25 years (1981–2005) of equilibrium-line altitude and mass-balance reconstruction on Glacier Blanc, French Alps, using remote-sensing methods and meteorological data

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ABSTRACT. Annual equilibrium-line altitude (ELA) and surface mass balance of Glacier Blanc, Ecrins region, French Alps, were reconstructed from a 25 year time series of satellite images (1981–2005). The remote-sensing method used was based on identification of the snowline, which is easy to discern on optical satellite images taken at the end of the ablation season. In addition, surface mass balances at the ELA were reconstructed for the same period using meteorological data from three nearby weather stations. A comparison of the two types of series reveals a correlation of $r > 0.67$ at the 0.01 level of significance. Furthermore, the surface mass balances obtained from remote-sensing data are consistent with those obtained from field measurements on five other French glaciers ($r = 0.76$, $p < 0.01$). Also consistent for Glacier Blanc is the total mass loss (10.8 m w.e.) over the studied period. However, the surface mass balances obtained with the remote-sensing method show lower interannual variability. Given that the remote-sensing method is based on changes in the ELA, this difference probably results from the lower sensitivity of the surface mass balance to climate parameters at the ELA.

1. INTRODUCTION

Both the equilibrium-line altitude (ELA) and annual surface mass balance depend on the climatic conditions that govern accumulation and ablation processes at the glacier surface (Lliboutry, 1965; Martin, 1975; Kuhn, 1989; Paterson, 1994; Vincent, 2002; Hooke, 2005). The advantage of using glacier ELA and surface mass balance as climate indicators, over other glaciological parameters such as surface area or length, is that they can be interpreted more directly in terms of climate signals. Glacier dynamics and the time lag of snout response do not influence the interpretation of the data. Unfortunately, unlike measurements of glacier length that are available for hundreds of glaciers (see Oerlemans, 2005; World Glacier Monitoring Service, http://www.geo.unizh.ch/wgms/), direct mass-balance and ELA measurements based on field data are rare in comparison with the number of glaciers worldwide. Series longer than a few decades are even rarer, due to the major logistical support required for field campaigns. Long series are nevertheless necessary to study climate at high altitudes, where meteorological data are also very scarce (Vincent, 2002), as well as to better understand the relationship between glaciers and climate. We need this understanding to improve our knowledge of past climate variations and the future evolution of glaciers in the current context of global climate change (Dyugerov, 2000). Long series are also needed for the numerical modelling of glaciers (Gudmundsson, 1999; Le Meur and Vincent, 2003).

Remote sensing is commonly used to assess changes in volume of large ice masses such as those in Greenland and Antarctica (e.g. Bindschadler, 1998; Rignot and Thomas, 2002). Given recent improvements in the resolution of satellite images, now fine enough to see details in small areas of a few square kilometres, satellite imagery can now also be used to monitor yearly variations of small mountain glaciers (e.g. Berthier and others, 2004; Paul and others, 2004, 2007). In previous studies (Rabatel and others, 2002, 2005), we successfully tested a method to determine annual surface mass-balance series from the altitude of the snowline inferred from optical remote-sensing images on three glaciers in the French Alps. In the present study, we apply the same method to determine a 25 year surface mass-balance series for Glacier Blanc, a glacier located in the southern French Alps. As no long-term direct mass-balance series is available at this latitude in the Alps, the data obtained from the present study will be useful in studying the relationship between climate and surface mass balance in this area.

In the following, we first present the ELA and surface mass-balance reconstructions using remote-sensing images. To test the consistency of the different methods, we then compare the remote-sensing mass-balance series both with in situ measurements performed since 1999 and with a mass-balance series computed from meteorological data. For this, the error is analyzed for each method. Finally, we compare the Glacier Blanc remote-sensing surface mass-balance series with series of surface mass balances measured on

