Recent rapid thinning of the "Mer de Glace" glacier derived from satellite optical images

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[1] The rapid wastage of mountain glaciers and their contribution to sea level rise require worldwide monitoring of their mass balance. In this paper, we show that changes in glacier thickness can be accurately measured from satellite images. We use SPOT image pairs to build Digital Elevation Models (DEMs) of the Mont Blanc area (French Alps) for different years. To register the DEMs, we adjust their longitude, latitude and altitude over motionless areas. The uncertainty of the thickness change measurement is greatly reduced by averaging over areas covering altitude intervals of 50 m. Comparisons with topographic profiles and a differential DEM from aerial photographs obtained on the *Mer de Glace* indicate an overall accuracy of 1 m for the thickness change measurement. Below 2100 m, satellite DEMs show an evolution of the thinning rate from 1 ± 0.4 $m.a^{-1}$ (years 1979–1994) to 4.1 ± 1.7 $m.a^{-1}$ (2000–2003). *INDEX TERMS:* 1224 Geodesy and Gravity: Photogrammetry; 1640 Global Change: Remote sensing; 1827 Hydrology: Glaciology (1863); 1884 Hydrology: Water supply. **Citation:** Berthier, E., Y. Arnaud, D. Baratoux, C. Vincent, and F. Rémy (2004), Recent rapid thinning of the ''Mer de Glace'' glacier derived from satellite optical images, *Geophys. Res. Lett.*, *31*, L17401, doi:10.1029/2004GL020706.

1. Introduction

[2] Mountain glaciers are considered to be a reliable indicator of climate change [*Intergovernmental Panel on Climate Change*, 2001]. Even if they only represent 4% of the cryosphere, they contribute to 27% of the sea level rise observed between 1988 and 1998 [*Dyurgerov*, 2003].

[3] Measuring mass balance is a straightforward approach for quantifying the temporal evolution of glaciers. It is directly related to local climate variability. Yearly changes in precipitation and/or energy balance affect the accumulation or ablation on the glacier [*Vincent*, 2002]. Mass balance is also a direct measurement of the contribution of glaciers to sea level rise [*Rignot et al.*, 2003]. Although the length of glaciers can be used as a climate indicator [*Oerlemans*, 1994], the low correlation between terminus position and volume change at short time scale [*Arendt et al.*, 2002] reinforces the need of mass balance measurements.

[4] The traditional way to measure mass balance, known as the glaciological method [*Paterson*, 1994], is time-consuming and difficult in harsh environment. According to *Braithwaite* [2002], only 246 mountain glaciers are (or have been) monitored with this method, representing less than 2% of their global area. There is a regional bias in these measurements: two thirds of the monitored glaciers are located in North America and Europe.

[5] Remote sensing provides a suitable way to increase the number of monitored glaciers, especially in remote areas. Most remote sensing approaches are based on the "geodetic" method [*Finsterwalder*, 1954], of comparing two maps or DEMs of the same area established during different years. If both maps cover the whole glacier, their difference, the volume change, can be converted to mass balance assuming a constant density of 900 $kg.m^{-3}$ [*Andreassen et al.*, 2002]. In this study, we address only the problem of measuring thickness change and not its conversion to mass balance.

[6] Differential DEMs derived from aerial photographs are considered as the most reliable measurement of mass balance over one or several decades [*Andreassen et al.*, 2002] and, thus, are used to check the quality of cumulative mass balance determined by the glaciological method [*Krimmel*, 1999]. This approach is limited by the small coverage of the photographs (30 to 40 km^2) and is generally restricted to glaciers already monitored on the field. Thus, it is not a suitable way to extend mass balance measurement to a large number of glaciers. Recently, airborne laser altimetry has also proved to be an efficient tool to estimate the volume change of glaciers [*Echelmeyer et al.*, 1996; *Baltsavias et al.*, 1999]. Its accuracy in the accumulation area and the possibility to extract thickness changes rapidly for large glaciers [*Arendt et al.*, 2002] are the advantages of this method. Yet, the cost and the limited sampling are important drawbacks.

[7] Applying the geodetic method to satellite images is a third way to measure mass balance by remote sensing. In this paper, we derived for the first time from satellite DEMs an accurate measurement of thickness change for a mountain glacier. We validate our results by comparison with topographic and aerial photographs measurements. The *Mer de Glace*, the largest glacier in the French Alps, has been chosen as the test area because good satellite image pairs are available and ground surveys are performed yearly.

