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Glacier topography and elevation changes from Pléiades very high resolution stereo images

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Abstract

In response to climate change, most glaciers are losing mass and hence contribute to sea-level rise. Repeated and accurate mapping of their surface topography is required to estimate their mass balance and to extrapolate/calibrate sparse field glaciological measurements. In this study we evaluate the potential of Pléiades sub-meter stereo imagery to derive digital elevation models (DEMs) of glaciers and their elevation changes. Our five validation sites are located in Iceland, the European Alps, the Central Andes, Nepal and Antarctica. For all sites, nearly simultaneous field measurements were collected to evaluate the Pléiades DEMs. For Iceland, the Pléiades DEM is also compared to a Lidar DEM. The vertical biases of the Pléiades DEMs are less than 1 m if ground control points (GCPs) are used, but reach up to 6 m without GCPs. Even without GCPs, vertical biases can be reduced to a few decimetres by horizontal and vertical co-registration of the DEMs to reference altimetric data on ice-free terrain. Around these biases, the vertical precision of the Pléiades DEMs is ±1 m and even ±0.5 m on the flat glacier tongues (1-sigma confidence level). We also demonstrate the high potential of Pléiades DEMs for measuring seasonal, annual and multi-annual elevation changes with an accuracy of 1 m or better. The negative glacier-wide mass balances of the Argentière Glacier and Mer de Glace (-1.21 ± 0.16 and -1.19 ± 0.16 m.w.e. yr^{-1}, respectively) are revealed by differencing SPOT5 and Pléiades DEMs acquired in August 2003 and 2012 demonstrating the continuing rapid glacial wastage in the Mont-Blanc area.

1 Introduction

In a context of nearly global glacier wastage, new tools to retrieve accurate and comprehensive measurements of glacier topography and elevation changes are welcome. Digital elevation models (DEMs) are always needed to properly orthorectify satellite images and to extrapolate point-wise glaciological mass balance measurements to entire ice bodies (Kääb et al., 2005). The geodetic method, based on the differencing of multi-temporal DEMs, has been used for decades to retrieve glacier-wide and region-wide glacier mass balances (e.g. Bamber and Rivera, 2007; Finsterwalder, 1954). This method reveals the spatial patterns of elevation changes over individual glaciers or entire regions. Furthermore, the differences between multi-temporal DEMs derived from aerial photos and/or airborne Lidar can be used to check and, if necessary, correct cumulative mass balances measured using the field-based glaciological method over periods of typically 5–10 years (e.g. Abermann et al., 2010; Jóhannesson et al., 2013; Soruco et al., 2009b; Zemp et al., 2013). However, airborne sensors cannot acquire data everywhere on Earth because of the logistical difficulties involved in flying an airplane over some remote regions (e.g. high-mountain Asia, polar regions). Lidar data from the ICESat satellite mission (and from the future ICESat-2) remain too sparse to provide a comprehensive coverage of individual glaciers and hence mass balances can be retrieved reliably only for sufficiently large (and thus well-sampled) regions (Arendt et al., 2013; Gardner et al., 2013; Kääb et al., 2012). The geodetic method has also been applied extensively to DEMs derived from spaceborne optical or radar sensors (e.g. Gardelle et al., 2013) but the vertical errors of these DEMs (typically ±5 m for the Shuttle Radar Topographic Mission – SRTM – and for Satellite pour l'Observation de la Terre – SPOT – DEMs) and their resolution (40 m to 90 m) limits the possibility of retrieving accurate glacier-wide mass balances on individual small to medium size glaciers (typically less than 10 km^2) for time periods of only a few years (typically less than 5 years). DEMs derived from sub-meter stereo images have the potential to fill this gap between coarse spaceborne DEMs and high resolution DEMs from aerial surveys.

After the launch of the first non-military sub-meter resolution satellite (Ikonos) in September 1999 and until recently, relatively little work was carried out on deriving DEMs from these images over glaciers, probably due to the cost of the images. However, over the last 2–3 years, interest in these datasets has grown due to easier accessibility by researchers (e.g. Haemmig et al., 2014; Sirguey and Cullen, 2014). In the US, WorldView-1,-2 images are distributed by the Polar Geospatial Center (PGC) to US-funded researchers (Noh and Howat, 2014a and b). Since the launch of the Pléiades 1A and 1B satellites, high resolution images have become available for researchers from the European Union through the ISIS program of the French Space Agency, CNES (http://www.isis-cnes.fr/). In this context, the goal of the present study is to assess the accuracy of the DEMs retrieved from Pléiades stereo images and to test their potential to estimate glacier elevation changes at seasonal, annual and multi-annual time scales.