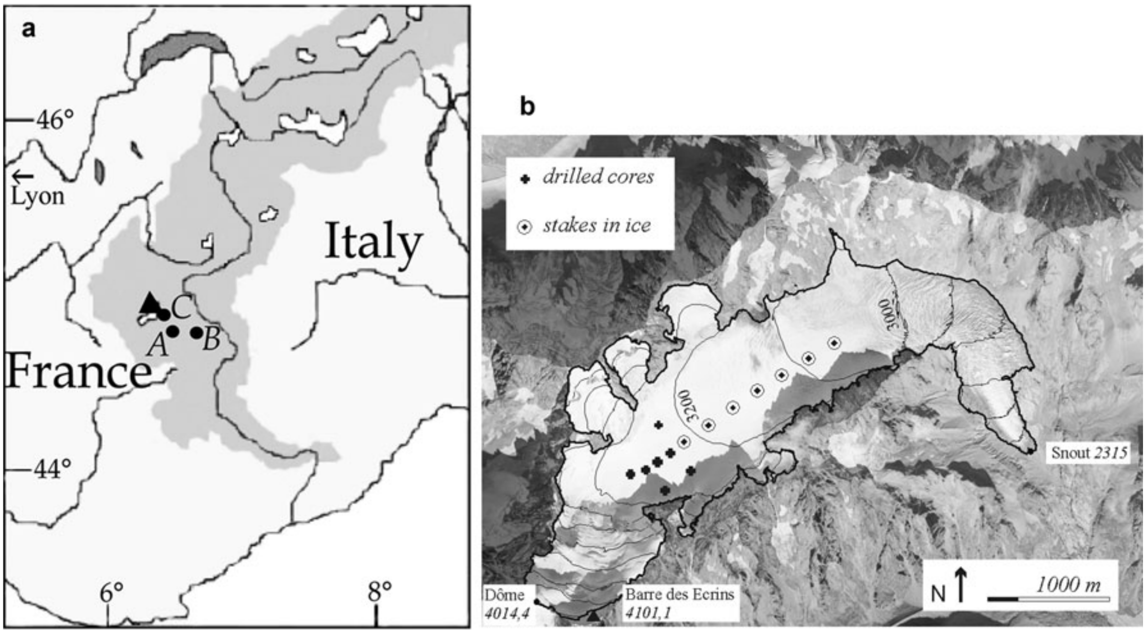

Fig. 1. (a) Location map. The triangle represents Glacier Blanc. Black circles are the weather stations used in this study: A: Pelvoux, B: Briançon, C: Cézanne. (b) Photogrammetric map of Glacier Blanc obtained from aerial photographs taken on 3 October 2002 (© Sintegra), and location of the sampling sites used for mass-balance measurements.

several French-studied glaciers and discuss the implications of the differences observed.

2. STUDY AREA

Glacier Blanc, Ecrins, (44°56′ N, 6°23′ E; Figs 1 and 2) is the largest glacier in the southern French Alps. From the Dôme des Ecrins at 4014 m a.s.l. down to the snout at 2315 m a.s.l., the glacier covers an area of 5.34 km^2, extends 5.9 km and has a mean slope of ~30% (aerial photogrammetry, 2002). The various measurements carried out on this glacier since 1887 (fluctuations in length, surface velocity, glacier thickness, photogrammetric survey) are summarized by Thibert and others (2005). Since 1999, surface-mass balance measurements have been performed on a limited area of the central plateau using the glaciological method (drilling cores and stakes; Fig. 1b). The ELA can thus be computed using these annual surface mass-balance observations from 1999 to 2005. However, due to the lack of measurements on the glacier tongue and on the upper reaches of the accumulation zone, the annual surface mass balance for the whole glacier is still unknown.

3. METHODS AND DATA

The annual surface mass balances were reconstructed from 1981 to 2005 using the method described by Rabatel and others (2005). This method, summarized in section 3.1, requires ELA measurements for each year between 1981 and 2005 and variations in glacier volume over the whole period. As explained below, ELA changes were obtained using satellite images, and volumetric variations were reconstructed from photogrammetric measurements.

3.1. Reconstruction of glacier surface mass balance from remote sensing

For temperate glaciers, the late-summer (September) snowline and the equilibrium line are very similar (Lliboutry, 1965; Braithwaite, 1984; Kuhn, 1989; Paterson, 1994). Moreover, the snowline is easy to discern on optical remote-sensing images (Fig. 2). As a result, it is possible to reconstruct variations in surface mass balance from changes in the ELA. The method has been described in detail and validated for three glaciers in the French Alps between 1994 and 2002 by Rabatel and others (2005). Only the basic principles are given here.

After geometrical and radiometrical correction of the remote-sensing images, we calculate the altitude of the snowline (henceforth considered to be the ELA) for each year over the study period (1981–2002) (written ELA_i) using a digital elevation model (DEM). The surface mass-balance series can then be reconstructed in two steps. First, we calculate for each year, i, the variation between ELA_i and ELA_{eq}, where ELA_{eq} is the theoretical altitude of the equilibrium line if the glacier were in steady state (mass balance = 0) for the studied period. It is written as

$$\mathrm{ELA_{eq}} = \frac{1}{n}\sum_{1}^{n} \mathrm{ELA}_i + \frac{\bar{B}}{\partial b/\partial z}, \qquad (1)$$

where $\bar{B}$ is the mean annual surface mass balance over 1981–2002 deduced from photogrammetry (see below), and $\partial b/\partial z$ is the mass-balance gradient at the ELA, fixed at 0.78 m w.e. $(100\,m)^{-1}$ according to Rabatel and others (2005). Rabatel and others demonstrated that even if $\partial b/\partial z$ for a specific glacier differs slightly from this value, using an average value on a regional scale does not depreciate the results.The surface mass balance, $b(t)$, computed for each year, t, from remote-sensing data at the level of ELA_{eq} can finally be expressed as

$$b(t) = \left(\mathrm{ELA_{eq}} - \mathrm{ELA}_i\right)\frac{\partial b}{\partial z}. \qquad (2)$$