2. Methodology

[8] Our approach adapts the geodetic method to satellite images. The first step calculates the DEMs. Some adjustments and corrections are needed to reduce the biases between the DEMs. The mean thickness change is then extracted for each altitude intervals on the glacier.

2.1. Construction of Satellite DEMs

[9] DEMs are calculated from pairs of SPOT satellite images with opposite incidence angles and short time

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Table 1. Satellite Images Used in This Study

Date	Sensor	Incidence Angle	Gain
1994-10-16	SPOT3	−4.6	7
1994-10-17	SPOT3	−30.3	8
2000-08-25	SPOT2	−22.3	6
2000-08-25	SPOT1	20.9	7
2000-08-29	SPOT4	−28.3	3
2000-08-29	SPOT2	+9.7	7
2003-08-19	SPOT5	−15.2	1
2003-08-23	SPOT5	+15.7	1

separation using the PCI Geomatica software as described by *Toutin and Cheng* [2002]. The main steps are the orientation of level 1A images from ground control points (GCPs), transformation to epipolar geometry, parallax-matching, and parallax-to-DEM conversion. The same set of 30 precise GCPs, measured in 2003 during a differential GPS (DGPS) field campaign to within ±0.5 m, is used for all the images.

[10] Following this method, we calculate satellite DEMs for 1994, 2000 and 2003 (Table 1). In 1994 and 2000, SPOT panchromatic images with 10 m ground resolution are used. For 2003, the DEM is deduced from SPOT5-THR images with a 2.5 m ground resolution. The same software is used to calculate DEMs from aerial photographs for 2000 and 2003.

2.2. Adjustment of the Different DEMs

[11] Even with a consistent set of GCPs, we observe some biases between the different DEMs off the glaciers, where no elevation change is expected. We attribute these biases to the non-uniform distribution of the GCPs in altitudes. To correct these biases, the 2003 DEM, the most accurate, is chosen as reference and the other DEMs are adjusted to this reference in two steps.

[12] The first adjustment corrects the shifts in latitude and longitude. This step is important because a small horizontal offset between two DEMs can produce a large elevation error where the topographic slope is steep. For each DEM, the corresponding orthorectified image is calculated. Where no movement is expected, off the glaciers, a precise cross correlation of each image with the 2003 reference image leads to a map of horizontal offsets in latitude and longitude. We then apply these shifts to correct the DEMs. The shifts are all less than 3 m and their standard deviation is of the order of 1 m. Combined with a mean slope of 18° for the *Mer de Glace*, it leads to an uncertainty of 0.4 m in elevation.

[13] After this adjustment, the difference between the DEMs does not show any spatial pattern and is corrected with an altimetric adjustment. For each altitude intervals on the unglaciated area, we compute the mean difference between each DEM and the reference 2003 DEM. Figure 1 illustrates how this bias is corrected in the case of the 2000 DEM. A fourth order polynomial curve provides a good approximation of this bias: it is used to correct all the altitudes in the 2000 DEM. After adjustment, the bias is never greater than 2 m, the value we interpret as the uncertainty introduced by this correction. This is a mean value but, locally, due to shadowing effects or steep slopes the bias can be larger.

2.3. Ablation Correction

[14] A thickness change on the glacier can be interpreted if the measurements are performed each year close to the end of the ablation season [*Krimmel*, 1999], near the 15th September in the French Alps. Since our different data sets (satellite images, aerial photographs and GPS measurements) do not meet this condition, we have to take into account the ablation occurring between the date of survey and the 15th September. Ablation is estimated from an empirical degree-day model tuned with field measurements [*Vincent*, 2002]. Each positive degree at a given altitude on the glacier is converted to an ablation of 6.6 mm of ice. The daily temperature is calculated from the temperature of the nearby Chamonix weather station assuming a constant lapse rate of 6°/km. The uncertainty induced by this correction is proportional to the time difference between the survey and the 15th September. It is never greater than 0.5 m. Future studies should plan to acquire data very near to the end of the ablation season, but before the first snowfall. They could also use an ablation model taking into account varying solar orientation.

