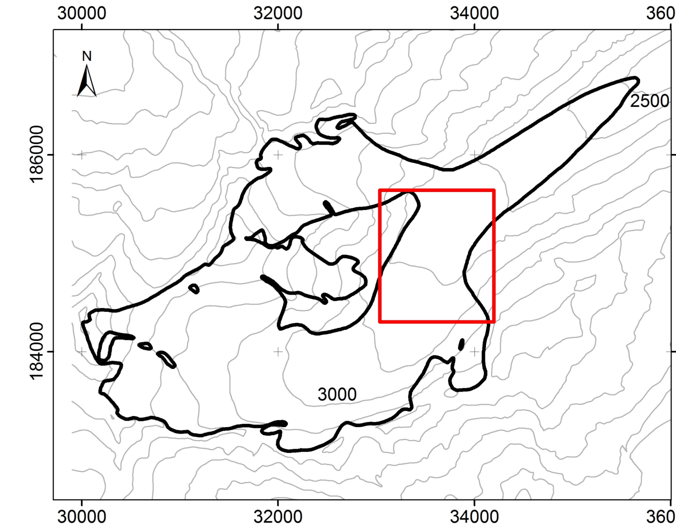
	Sarennes	Saint Sorlin	Gries	Silvretta	Hintereisferner	Vernagtferner
Sarennes	1	0.90 **0.88**	0.54 **0.59**	0.39 **0.51**	0.41 **0.55**	0.37 **0.44**
Saint Sorlin		1	0.60 **0.66**	0.47 **0.52**	0.48 **0.60**	0.46 **0.52**
Gries			1	0.54 **0.60**	0.67 **0.81**	0.59 **0.77**
Silvretta				1	0.67 **0.73**	0.79 **0.66**
Hintereisferner					1	0.82 **0.86**
Vernagtferner						1

Table S2. Glacier-to-glacier correlation (coefficient of determination R^2) between a) glacier-wide mass balances (normal characters) and b) centered point mass balances (bold characters).