The satellite images used are listed in Table 1. Some images do not match the end of the ablation season when cloud cover or early snowfalls recorded in September may prevent

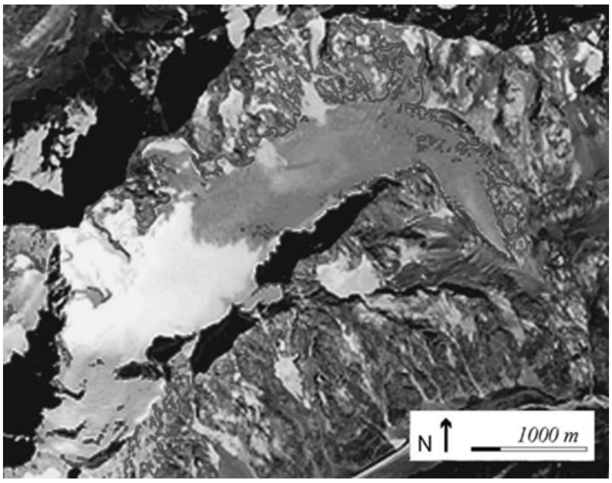

Fig. 2. SPOT-5 image of Glacier Blanc taken on 5 August 2005; pixel size: 10 m. © Centre National d'Etudes Spatiales SPOT Image.

detection of the snowline. Missing ablation values between the date of each satellite image and the end of the ablation season were computed using a cumulative positive degree-day (CPDD) model (see section 3.2) to homogenize the remote-sensing surface mass-balance series.

The 1981–2002 cumulative surface mass balance of Glacier Blanc was obtained by photogrammetric measurements from aerial photographs. Details can be found in Thibert and others (2005). The 1981 and 2002 photographs were taken on 29 July and 3 October, respectively (Table 2). Subtraction of the 2002 and 1981 DEM gives the total volumetric variation. The cumulative surface mass balance is calculated by dividing the total volumetric variation between the two dates by the mean surface area of the glacier, assuming a constant ice density of 0.9 g cm^{-3}. An ablation correction of +1.4 m w.e. was added, as the date of the 1981 photograph did not coincide with the end of the ablation season. This correction was calculated by the CPDD method using mean daily temperatures measured at Pelvoux weather station (see section 3.2). The cumulative surface mass balance at the end of the ablation season was thus found to be –10.8 m w.e. between 1981 and 2002. The overall error (at 95% confidence level) on the cumulated mass balance between 1981 and 2002 was found to be ±0.90 m w.e. (Thibert and others, 2005). Consequently, the mean annual surface mass balance calculated between 1981 and 2002, $\bar{B}$, is –0.51 m w.e. a^{-1}.

Note that the annual surface mass balance was reconstructed for 1981–2005, whereas $\bar{B}$ and ELA_{eq} (= 3040 m a.s.l.) were computed for 1981–2002. During 2002–05, surface mass balances computed from field measurements on the Glacier Blanc plateau were very negative and there was a significant loss in glacier surface area at the snout (4% of the total area of the glacier). As a result, the use of $\bar{B}$ and ELA_{eq} computed over 1981–2002 introduced a bias in the remote-sensing surface mass-balance computation for the last 3 years of the series. This bias was estimated from the surface area lost between 2002 and 2005 (0.18 km^2) and from the surface mass balance of this lost area inferred from the surface mass balance measurements made over the Glacier Blanc plateau. The resulting value, 0.18 ± 0.03 m w.e. a^{-1}, was added to the last 3 years of the series.

Table 1. Remote-sensing data

Satellite	Pixel size m	Path/row	Date
Landsat-3 MSS	75	211/029	18 Aug 1982
Landsat-4 TM	30	195/029	22 Sep 1983
Landsat-5 TM	30	195/029	31 Aug 1984
Landsat-5 TM	30	195/029	28 Sep 1985
SPOT-1 Pan	10	051/259	5 Oct 1986
Landsat-5 TM	30	195/029	18 Sep 1987
SPOT-1 XS	20	050/259	26 Sep 1988
Landsat-5 TM	30	195/029	13 Aug 1989
SPOT-1 XS	20	051/259	22 Jul 1990
SPOT-2 Pan	10	051/259	30 Aug 1991
SPOT-1 XS	20	051/259	17 Sep 1992
SPOT-2 XS	20	051/259	2 Sep 1993
SPOT-3 XS	20	051/259	15 Aug 1994
SPOT-2 XS	20	051/259	31 Aug 1995
SPOT-3 Pan	10	051/259	31 Jul 1996
SPOT-1 XS	20	051/259	30 Sep 1997
SPOT-4 XS	20	052/259	30 Aug 1998
SPOT-4 Pan	10	051/259	10 Sep 1999
SPOT-2 XS	20	051/259	15 Sep 2000
ASTER-1	15	195/029	7 Sep 2001
SPOT-5 Pan	10	051/259	14 Sep 2002
SPOT-2 Pan	10	051/259	22 Aug 2003
SPOT-5 XS	10	051/259	27 Aug 2004
SPOT-5 XS	10	051/259	5 Aug 2005

Notes: MSS: multispectral scanner; TM: Thematic Mapper; SPOT: Système Probatoire pour l'Observation de la Terre; ASTER: Advanced Spaceborne Thermal Emission and Reflection Radiometer.