2.4. Extraction of the Mean Thickness Change

[15] At each position, we now compute the difference between the younger and the older DEM, such that thickening is reckoned positive. The right panel in Figure 2 shows the satellite differential DEM for the 2000–2003 period. A vertical accuracy of the order of the pixel size is assumed for DEMs derived from optical images [*Toutin and Cheng*, 2002], i.e., 10 m for our DEMs, except the one derived from SPOT5 images. Although this is not precise enough to measure the thickness change for each individual pixel on the glacier, we can reduce the uncertainty assuming that all points at a given altitude experience the same thickness change. For each 50 m altitude interval, we compute the histogram of the thickness change. The distribution is well-approximated by a Gaussian curve (Figure 2), which permits the calculation of the mean thickness change as the mean of all the values less than 3 σ from the mean. The scatter is explained by two reasons. First, shadowing and debris coverage on the glacier make the assumption of a similar behaviour for all points at a given altitude only partly true. The scatter also reflects the random errors in the two DEMs. Accordingly, this standard deviation is a reasonable first assessment of the uncertainty in the thickness change measurement.

[16] The total uncertainty can be estimated by the quadratic sum of the different independent errors in the processing: errors in the two compared DEMs, errors introduced by the planimetric, altimetric adjustments and due to our correction of the ablation. This equation yields an overall uncertainty of 14 m, mainly due to the errors in the

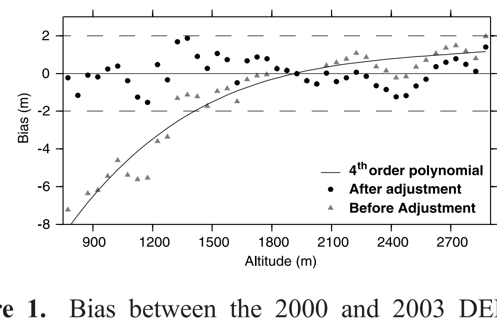

Figure 1. Bias between the 2000 and 2003 DEM as a function of altitude on the unglaciated areas before (gray triangles) and after adjustment (black circles).

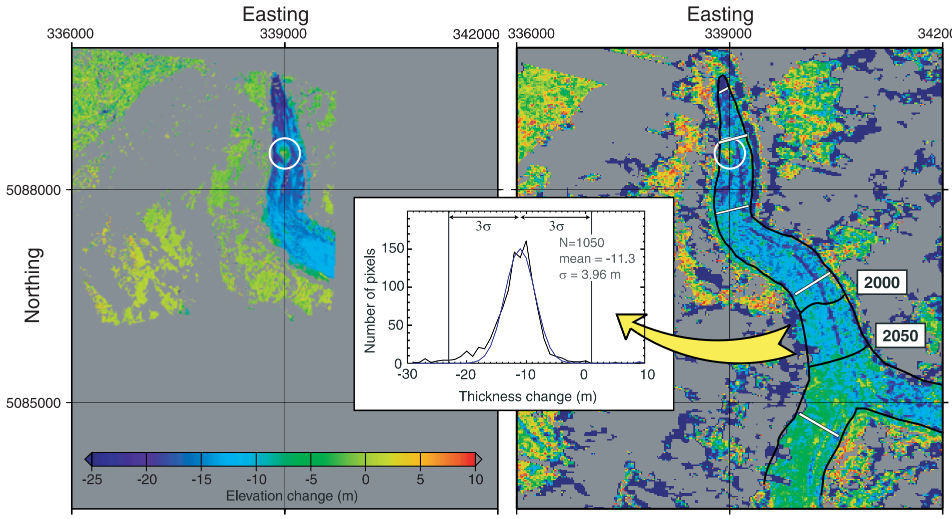

Figure 2. Differential DEMs for the 2000–2003 period derived from aerial photographs (left panel) and satellite images (right panel). A debris-covered area on the glacier is surrounded by a white circle. The white lines (right panel) locate the topographic profiles. The histogram of the thickness change for the 2000–2050 m altitude interval is drawn in black in the center of the figure. The distribution is well approximated by a Gaussian curve (blue line).

satellite DEMs. This uncertainty is large compared to the thickness change, that we expect to be of the order of a few meters. But it is reduced by averaging. If the scatter observed in the histogram in Figure 2 was purely due to Gaussian noise, this uncertainty would be divided by the square root of the number of pixels within an altitude interval (around 500), and would vary from 0.5 to 1 m. To account for non-Gaussian (systematic) effects such as local thickness change variations, the true validation is obtained by comparison with ground truth.