2 Pléiades images and DEM generation

2.1 Study areas

Pléiades stereo pairs acquired in five different regions are used in this study (Fig. 1). The study sites were selected to represent a variety of glacial settings ranging from the small (1 km^2) Agua Negra Glacier in the high (> 5000 m a.s.l.), steep and arid Andes of Argentina to the flat and 7 km wide Astrolabe Glacier, an outlet glacier of the East Antarctic Ice Sheet in Adélie Land. The main reason for selecting these glaciers was that they were all targets of ongoing field programs (Björnsson et al., 2013; Le Meur et al., 2014; Vincent et al., 2009, 2014; Wagnon et al., 2013) so that accurate reference data were available. A Pléiades image is shown for each study site in Fig. 2.

2.2 Pléiades stereo images

The Pléiades 1A and 1B twin satellites were launched 17 December 2011 and 2 December 2012, respectively. Images are delivered at a ground sampling distance (pixel size) of 0.5 m (panchromatic channel, with a wavelength in the 480–830 nm range) and 2 m (multi-spectral channels, blue, green, red and near infra-red bands, see http://smsc.cnes.fr/PLEIADES/). However, the actual resolution of the sensor is slightly coarser (0.7 m and 2.8 m) and the images are therefore oversampled by the ground segment (Gleyzes et al., 2012). One great advantage of the Pléiades satellites (compared to SPOT1–5 and ASTER, Advanced Spaceborne Thermal Emission and Reflection Radiometer) for glaciological studies is the fact that the panchromatic band images are coded on 12 bits (digital numbers range = 2^n, where n is the number of bits). Such a wide radiometric range gives much better image contrast over flat and textureless regions (such as snow-covered accumulation areas) and the risk of saturation is reduced. It also means that nearly all images from the archive are now useful for the study of ice and snow surfaces, whereas with SPOT1–5 or ASTER (8-bit encoding), special acquisition plans with a low gain had to be defined to avoid saturation and to enhance image contrast over snow and ice (Korona et al., 2009; Raup et al., 2000).

The images of a Pléiades stereo pair are acquired along the orbit (along-track) within a few tens of seconds thanks to the agility (pitch) of the platform. In the Andes and the Alps, triplets of images (referred to as tri-stereos) are available. A tri-stereo is made of three images (front, nadir and back images) that can be combined in three stereo pairs (front/nadir, nadir/back and front/back) for multiple DEM generation (see for example http://www2.astrium-geo.com/files/pmedia/public/r12260_9_pleiadesdem_stereo_tristereo.jpg). The front/nadir and nadir/back pairs are acquired from closer points of view than the front/back pair and hence exhibit less distortion, facilitating the recognition of identical features in the images by automatic matching algorithms. However, the sensitivity to topography is reduced by a factor of about two, so matching errors will lead to doubled altimetric errors.

Table 1 indicates the characteristics of the images used in this study. The type and date of the reference data available to evaluate the Pléiades DEMs are also given. Most of the reference data are differential GNSS (global navigation satellite system including the US GPS and Russian GLONASS constellations) measurements, processed relative to the closest available base station. A centimetric precision can be reached in the best cases (the Mont-Blanc area), whereas, in the worst case, the precision is closer to ±0.5 m in the Andes due to the fact that the base station (TOLO) is located as far as 100 km away from Agua Negra Glacier. For Iceland, the Pléiades DEM was also compared to an airborne Lidar DEM (2 m pixel size) acquired 7 and 8 August 2011, slightly more than 2 years before the acquisition of Pléiades images (Jóhannesson et al., 2013). The vertical accuracy of the Lidar DEM and its horizontal positioning accuracy has been estimated to be well within 0.5 m (Jóhannesson et al., 2011).

As a direct result of the 12-bit encoding, the percentage of our Pléiades images with saturation (digital numbers equal to 4095) is low (Table 1). The maximum percentage is observed over the Mont-Blanc area (5 %) and is due to several snowfalls during the days preceding the 20 September 2013 acquisition. This date excluded, the percentage is always lower than 1 %.