3.2. Glacier surface mass balance derived from meteorological data

In addition, a surface mass-balance series was computed for Glacier Blanc at the mean altitude of the field measurements (3200 m a.s.l.) using meteorological data. The purpose is to compare these data with surface mass balances obtained using the remote-sensing method, especially for the period 1981–99 for which no field measurements are available.

The data came from three nearby stations: Cézanne (1870 m a.s.l.), a snow-measurement station maintained by Electricité de France, and two Météo-France weather stations, Pelvoux (1250 m a.s.l.) and Briançon (1324 m a.s.l.), located 1, 8 and 17 km, respectively, from the glacier (see Fig. 1a).

Winter mass balances were reconstructed from total solid precipitation over the winter period at Cézanne and Pelvoux weather stations. The winter mass-balance term can be expressed as

$$b_{winter} = C_{accumulation} \sum P, \quad (3)$$

where $C_{accumulation}$ is a coefficient that corresponds to the increase in accumulation with altitude (wind redistribution,

Table 2. Aerial photographs

Supplier	Scale	Date
Institut Géographique National (Inventaire Forestier National), France	1 : 17 000	29 Jul 1981
Sintegra	1 : 20 000	3 Oct 2002

Table 3. Glacier Blanc ELA determined from remote-sensing images, remote-sensing surface mass balance corrected with the CPDD method (RS MB) and surface mass balance computed from ground measurements made on the plateau at ~3200 m a.s.l. (GMB). As explained in section 2, GMB values do not represent the annual surface mass balance of the glacier but rather the local surface mass balance of the central plateau

Hydrological year	ELA	RS MB	GMB
	m a.s.l.	m w.e.	m w.e.
1980/81	3020	−0.40	
1981/82	3040	−0.09	
1982/83	3060	−0.06	
1983/84	3000	0.53	
1984/85	3130	−0.57	
1985/86	3100	−0.19	
1986/87	3180	−0.94	
1987/88	3160	−0.70	
1988/89	3170	−1.66	
1989/90	3060	−1.50	
1990/91	3100	−0.77	
1991/92	3150	−0.60	
1992/93	3140	−0.63	
1993/94	3030	−0.12	
1994/95	3060	0.07	
1995/96	2990	0.28	
1996/97	3070	−0.06	
1997/98	3170	−0.97	
1998/99	3190	−1.10	
1999/2000	3170	−0.82	0.90
2000/01	3030	0.28	1.73
2001/02	3220	−1.18	0.20
2002/03	3260	−1.43	−0.53
2003/04	3200	−0.55	−0.24
2004/05	3220	−1.85	−0.72

avalanches, etc.) and $\sum P$ is the measured value of precipitation. Values for $C_{\text{accumulation}}$ were obtained by correlation of data measured at the weather stations with data measured on the glacier. $C_{\text{accumulation}}$ values, 2.6 and 2.3 for Pelvoux and Cézanne, respectively, are within the 1–3 range observed by Vincent (2002) on four other French glaciers (Saint-Sorlin, Gébroulaz, Argentière and Mer de Glace). $\sum P$ is consistent with the cumulative snow height (expressed in water equivalent) observed in April at Cézanne meteorological station and with the cumulated daily precipitation at temperatures <0°C at 3200 m a.s.l. between 25 September and 15 May at Pelvoux station. This period matches field measurement dates. The temperature was calculated at 3200 m a.s.l. using temperature data recorded at Briançon and an assumed fixed temperature gradient, $\partial T/\partial z$, of –7.1°C km^{-1}.

Summer mass balances were estimated by the CPDD method using precipitation values from Pelvoux and temperature data from Briançon. With this method, widely used for other glaciers (e.g. Braithwaite and Zhang, 2000; Vincent 2002), the summer mass balance is expressed as follows:

$$b_{\text{summer}} = \sum_{t_1}^{t_2} \max\left[T(t) + \frac{\partial T}{\partial z}\left(z_{\text{glacier}} - z_{\text{station}}\right), 0\right] \times C_{\text{melt}} + \sum_{t_1}^{t_2} P_{\text{snow}},$$

where t_1 and t_2 are the dates of the beginning and end of the ablation period; $\sum_{t_1}^{t_2} P_{\text{snow}}$ is the solid precipitation amount for the summer period estimated using precipitation values recorded at Pelvoux station for the days with temperature around and below 0°C at ELA_{eq} (according to our data, this parameter can be neglected with regard to the other terms); z_{station} is the altitude of the weather station; z_{glacier} the average altitude of ground measurements; $T(t)$ the daily average temperature at Briançon; and C_{melt} the melt coefficient. A value of 0.004 m w.e. °C^{-1} d^{-1} was obtained for C_{melt} by fitting the data. This corresponds to the snowmelt values observed by Vincent (2002). At 3200 m a.s.l. the glacier is free of snow at the end of the ablation season only when surface mass-balance values are very negative. Between 1981 and 2005, this is the case for 2003, 2004 and 2005 only (see Table 3). For these three years, an ice-melt value was considered for C_{melt} (equal to 0.006 m w.e. °C^{-1} d^{-1} according to Vincent, 2002).