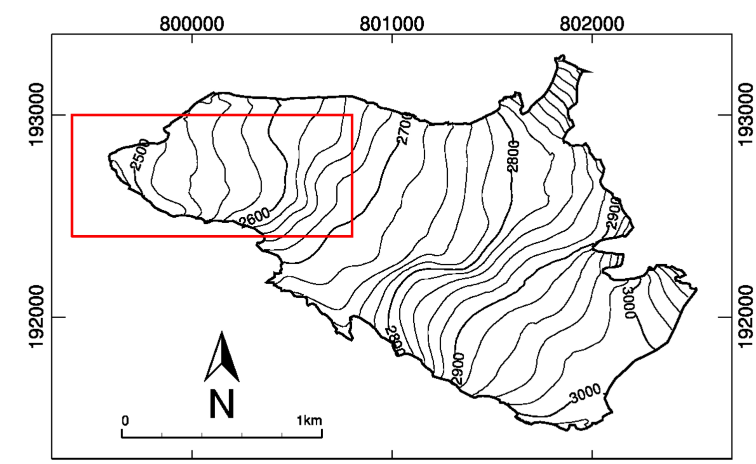
a) Vernagtferner



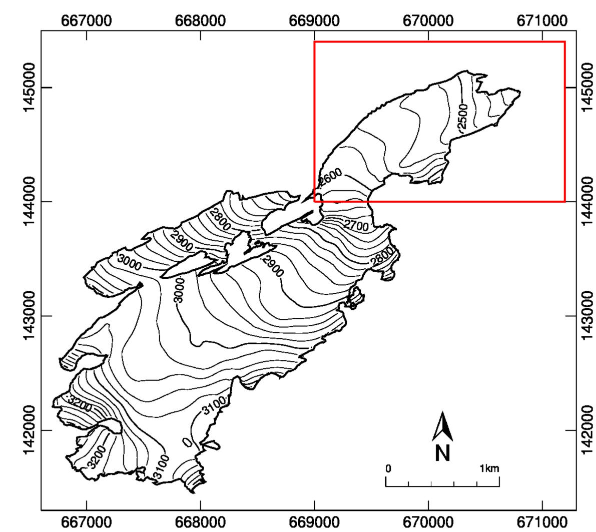
b) Hintereisferner



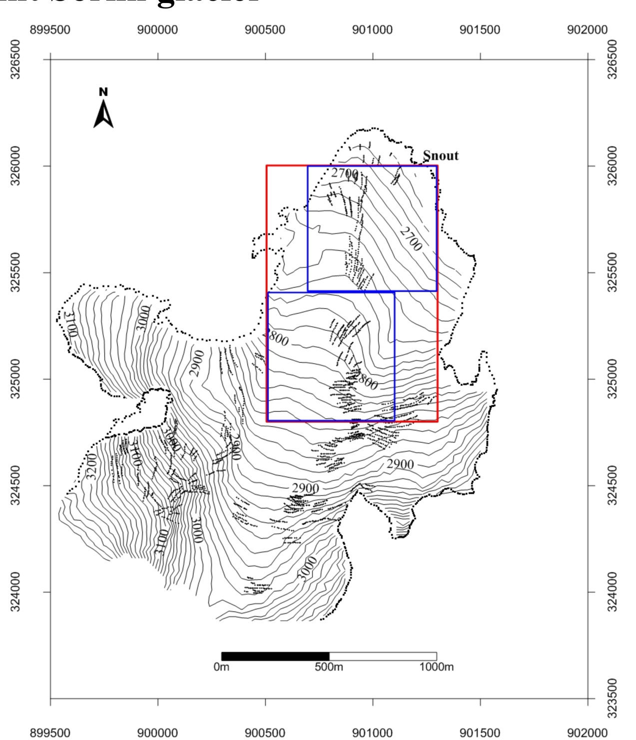
c) Silvrettagletscher



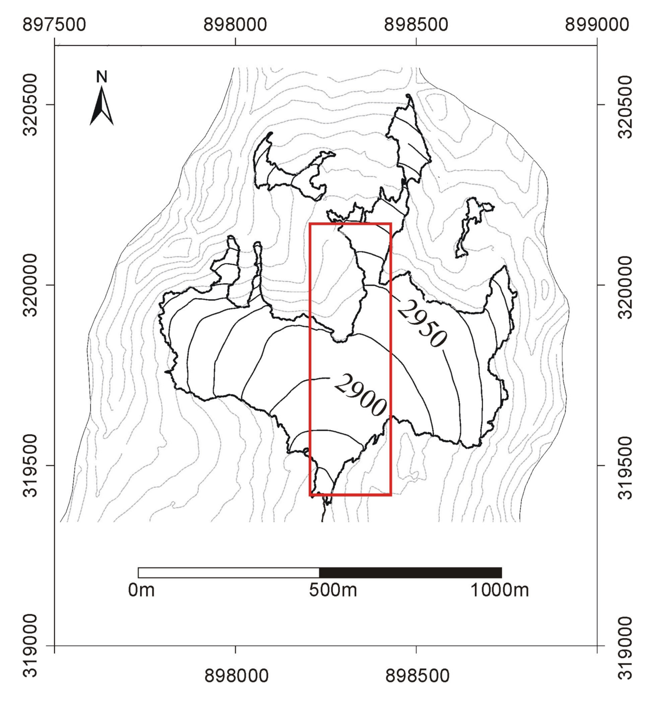
d) Griesgletscher

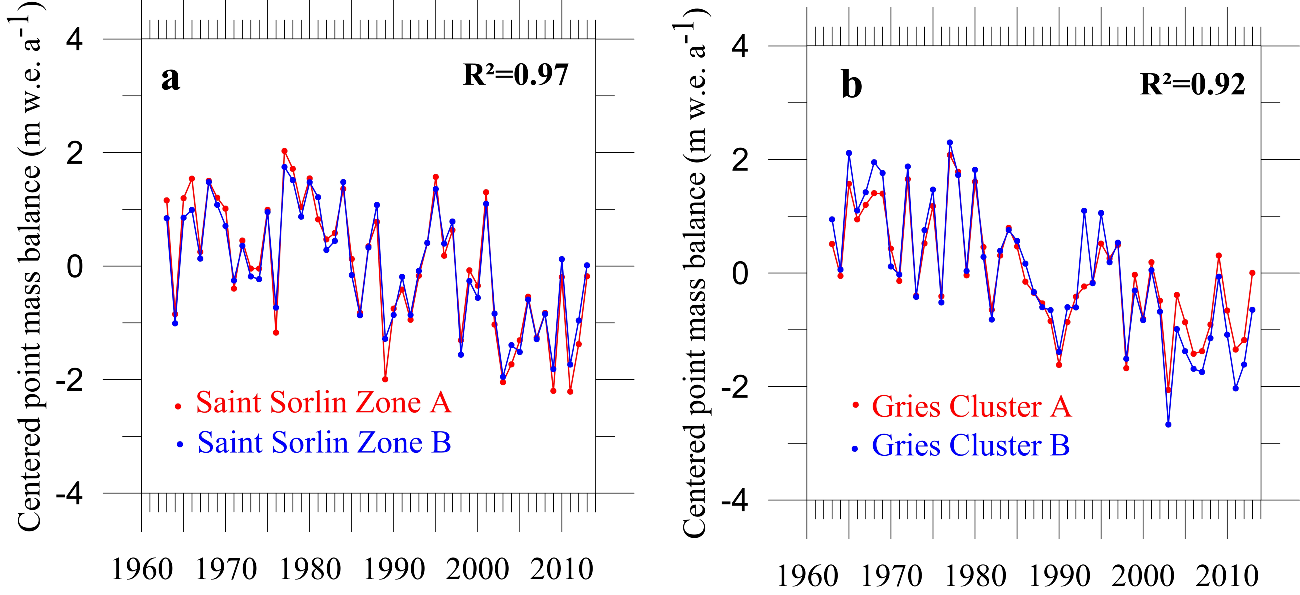


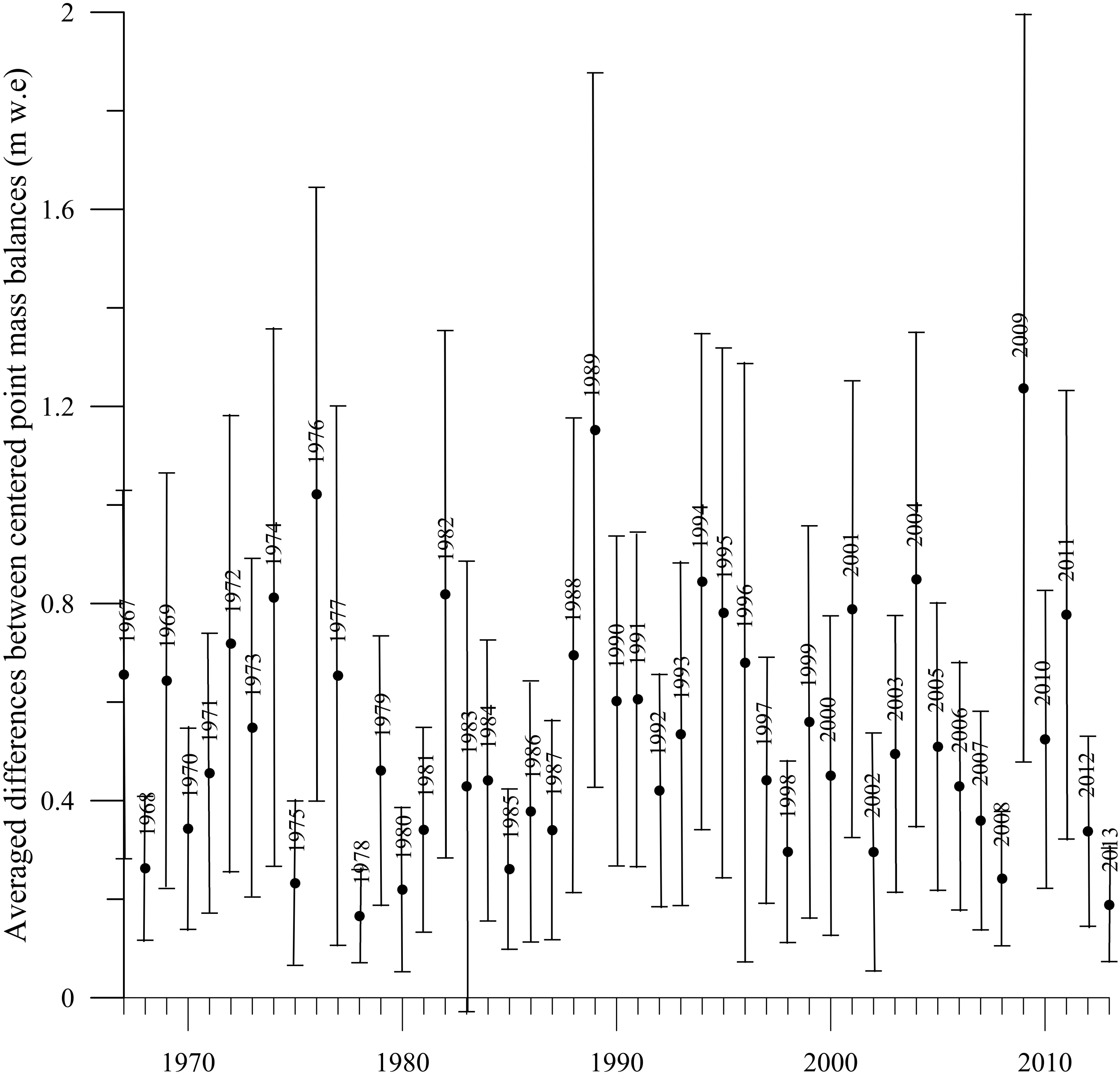
e) Saint Sorlin glacier



f) Sarennes glacier




a
R²=0.97
Saint Sorlin Zone A
Saint Sorlin Zone B
b
R²=0.92
Gries Cluster A
Gries Cluster B
Centered point mass balance (m w.e. a-1)
4
2
0
-2
-4
1960
1970
1980
1990
2000
2010


Averaged differences between centered point mass balances (m w.e)
0
0.4
0.8
1.2
1.6
2
1970
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