In this study, all elevation differences between the Pléiades DEMs and the reference data (GNSS surveys or Lidar DEM) are attributed to errors in the Pléiades DEMs. In fact the total error budget also includes (i) on glaciers only, real and spatially-varying elevation changes over the period (a few days or weeks) separating the acquisition of the Pléiades images and the reference data and (ii) everywhere, errors in the reference data themselves. Error (i) can also matter off-glacier if snow was present during the acquisition of the Pléiades images or the reference data. Therefore, the present study provides an upper bound for the uncertainties of the Pléiades DEMs. When the time between satellite acquisition and field measurements exceeds a few weeks (e.g. the Lidar DEM in Iceland), only reference data not on glaciers are considered for the evaluation and data on glaciers are used only for the study of glacier elevation changes.

2.3 Generation and evaluation of the Pléiades DEMs

All Pléiades DEMs presented in this paper were calculated using the Orthoengine module of PCI Geomatica 2013. The original orientation of each image was read in the ancillary data provided with the images in the form of rational polynomial coefficients. Without ground control points (GCPs), the horizontal location accuracy of the images was estimated at 8.5 m (CE90, Circular Error at a confidence level of 90 %) (Astrium, 2012). This initial orientation was then refined using GCPs when available. DEMs were generated with a pixel size of 4 m, a compromise offering relatively fast processing and sufficient resolution. Some tests were also performed with a pixel size of 2 m that did

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not improve results and are therefore not reported here. In addition to pixel size, two other main parameters can be tuned during DEM generation with Orthoengine: the level of detail of the DEM (from "low" to "very high") and the type of relief in the scene (from "plain" to "mountainous"). Unless otherwise mentioned, all DEMs evaluated in the present paper were obtained with the "low" and "mountainous" settings. The choice of these parameters is justified in Sect. 3.1. Except when indicated, data voids were not filled by interpolation during DEM generation because our aim was not to obtain complete coverage but rather to determine where elevations were extracted and what their quality was. Thus, the statistics on elevation differences are only provided outside of Pléiades DEM data voids, except when mentioned explicitly.

The metrics used to describe the quality of the DEMs are the percentage of data voids and various statistics on the elevation differences between the Pléiades DEMs and the reference (GNSS or Lidar) data: (i) their mean and median to evaluate the vertical accuracy of the DEMs, (ii) their standard deviation and normalized median absolute deviation (NMAD) to characterize their vertical precision. The NMAD is a metric for the dispersion of the data (also at the 1-sigma confidence level) that is not as sensitive to outliers as the standard deviation and is recommended to evaluate DEM precision (Höhle and Höhle, 2009).

$$\mathrm{NMAD} = 1.4826 \cdot \mathrm{median}(|\Delta h_j - m_{\Delta h}|) \quad (1)$$

where Δh_j denotes the individual errors and $m_{\Delta h}$ is the median of the errors.

All statistics were computed after horizontal co-registration of the DEMs to the reference data. The horizontal shifts were obtained (i) by minimizing the standard deviation of the elevation differences when two DEMs were compared (e.g. Rodriguez et al., 2006), (ii) in other cases by correcting the shift between a Pléiades ortho-image and the GNSS measurements acquired along certain trails or roads clearly visible in the images (e.g. Wagnon et al., 2013). When GCPs were used to compute the DEMs, we always verified that no detectable horizontal shift remained between the Pléiades ortho-images and the GPS tracks so that no planimetric correction was required. For

Tungnafellsjökull, the GCPs were derived from a shaded relief image of the Lidar DEM and a small shift remained between the Pléiades and the Lidar DEM (see Sect. 3.2).

3 Accuracy and precision of the Pléiades DEMs

We chose the ice-free terrain around the Tungnafellsjökull Ice Cap (Iceland) to explore the influence of the different processing parameters in PCI Geomatica (Sect. 3.1) because of the extensive coverage and high accuracy provided by the Lidar DEM. We analysed the influence of the number of GCPs (Sect. 3.2) and the occurrence of spatially varying biases in the Pléiades DEM (Sect. 3.3). The Pléiades DEMs for the other study sites were then evaluated (Sect. 3.4).

3.1 Processing parameter settings

Our criteria for selecting processing parameter settings for the DEM generation were (i) the percentage of coverage with valid data ("covered area" column in Table 2) and (ii) the dispersion of the elevation differences around the mean and median (quantified using the standard deviation and NMAD, respectively).

With the parameters "Type of relief" set to "Mountainous" and "DEM detail" set to "Low", the dispersion is just slightly larger and the area covered is greatly improved (nearly 99 % vs. less than 93 %). All DEMs examined in the rest of this study were generated using these parameter settings, which is the best compromise between a low percentage of data voids and a low dispersion of the elevation differences around the mean and median. We acknowledge that the differences obtained for different processing parameter settings are not very large and hence that other settings may be more appropriate in some cases. For instance, to map crevasses using the DEM, a "high" level of detail would probably be a better setting. Filling data voids by interpolation leads to much larger errors (the standard deviation is multiplied by a factor of three) and is

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not recommended except if a complete DEM is really needed (e.g. for orthorectification of an image).