3.3. Errors in surface mass balances

Note that in the following paragraph, errors in the surface mass-balance computations are relative to one standard deviation.

According to Equations (1) and (2), remote-sensing surface mass-balance uncertainty depends on the computation of the equilibrium line, the mass-balance gradient, $\partial b/\partial z$, and the mean annual surface mass balance, $\bar{B}$. Uncertainties with respect to the position of the equilibrium line for each year, i, are within the interval 0.02–0.06 m w.e. a^{-1}, depending on the pixel size of the images and the slope of the surface (Rabatel and others, 2002, 2005). The standard error of $\partial b/\partial z$ results from its temporal and spatial variability. The temporal variability of $\partial b/\partial z$ is estimated to be ±0.078 m (100 m)$^{-1}$ (see fig. 5 of Rabatel and others, 2005), which results in an error of ±0.03 m w.e. a^{-1} in the computed mass balance. Using available surface mass-balance data on the Glacier Blanc central plateau for 1999–2005, the mean $\partial b/\partial z$ was found to be 0.89 ± 0.07 m (100 m)$^{-1}$. Its spatial variability in the vicinity of the ELA was estimated, using all the surface mass-balance measurements of the plateau, to be ±0.14 m (100 m)$^{-1}$, resulting in an error in surface mass balance of ±0.06 m w.e. a^{-1}. The error in the mean annual surface mass balance, $\bar{B}$, computed by photogrammetry was estimated to be ±0.20 m w.e. a^{-1}. Finally, the total error in the remote-sensing surface mass balance was found to be ±0.29 m w.e. a^{-1}.

The error for the surface mass balance computed with ground data has been estimated by Gerbaux and others (2005). On the basis of measurements made on Glacier de Saint-Sorlin, these authors reported uncertainties of ±0.1 m w.e. a^{-1} and –0.25 to +0.40 m w.e. a^{-1} in the individual surface mass balances obtained from ablation stakes and drilling cores, respectively. Given that annual field surface mass balances for Glacier Blanc were obtained from five to ten ablation stakes in the area of the ELA, the error should be reduced to roughly ±0.10 m w.e. a^{-1}.

Concerning the surface mass balance computed on the basis of meteorological data, uncertainties in both winter and summer mass balance have to be taken into account. For the winter mass balance, the error depends on the value of $C_{\text{accumulation}}$, which results in a combination of (1) the standard error related to the snow density measurements (estimated to be ±0.21 m w.e. on the basis of the

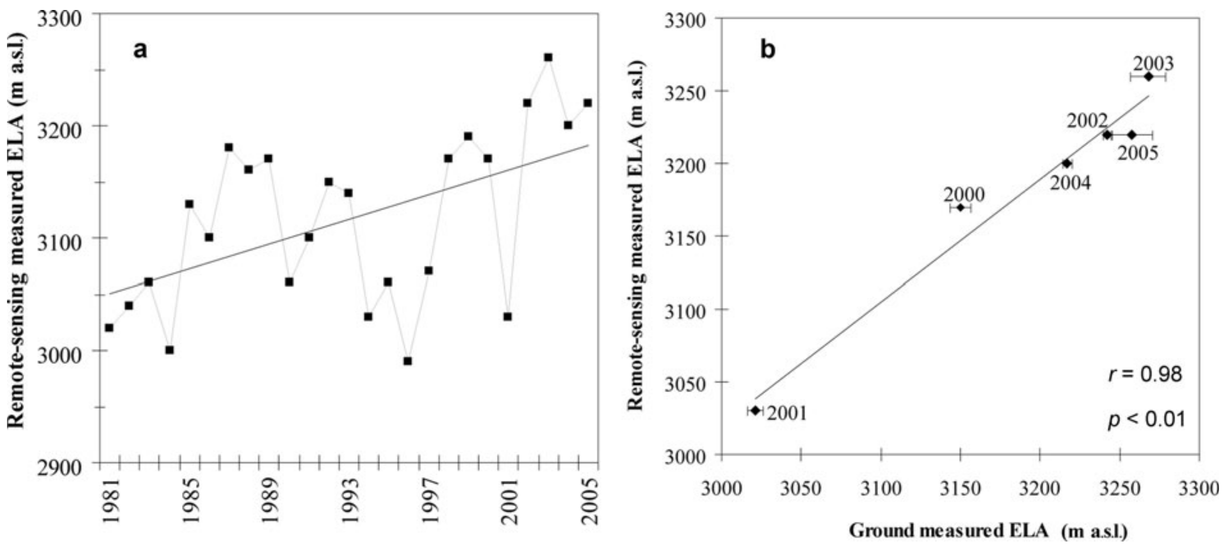

Fig. 3. (a) 1981–2005 Glacier Blanc ELA series computed using satellite images. For some years the ELA values do not match the end of the ablation season (see Table 1). Raw ELA values directly measured from the images are plotted here. (b) Comparison between ELAs derived from remote-sensing data and ELAs derived from ground measurements. Uncertainty bars on ELA values based on ground measurements represent the confidence intervals obtained from the linear regression of the mass balance with stakes. As for (a), for some years the ELA values do not match the end of the ablation season (see Table 1).