3. Validation of Our Methodology

[17] In 2000, DEMs were calculated from satellite image pairs acquired the 25th and the 29th of August. Since August 29th DEM includes only the northern part of the *Mer de Glace*, the differential DEM covers the lower part of the glacier from 1500 to 2050 m. Using altitude intervals of 50 m, we obtain 11 measurements of thickness change. The surface of the glacier is 1.3 m (σ = 1.28 m, N = 11) lower on the 29th DEM than on the 25th. Of this, ablation deduced from the degree-day model, explains around 0.34 m (0.3 m at 2050 m altitude and 0.39 m at 1500 m). The remaining 0.96 m is the uncertainty on our measurement.

[18] In Figure 3, we compare the thickness change derived from satellite differential DEMs to topographic transverse surveys performed each year on the glacier, with a typical accuracy of 0.3 m. Five profiles are measured each year on the lower part of *Mer de Glace* at locations shown in Figure 2. For the 1994–2000 time interval, the agreement is excellent. For the 2000–2003 time interval, the agreement is also good except for the measurement at 1690 m where the topographic profile gives a thinning of 16.7 m but the satellite measurement 12 m. This difference is explained by the fact that the satellite measurement includes an area where the glacier is covered by debris (Figure 2) which slows the ablation between 1690 and 1760 m. The topographic profile, performed on bare ice just downstream of the debris-covered area, is not affected by this limited ablation. For the nine remaining measurements, we interpolate the satellite measurements at the altitude of the topographic profile to find a mean difference of 0.65 m (σ = 1.57 m, N = 9).

[19] In Figure 2, we compare the spatial distribution of thickness change for the 2000–2003 period deduced from aerial photographs and satellite images. Despite its coarser spatial resolution, the satellite differential DEM is able to capture the small-scale features of the thickness change map. For example, the debris-covered area has the same extent in both differential DEMs. Between 1500 and 1950 m (9 altitude intervals of 50 m), the mean difference between the two differential DEMs is 1.14 m (σ = 1.67 m, N = 9).

4. Evolution During the Last 25 Years

[20] From satellite DEMs for 1994, 2000, 2003 and an aerial DEM for 1979 (obtained from the French National Geographic Institute), the rate of thickness change for each

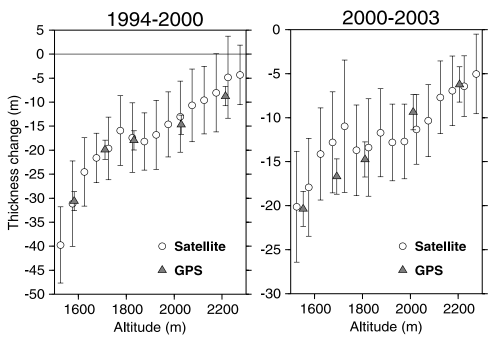

Figure 3. Comparison of the thickness change extracted from satellite images (circles) and deduced from topographic (traditional or DGPS) measurements (triangles). The left panel show the thickness change for the 1994–2000 time interval, the right panel for 2000–2003.

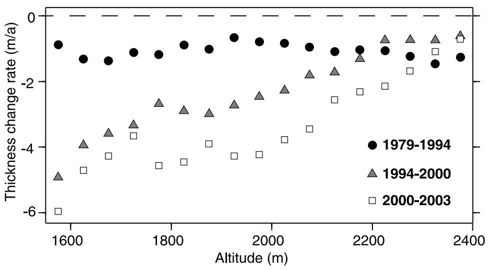

Figure 4. Rate of thickness change on the lower *Mer de Glace* for the last 25 years. The errors bars were not added to preserve the clarity of the figure.

period is calculated. At altitudes over 2500 m, our data does not permit any definitive conclusion. Indeed, in the snow-covered accumulation area, the weak contrast of the images reduces the accuracy of the DEMs. At lower altitude (Figure 4), the thinning rate is strong during the last 10 years. Between 1600 and 2100 m, it increased markedly from 1 ± 0.4 m.a^{-1} (1979–1994) to 4.1 ± 1.7 m.a^{-1} (2000–2003), with a value of 2.9 ± 1.1 m.a^{-1} for 1994–2000.

[21] It is beyond the scope of this paper to explain this rapid thinning at low altitude. It is probably the delayed response of the glacier to a series of negative mass balances during the period 1982–2002. An enhanced and longer summer ablation is responsible for this loss of mass and is related to the regional increase of the air temperature [*Vincent et al.*, 2004]. Only modelling of the ice fluxes based on a good knowledge of the ice flow could lead to an explanation of this rapid thinning.