3.2 Influence of the numbers of GCPs and tie points

Our study sites are the target of ongoing glacier monitoring measurements, therefore GCPs were available from static GNSS measurements of proeminent features such large boulders or crossing roads or could be measured in the future during dedicated campaigns. However, GCPs are not available in all ice-covered regions and it is important to assess their influence on DEM quality and determine whether useful DEMs can be retrieved in remote regions where no GCPs are available. At the time of DEM processing, no GCPs were available for the Astrolabe (Antarctica) and Mera (Nepal) study sites. The best GCP coverage was around Tungnafellsjökull where GCPs were identified manually on a shaded relief image (pixel size of 2 m) derived from the Lidar DEM. Tungnafellsjökull was thus the site chosen to test the influence of the number of GCPs (Table 3).

For the Tungnafellsjökull site, the Pléiades DEM derived without any GCPs exhibits a horizontal shift of about 3.3 m and its elevations are about 3 m too high on the average. The addition of GCPs reduces the horizontal shift to about 2 m and the vertical shift nearly vanishes. In fact, a single accurate GCP appears to be sufficient to eliminate most of the vertical bias. In contrast, the horizontal shift is never entirely removed, even with 19 GCPs, possibly because a systematic shift may arise from GCP identification in the shaded relief image of the Lidar DEM. The last column of the table corresponds to the mean elevation difference between August 2011 and October 2013 on the ice cap after horizontal and vertical co-registration (referred to as 3-D co-registration hereafter) of the Pléiades and Lidar DEMs. The similarity of these values (within 0.03 m) illustrates the effectiveness of 3-D co-registration. It implies that, if the subtracted DEMs include a sufficient proportion of stable areas (i.e. ice-free terrain), accurate elevation change measurements can be retrieved even without GCPs.

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In the case of the Icelandic study site, the collection of tie points (TPs, i.e. homologous points identified in both images of the stereo pair but with unknown geographic coordinates) had no clear influence on the quality of the DEM: the vertical bias is slightly larger (increasing by 0.5 m) and dispersion slightly lower. In Sect. 3.4, we will show that this conclusion does not hold for the other study sites.

3.3 Spatial pattern of the off-glacier elevation differences

In the previous sections, we assessed the overall accuracy of the Pléiades DEMs on the whole ice-free terrain surrounding Tungnafellsjökull. However, previous studies have highlighted the occurrence of spatially-varying elevation errors in ASTER and SPOT5 DEMs due notably to unrecorded variations in satellite attitude (Berthier et al., 2012; Nuth and Kääb, 2011). To quantify these errors, we split the map of elevation differences between the Pléiades DEM (computed using 5 GCPs) and the Lidar DEM into X by X tiles (with X the number of tiles in each direction, varying from 2 to 5) and computed the median elevation difference on the ice-free terrain of each tile. The median was preferred here because it is a metric of centrality less affected by outliers (Höhle and Höhle, 2009). The results are shown in Fig. 3 for $X = 3$. The maximum absolute departure from 0 is observed for the northwest tile where the absolute median elevation difference between the Pléiades and Lidar DEMs reaches 0.15 m, followed by the southeast tile (0.10 m). These two tiles are also those with the most limited data coverage. This maximum absolute median elevation difference is 0.08 m, 0.26 m, and 0.24 m when X equals 2, 4, and 5, respectively. These statistics show very limited spatially-varying elevation differences between the Pléiades and Lidar DEMs, implying that, within each quadrant, elevation changes of a sufficiently large ice body could be retrieved with an uncertainty of about ±0.3 m or less.

3.4 Accuracy of the Pléiades DEMs from other study sites

Table 4 summarizes the results of the evaluation of the Pléiades DEMs with GNSS measurements for all study sites. In the Andes and for Mont-Blanc, 5 to 13 GCPs were available to compute the DEMs. For Mera Glacier (Himalaya), no accurate GCPs were available at the time of processing but a set of 22 GCPs was derived from a coarser resolution SPOT5 dataset (2.5 m ortho-image and 40 m DEM), previously co-registered to GNSS data acquired along the trails of the Everest base camp (see Wagnon et al., 2013, for a complete description). The horizontal precision of these GCPs is limited by the SPOT5 pixel size (2.5 m) and their vertical precision is about ±5 m. For Astrolabe Glacier, no GCPs were available at the time of processing.