observations made on the glacier); (2) uncertainties in the precipitation measurements made using rain gauges (~5%); and (3) the spatial variability of accumulation on the Glacier Blanc plateau given by the standard deviation of the ground measurements and equal to ±0.53 m w.e. Thus $\Delta C_{\text{accumulation}}$ can be estimated at ±0.82. Considering the average winter accumulation amount over the whole period, the error in winter mass balance is ±0.27 m w.e. For the summer mass balance, $\partial T/\partial z$ and C_{melt} are the main sources of uncertainties in Equation (4).

Errors in the other terms, $T(t)$, z_{station}, z_{glacier} and $\sum_{t_1}^{t_2} P_{\text{snow}}$, are negligible. Uncertainty for C_{melt} can be estimated as 0.00088 m °C^{-1} d^{-1} on the basis of values compiled by Braithwaite and Zhang (2000). Temperature data from Chamonix and Aiguille du Midi weather stations reveal a standard deviation of ±0.02°C (100 m)$^{-1}$ for $\partial T/\partial z$ for the summer period. The error in the summer mass balance is thus ±0.33 m w.e. and, finally, the error in the annual surface mass balance computed with meteorological data is ±0.43 m w.e. a^{-1}.

4. RESULTS AND DISCUSSION

Results are of two types. We first present the measurements of the ELA (derived from identification of the snowline on the satellite images) and compare our results with the few ELA measurements made on Glacier Blanc. We then present the remote-sensing surface mass-balance series based on the ELA variation and compare it with field and meteorological surface mass balances computed for Glacier Blanc, and with field surface mass-balance series from five other French glaciers.

4.1. ELA reconstruction

Annual ELA values were estimated on Glacier Blanc from satellite images. These data are given in Table 3 and illustrated in Figure 3a. For 1981–2005, the mean ELA was located at 3117 m a.s.l. (standard deviation: $\sigma = 77$ m). During 1981–2005 the ELA of Glacier Blanc increased by ~140 m. This significant rise should, however, be interpreted with caution because the first and last 4 years represent extreme events with regard to the whole series. The early 1980s coincide with the end of a positive mass-balance period between about 1975 and 1984 (Vincent and others, 2004), and the first years of the 21st century have been among the warmest recorded since the beginning of direct temperature measurements. Taking only the 1985–2001 period into account, no significant trend can be observed.

Figure 3b illustrates the comparison between the ELA obtained from satellite images and the ELA calculated from field measurements, showing good agreement ($r = 0.98$, $p < 0.01$) over this 6 year period. This confirms that the snowline measured using satellite images constitutes an accurate proxy of the ELA and can thus be used to compute the mass balance, as already shown in previous studies (e.g. Braithwaite, 1984; Rabatel and others, 2005).

4.2. Comparison between the three surface mass-balance series

On the basis of the ELA series measured using remote sensing, the annual surface mass balance of Glacier Blanc was reconstructed using the protocol presented in section 3. Table 3 presents these reconstructed surface mass balances corrected with the CPPD method and surface mass balances calculated from field measurements. Figure 4 shows the comparison between the different series based on remote sensing, meteorological measurements and field measurements on the central plateau.

The correlation between the remote-sensing surface mass balance and the Pelvoux/Cézanne meteorological surface mass balance or the field surface mass-balance series is always significant at the 1% threshold (0.71, 0.67 and 0.85, respectively). The standard deviation of the difference between the centred series is 0.44 m w.e. for Pelvoux, 0.52 m w.e. for Cézanne and 0.56 m w.e. for field measurements. The agreement between the results of the different