5. Conclusion

[22] In this study, we have demonstrated that accurate thickness changes of mountain glaciers can be derived from satellite data. We used some simple, but precise, adjustments and statistical procedures to reach an overall accuracy of 1 m for the thickness change. Moreover, the satellite differential DEM is also able to capture the spatial pattern of the thickness change map. Our data show a rapid thinning of the *Mer de Glace* during the last 10 years below 2500 m.

[23] To validate our methodology, we have focused on the *Mer de Glace*. We plan now to extend this work to other glaciers of the Mont Blanc area, included in our images, to study the effect of slope and orientation on their wasting. Here, we have concentrated on the glacier thickness changes at low elevations and could not calculate the total mass budget of the glacier. Indeed, this budget can only be determined if the two compared DEM covers the whole glacier. Only the 2003 DEM, derived from SPOT5 scenes, meets this requirement because the images were acquired with the low gain needed for contrast in the snow-covered accumulation area. In the near future, another accurate SPOT5 DEM over the Mont Blanc glaciers could allow us to calculate their total mass balance.

[24] Now that accurate thickness change can be derived from satellite images, glaciologists can take advantage of their large footprints (3600 km^2 for SPOT images), 100 times larger than an aerial photograph. Satellite images also enable monitoring of remote area at regular intervals. The accuracy of our thickness change measurements is of the order of 1 m, i.e., 1/10th of the pixel size. In the near future, applying our method to satellite optical images with sub-meter resolution could monitor the thickness change of remote glaciers with a precision of the order of 10 cm.

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References

Andreassen, L. M., H. Elvehy, and B. Kjllmoen (2002), Using aerial photography to study glacier changes in Norway, *Ann. Glaciol.*, *34*, 343–348.
Arendt, A. A., K. A. Echelmeyer, W. D. Harrison et al. (2002), Rapid wastage of Alaska glaciers and their contribution to rising sea level, *Science*, *297*, 382–386.
Baltsavias, E. P., E. Favey, A. Bauder et al. (1999), Digital surface modelling by airborne laser scanning and digital photogrammetry for glacier monitoring, *Photogramm. Rec.*, *17*, 243–273.
Braithwaite, R. J. (2002), Glacier mass balance: The first 50 years of international monitoring, *Prog. Phys. Geogr.*, *26*, 76–95.
Dyurgerov, M. B. (2003), Mountain and subpolar glaciers show an increase in sensitivity to climate warming and intensification of the water cycle, *J. Hydrol.*, *282*, 164–176.
Echelmeyer, K., W. Harrison, C. Larsen et al. (1996), Airborne surface profiling of glaciers: A case-study in Alaska, *J. Glaciol.*, *42*, 538–547.
Finsterwalder, R. (1954), Photogrammetry and glacier research with special reference to glacier retreat in the eastern Alps, *J. Glaciol.*, *2*, 306–315.
Intergovernmental Panel on Climate Change (2001), *Climate Change 2001: The Scientific Basis*, edited by J. T. Houghton et al., Cambridge Univ. Press, New York.
Krimmel, R. M. (1999), Analysis of difference between direct and geodetic mass balance measurements at South Cascade glacier, Washington, *Geogr. Ann.*, *81A*, 653–658.
Oerlemans, J. (1994), Quantifying global warming from the retreat of glaciers, *Science*, *264*, 243–245.
Paterson, W. S. B. (1994), *The Physics of Glaciers*, 3rd ed., Pergamon, New York.
Rignot, E., A. Rivera, and G. Casassa (2003), Contribution of the Patagonia icefields of South America to sea level rise, *Science*, *302*, 434–437.
Toutin, T., and P. Cheng (2002), A comparison of automated DEM extraction results using along-track ASTER and across-track SPOT stereo images, *Opt. Eng.*, *41*, 2102–2106.
Vincent, C. (2002), Influence of climate change over the 20th century on four French glacier mass balances, *J. Geophys. Res.*, *107*(D19), 4375, doi:10.1029/2001JD000832.
Vincent, C., G. Kappenberger, F. Valla et al. (2004), Ice ablation as evidence of climate change in the Alps over the 20th century, *J. Geophys. Res.*, *109*, D10104, doi:10.1029/2003JD003857.
Wessel, P., and W. H. F. Smith (1998), New, improved version of Generic Mapping Tools released, *Eos Trans. AGU*, *79*(47), 579. [version 3.1]

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