First, a common result for all sites is that the vertical precision (quantified using the standard deviation and the NMAD) is relatively consistent and generally between ±0.5 m and ±1 m (NMAD values ranging from 0.36 to 1.1 m and standard deviations from 0.51 to 1.26 m). These precision values are slightly better than those obtained using Pléiades stereo pairs in two other recent studies (Poli et al., 2014; Stumpf et al., 2014). For the relatively steep and vegetated terrain around landslides in the southern French Alps (Stumpf et al., 2014), the precision of the Pléiades DEM is around ±3 m. For the urban landscape around the city of Trento in Italy (Poli et al., 2014), it is ±6 m or more. These seemingly lower precision in other studies are probably not due to differences in the processing of the Pléiades images but more likely due to the influence of the landscape on the DEM precision. A quasi linear relationship has been found between DEM precision and terrain slope (e.g. Toutin, 2002). It is also problematic to extract precise DEMs in urban areas (e.g. Poli et al., 2014). We would therefore expect to obtain a better precision on smooth glacier topography. This is confirmed by the results for the two study sites (Agua Negra and Tungnafellsjökull) where GNSS data have been collected on and off glaciers (Table 4). The precisions are always higher on glaciers. The improvement is particularly spectacular on the Tungnafellsjökull study site where the standard deviation of the elevation difference is 0.53 m on the ice cap

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and 1.33 m elsewhere. The decrease of the standard deviation is not as strong for the Agua Negra study site, possibly because the glacier presented a rough topography (0.5 to 1 m high penitents) when the Pléiades images and GNSS measurements were acquired.

When GCPs are available, the vertical bias (i.e. mean or median of the elevation differences) is generally lower than 1 m. The GNSS surveys on glaciers are not exactly temporally coincident with the acquisition dates of the Pléiades images (Table 1). Hence, part of these vertical biases may be explained by real (but unknown) glacier elevation changes during this time interval. For example, in the case of the Mont-Blanc 2012 DEM, the 1 m elevation difference could be easily explained by the thinning that likely occurred between 21 August 2012 (Pléiades DEM) and 5–8 September 2012 (GNSS survey) on the rapidly thinning tongues of Argentière Glacier and Mer de Glace. Ablation field measurements performed on stakes on Argentière Glacier between 16 August and 5 September 2012 gave values of −0.98 m water equivalent (w.e.) at 2400 m a.s.l., −0.75 m.w.e. at 2550 m a.s.l., and −0.60 m.w.e. at 2700 m a.s.l. These ablation values, measured during a similar time period, approach the 1 m elevation difference obtained between the Pléiades DEM and the GNSS survey but this agreement can only be considered as a general indication because glacier elevation changes are the combination of surface mass balance (i.e. here ablation) and ice dynamics processes.

Without GCPs, the vertical biases of the DEMs are larger: about 1 m for the Agua Negra study site, 2 m for the Astrolabe Glacier (Antarctica) and as much as 7 m for the August 2012 Mont-Blanc DEM. These results clearly demonstrate the necessity to vertically adjust the Pléiades DEMs built without GCPs on stable terrain before using them to retrieve elevation changes (Paul et al., 2014).

We already mentioned above that TPs had no influence on the coverage and the precision of the DEM of the Tungnafellsjökull Ice Cap (Table 3). However, this does not hold for the Mont-Blanc area and the Astrolabe Glacier, two other sites where DEMs were generated without GCPs. In both cases, the collection of about 20 TPs provided

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far better coverage probably by improving the relative orientation of the two images of the stereo pairs. The necessity of collecting TPs will depend on the accuracy of the navigation data (position and attitude of the satellite) provided with the images. Given that the latter is not known a priori, we recommend collecting TPs between the images.

The added value of a tri-stereo instead of a simple stereo pair is not obvious from our results. In general, among the 3 possible pair combinations of the three images, the largest percentage of data gaps is observed for the nadir/back pair, due to the stronger distortion between these images. This is especially true when the base-to-height ratio is high (> 0.5), for example in the case of the Mont-Blanc 2013 tri-stereo where the data voids represent as much as 30 % for the nadir/back pair and only 15 % for the front/nadir and nadir/back pairs. For the latter two pairs, we combined the two DEMs in a merged DEM as follows: (i) for pixels where both DEMs were available, the mean of the two values was calculated, (ii) for pixels where only one DEM was available, this single value was retained, (iii) for pixels corresponding to data voids in both DEMs, a data void was kept in the merged DEM (i.e. no gap filling was used). The percentage of data voids in the Mont-Blanc 2013 merged DEM was greatly reduced, from 15 % to 6 %, showing that data voids were not at the same location in the front/nadir and nadir/back DEMs. For Agua Negra Glacier (Andes), the same merging reduced the percentage of data voids by only 1 % (but the initial coverage in the DEMs was higher) with no significant improvements in vertical precision.