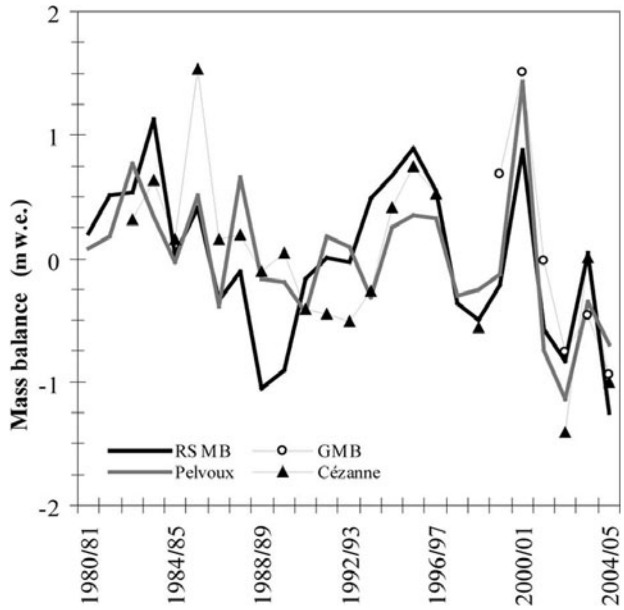

Fig. 4. Mass-balance time series for Glacier Blanc, 1981–2005. The plotted values are centred, i.e. they represent deviations from the mean. RS MB is remote-sensing mass balance corrected with the CPDD method; Pelvoux and Cézanne are mass-balance series reconstructed from meteorological data provided by Pelvoux and Cézanne weather stations, respectively; GMB is the local surface mass balance calculated from direct ground measurements for the central plateau (see section 2 and Table 3). Error bars are not shown, to improve legibility. At the 95% confidence interval (two standard deviations), errors on RS MB, Pelvoux/Cézanne and GMB are, respectively, equal to ±0.6, ±0.86 and ±0.2 m w.e. (see section 3.3).

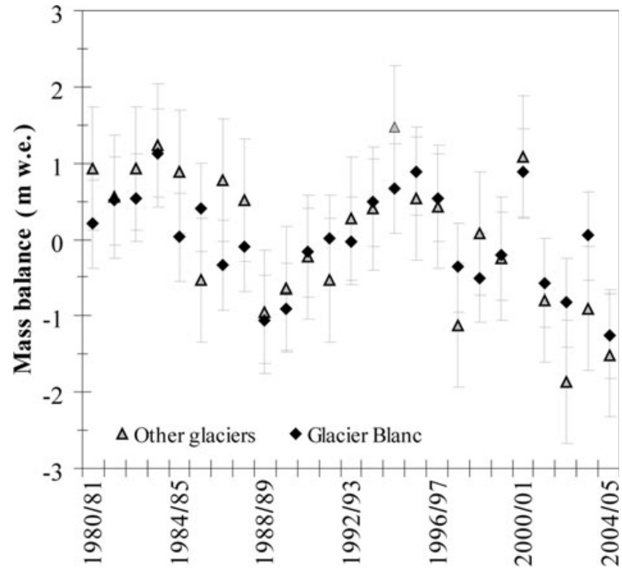

Fig. 5. Comparison of mass-balance series of French alpine glaciers. Glacier Blanc: black diamonds represent centred values computed by remote sensing and corrected with the CPDD method; vertical bars (black line) represent the 95% confidence interval. Other glaciers: triangles represent the average of the centred mass-balance series of five monitored glaciers in the French Alps (Argentière, Tacul, Gébroulaz, Saint-Sorlin and Sarennes); vertical bars (dashed line) represent the 95% confidence interval.

methods (remote-sensing, meteorological and field measurements) shows that data derived from remote sensing are valid.

4.3. Comparison with surface mass-balance time series of other alpine glaciers

The Glacier Blanc series was also compared to surface mass-balance series from five French alpine glaciers monitored using the glaciological method: Glaciers d'Argentière and du Tacul in the Mont Blanc area, Glacier de Gébroulaz in the Vanoise area and Glaciers de Saint-Sorlin and de Sarennes in the Grandes Rousses area. The mean annual surface mass balances of these five glaciers and the annual surface mass balance of Glacier Blanc are shown in Figure 5. Both series have been centred, i.e. the plotted values are deviations from the mean. The 95% confidence intervals of the surface mass balances of the five glaciers were computed from the standard deviation obtained for each year from measurements of the five glaciers. These confidence intervals show roughly the spatial variability of the surface mass balance in the French Alps. The 95% confidence interval of the Glacier Blanc series corresponds to two standard deviations of the surface mass balance obtained by remote sensing. There is overall agreement between the two series. The correlation is significant at the 1% threshold ($r = 0.76$). Moreover, the 95% confidence interval of the Glacier Blanc series is consistent with the 95% confidence interval of the other glacier surface mass-balance series. The standard deviation of the differences between these centred series is 0.35 m w.e.