For the Agua Negra study site, we obtained more homogeneous vertical biases between the different versions of the Pléiades DEMs (front/nadir, nadir/back, front/back) computed without GCPs (range of mean vertical bias: 0.99 m to 1.33 m). With our 5 GCPs, the mean vertical bias ranges from −0.33 m to 1 m. There are two possible reasons for this. First, the coordinates of the GCPs were calculated using a base station located as far as 100 km away and are more uncertain than for other test sites. Second, the identification on the Pléiades images of the features (GCPs) measured in the field (e.g. large boulders) was sometimes ambiguous.

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4 Seasonal, annual and multi-annual glacier elevation changes

4.1 Seasonal elevation changes

A comprehensive GNSS survey of Tungnafellsjökull Ice Cap was performed using a snowmobile on 2 May 2013, 6 months before the acquisition of the Pléiades stereo pair. The Pléiades DEM, first co-registered horizontally and vertically to the Lidar DEM, was compared to GNSS elevations to reveal the surface elevation changes during the 2013 melt season between 2 May and 10 October. As expected, the surface was lower in October due to firn compaction and surface melt during summer (Fig. 4). Part of this lowering is also due to ice dynamics in the accumulation area, whereas ice motion (i.e. emergent velocity) only partly counteracts the strong lowering due to melting in the ablation zone in summer. A clear pattern with elevation is observed, with greater thinning at lower elevations close to the margins of the ice cap (inset of Fig. 4). There is good agreement between the Pléiades-GNSS elevation changes and the field measurements (repeated GNSS surveys available at cross-over points between the extensive GNSS survey in May 2013 and the more limited coverage in September 2013, see Fig. 2). On the average, the surface lowering between May and October 2013 was 3.1 m (standard deviation = 0.89 m; $N = 4800$).

4.2 Annual elevation changes

For the Mont-Blanc area, two Pléiades DEMs were available with a time difference of slightly more than a year (21 August 2012 and 20 September 2013). These two DEMs were first co-registered by minimizing the standard deviation of their elevation differences on the ice-free terrain (e.g. Berthier et al., 2007). The corrected horizontal shifts were 1 m in easting and northing. The remaining vertical shift on the ice-free terrain after horizontal co-registration was only 0.1 m (median of the elevation differences) and the dispersion (NMAD) was 1.79 m. These very low horizontal and vertical shifts could be expected given that the 2012 and 2013 DEMs were built using the same set of

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GCPs. This negligible median elevation difference off glaciers tends to confirm that the 21 August 2012 DEM is not biased and that the ca. 1 m average elevation difference between the 21 August 2012 DEM and the 5–8 September 2012 GNSS measurements (Table 4) is due to real elevation changes, not errors in the 2012 Pléiades DEM.

Once co-registered in 3-D, the DEMs were differentiated to map the glacier elevation changes that occurred over the 13 months between 21 August 2012 and 20 September 2013 (Fig. 5). Due to the difference in seasonality, the glaciological interpretation of these changes and their comparison to field measurements (performed annually around 10 September) is not straightforward. However, the map reveals a clear thinning for all glacier tongues whereas thickening is observed on most glaciers above 3000 m a.s.l., with some localized elevation gains of over 5 m probably due to avalanches. This high elevation thickening cannot be confirmed by field measurements but is in line with the above-average accumulation during winter 2012/13 (unpublished GLACIOCLIM-LGGE data). We did not attempt to compute a glacier-wide or region-wide annual mass balance over such a short time span (13 months) since it would likely be skewed by seasonal variations and because of the high uncertainties that would arise from the poorly-constrained density of the material gained or lost for such a short period of time (Huss, 2013). Despite these issues, this result highlights the very strong potential of repeat Pléiades DEMs for accurate mapping of glacier elevation changes, even over short time periods.

4.3 Multi-annual elevation changes

To fully explore the potential of repeated high resolution satellite DEMs for measuring glacier elevation changes and glacier-wide mass balances, the 21 August 2012 Pléiades DEM was next compared to a 10 m DEM derived from SPOT5 images acquired 19 and 23 August 2003 over the Mont-Blanc area (Berthier et al., 2004). The 21 August 2012 Pléiades DEM was preferred to the 20 September 2013 DEM because it was acquired at the same time of year as the SPOT5 DEM and contains less data voids. The 2012 Pléiades DEM is used as reference DEM for 3-D co-registration of the two DEMs on the stable terrain. We measured a 4.6 m total horizontal shift (2.5 m in easting and 3.9 m in northing) and a vertical shift of 2.3 m, the 2003 DEM being lower than the 2012 DEM. After 3-D co-registration, nine full years of elevation changes in the Mont-Blanc area are depicted (Fig. 6).

These satellite-derived elevation changes are compared to the mean elevation changes derived from GNSS measurements performed every year around 10 September by LGGE on 9 transverse profiles (5 on the Mer de Glace and 4 on the Argentière Glacier, Fig. 6). Due to the retreat of the front of the Mer de Glace, the lowest profile, Mottet, has been deglaciated since 2009 and could not be used in our comparison. The 2003–2012 elevation differences derived from satellite data are, on the average, only 0.3 m higher than those measured in the field (standard deviation = 1.3 m; $N = 8$). To evaluate how the two satellite DEMs contribute to the dispersion of the elevation differences (±1.3 m), we directly extracted the DEM elevations at the location of the GNSS transverse profiles for each DEM separately. The mean elevation difference between the 2003 SPOT5 DEM and the 2003 field data is 0.5 m (standard deviation = 1.3 m, $N = 8$), and the mean elevation difference between the Pléiades DEM and the 2012 field measurements is 0.8 m (standard deviation = 0.4 m, $N = 8$). As expected from the higher resolution of the stereo images, the Pléiades DEM is more precise than the SPOT5 DEM. The fact that both satellite DEMs are higher than the GNSS profiles can be explained by glacier thinning between the DEM acquisition dates (around 20 August) and the dates of the field surveys (around 10 September) in late summer when strong ablation (and thus thinning) is still ongoing in the European Alps.

Conservatively, the standard deviation of the elevation differences at these eight transverse profiles (±1.3 m) is used as our error estimate for the 2003–2012 satellite-derived elevation differences. These elevation differences are converted to annual mass balances using a density of $850 \pm 60\,\mathrm{kg\,m^{-3}}$ (Huss, 2013). The resulting glacier-wide mass balances for Argentière Glacier and Mer de Glace are negative (about $-1.2 \pm 0.2\,\mathrm{m\,w.e.\,yr^{-1}}$, Fig. 6) and reflect the strong mass loss that has occurred in the Mont-Blanc area over the last decade, in agreement with recent studies elsewhere in the European Alps (Abermann et al., 2009; Carturan et al., 2013; Huss, 2012; Kropáèek et al., 2014; Rabatel et al., 2013).

5 Discussion and conclusion

Our evaluation of Pléiades DEMs over five different glacial environments demonstrates that Pléiades stereo images are a promising tool for the monitoring of glacier topography and elevation changes. Overall the precision of these DEMs (at the 1σ confidence level) is ca. ±1 m, sometimes better (±0.5 m) for the flat glacier tongues. The higher precision on glaciers compared to the surrounding ice-free terrain implies that an error estimate performed on the ice-free terrain will be conservative. Vertical biases are greater (as much as 7 m) if no GCPs are available but can be greatly reduced through proper 3-D co-registration of the Pléiades DEMs with a reference altimetry dataset on ice-free terrain.

The added value of a tri-stereo is not clear although we have shown for the Mont-Blanc area that a simple combination of the different DEMs derived from the 3 images of a tri-stereo can reduce the percentage of data voids and slightly improve precision. However, because glacier topography is often relatively smooth, a standard stereo coverage with a limited difference in incidence angles (typically a base-to-height ratio of about 0.35–0.4) provides a relatively comprehensive and cost-effective coverage of the glacier surfaces.

One strong advantage of DEMs derived from Pléiades (and from other optical stereo sensors) compared to DEMs derived from radar images (such as the SRTM and Tandem-X DEMs) is the absence of penetration into snow and ice. Thus, all measured elevation differences correspond to real ice and snow elevation changes. Given their accuracy, DEMs derived from Pléiades (or other similar optical sensor) could be used in the future to check the magnitude and spatial pattern of the penetration depth of the Tandem-X radar signal into snow and ice, if temporally concomitant acquisitions can be found in the image archives. As for all optical sensors, the main drawback of the Pléiades constellation is the need for clear sky conditions to obtain suitable images.