However, in spite of this good agreement, Figure 5 reveals an interesting feature of Glacier Blanc, i.e. the temporal variability of the surface mass balance. Indeed, interannual variability of the surface mass balance of Glacier Blanc based on remote sensing, represented by its standard deviation ($\sigma = 0.65$ m w.e.), is lower than that of the mean of the five other glaciers ($\sigma = 0.90$ m w.e., varying between 0.77 (Glacier d'Argentière) and 1.15 m w.e. (Glacier de Sarennes)). This discrepancy can be explained by the following features:

On the one hand, the surface mass balance of Glacier Blanc based on remote sensing was derived from measurements of the ELA and, consequently, computed at the level of ELA_{eq}, i.e. 3040 m a.s.l. For the other glaciers, the surface mass balance was computed from field measurements performed over the whole surface area of the glacier with numerous observations in the ablation zone (~2300 m a.s.l. for Glacier du Tacul, 2400–2800 m a.s.l. for Glacier d'Argentière, 2700–2850 m a.s.l. for Glacier de Gébroulaz, 2700–2900 m a.s.l. for Glacier de Saint Sorlin and 2900–3050 m a.s.l. for Glacier de Sarennes). Given that the variability of the annual surface mass balance decreases with altitude (Vallon and others, 1998), it is not surprising that the variability of the surface mass balances inferred from ELA changes is lower than that of the surface mass balances obtained from field measurements. Moreover, the sensitivity of summer ablation to temperature decreases with altitude to reach a value close to 0.5 m w.e. $^{\circ}C^{-1}$ in the area of the equilibrium line, and the accumulation sensitivity to precipitation increases with altitude (Vincent, 2002). Consequently, the observed lower interannual variability of the surface mass balance of Glacier Blanc based on remote sensing could result from the lower sensitivity of the surface mass balance to parameters governing ablation at the ELA, and from its higher sensitivity to winter accumulation, for which interannual variability is lower than that of ablation.

On the other hand, local/regional variations in winter accumulation (Glacier Blanc being the only glacier in this study located in the southern French Alps) might also have an influence on the observed lower interannual variability of the Glacier Blanc surface mass balance. This assumption has been tested using winter precipitation measurements (October to May) from six weather stations, including three in the northern French Alps and three in the southern French Alps. Even if a difference in the total winter precipitation can be noted (average values of 757 and 577 mm w.e. for the northern and southern weather stations, respectively, for 1981–2005), their interannual variability is similar ($\sigma = 161$ and 181 mm w.e for the northern and southern stations, respectively). More direct accumulation measurements on the glacier are needed before any conclusion can be drawn on the influence of winter precipitation on the interannual surface mass-balance variability of Glacier Blanc.

5. CONCLUSION

This study presents new series of ELA and surface mass balances computed for Glacier Blanc using satellite images and photogrammetric data for 1981–2005. Annual ELAs were measured from optical satellite images and used to compute the glacier surface mass balance following the protocol validated by Rabatel and others (2005). The resulting remote-sensing surface mass-balance series was adjusted using the CPDD method to homogenize the series. Another Glacier Blanc surface mass-balance series was computed using meteorological data from three nearby weather stations. The good correlation between these surface mass-balance series shows that these methods are consistent. Furthermore, the correspondence between the present results and the surface mass balances of five other glaciers monitored in the French Alps is encouraging. However, this comparison revealed that the interannual variability of the surface mass balance of Glacier Blanc based on remote sensing is lower. This difference can be explained by the decreasing sensitivity of surface mass balance to climate change with increasing altitude. Although changes in ELA do not comprise total mass-balance variability, the surface mass-balance data obtained from ELA changes by remote sensing are closely correlated with annual surface mass balances.

This study has produced a 25 year series of annual surface mass balance for Glacier Blanc. Only a short, 6 year, local surface mass-balance series of the Glacier Blanc central plateau was previously available. This improves our knowledge of the past balance variations of this glacier. The next step is to apply the remote-sensing method to the many glaciers for which no ground observations exist. This will be of interest to related remote-sensing programs such as GLIMS (Global Land Ice Measurements from Space) and GlobGlacier, funded respectively by the National Snow and Ice Data Center (NSIDC), Boulder, USA and the European Space Agency and for the addition of ELA and surface mass-balance series to glaciological databases such as the World Glacier Inventory (NSIDC) and the World Glacier Monitoring Service, Zürich, Switzerland.

ACKNOWLEDGEMENTS

We are grateful to the space agencies that provided satellite images through CNES–Isis/SPOT-Image contracts No. 0103-157 and 0412-725, and to the GLIMS Program for ASTER images. We are also grateful to G. Bonne (Groupement pour le Développement de la Télédelection Aerospatiale/Centre National d'Etudes Spatiales, France); J. K. Austrad and J. L. Dwyer (Technical Support Services, US Geological Survey National Center) and R. Armstrong (NSIDC) for providing LandsatMSS and LandsatTM data. We thank the Parc National des Ecrins for allowing us to use unpublished measurements of mass balance and snout fluctuations on Glacier Blanc, all those who carried out field measurements and L. Reynaud for his involvement in this work. We also thank H. Rott (Scientific Editor), M. Demuth and two anonymous referees for helpful comments and suggestions. This study was funded by the French Glacier Observatory Service (Observatoire des Sciences de d'Univers de Grenoble–Institut National des Sciences de l'Univers) and the 'Observation de la Terre' ACI (French Ministry of Research). Electricité de France provided the Cézanne snow measurements, and Météo-France provided meteorological data from Pelvoux and Briançon stations.

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MS received 28 April 2007 and accepted in revised form 30 January 2008