Our results open some promising perspectives. In the future, the differencing of Pléiades DEMs acquired ~ 5 years apart could make it possible to determine glacier-wide mass balances with an uncertainty of ±0.1 to ±0.2 m.w.e. yr^{-1}. Such an error level is sufficiently low to check the cumulative glaciological mass balances measured in the field (e.g. Zemp et al., 2013) and explore the spatial variability of glacier-wide mass balances at the scale of a glaciated massif (Abermann et al., 2009; Soruco et al., 2009a). It is already possible to differentiate recent Pléiades and older SPOT5 DEMs to provide accurate glacier-wide and region-wide mass balance, as shown here for the Mont-Blanc area. Pléiades DEMs acquired at the beginning and end of the accumulation seasons could probably be used to map snow thickness if the ice dynamics component can be estimated. If this is confirmed, Pléiades will represent a good alternative to recently developed techniques based on Lidar (Deems et al., 2013; Helfricht et al., 2014) and stereo-photogrammetry (Bühler et al., 2014), especially for remote areas where acquiring airborne data can be difficult. Still, the conversion of glacier elevation changes measured over short time periods (one season or one year) to mass balances will remain a complicated task due to the lack of knowledge of the actual density of the material (ice-firn-snow) gained or lost.

Apart from their cost and their sensitivity to cloud coverage, the main limitation of Pléiades images is their relatively limited footprint, typically 20 km by 20 km for a single scene. No large scale stereo mapping has yet been planned using these two satellites and the cost of covering all glaciers on Earth (> 700 000 km^2) would be very high. For mapping vast glaciated areas, the recently launched SPOT6 and SPOT7 satellites may prove to be a good compromise given their resolution (1.5 m) and wider swath (60 km). Like Pléiades, they benefit from a very broad radiometric range (12 bits), avoiding saturation in most cases and improving contrast on snow-covered areas. However, the accuracy of the DEMs that can be derived from these stereo images has yet to be demonstrated over glaciers, ice caps and ice sheets.

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Glacier topography from Pléiades images

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Table 1. Characteristics of the study sites and Pléiades images. For each site, the approximate geographic coordinates (longitude and latitude) and maximum altitude (m a.s.l.) are indicated. The format for the dates is DD MM YYYY. All images were acquired by Pléiades-1A, except over Tungnafellsjökull (Pléiades-1B). The base-to-height ratio (B/H, ratio of the distance between two successive positions of the satellite to its height above ground) is an indicator of the sensitivity to topography. A single B/H is indicated for stereo pairs whereas three values are provided for tri-stereos (B/H indicated successively for the front/nadir, nadir/back and front/back pairs). The percentage of saturation in the image is given for successively the front/back images (for stereo pairs) and front/nadir/back (for tri-stereos). The reference altimetric data used to evaluate the Pléiades DEMs are kinematic GNSS measurements (kGNSS), Stop and Go GNSS measurements and a LIDAR DEM (Tungnafellsjökull Ice Cap). IDs of the Pléiades images are not listed for the sake of concision.

Study site Lon/Lat/Z_{max}	Pléiades date	B/H	Saturation (%)	Ref. data	Date Ref. data
Andes Agua Negra 69.8° W/30.2° S/5200	4 Apr 2013	0.22; 0.17; 0.39	0.01; 0.01; 0.01	kGNSS	20 Apr 2013
European Alps Mont-Blanc 6.9° E/45.9° N/4800	21 Aug 2012	0.33	0.02; 0.01	Stop&Go GNSS	5–8 Sep 2012, 26 Oct 2012
	20 Sep 2013	0.31; 0.35; 0.66	3.23; 4.29; 5.22	Stop&Go GNSS	13–14 Sep 2013
Iceland Tungnafellsjökull 17.9° W/64.7° N/1500	9 Oct 2013	0.37	0	kGNSS	2 May 2013 18 Sep 2013
				Lidar DEM	7–8 Aug 2011
Himalaya Mera 86.9° W/27.7° N/6400	25 Nov 2012	0.47	0.46; 0.91	Stop&Go GNSS	20–27 Nov 2012
Antarctica Astrolabe 140° E/66.7° S/800	6 Feb 2013	0.45	0.12; 0.04	Stop&Go GNSS	18 Jan 2013

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Table 2. Influence of different processing parameter settings on the coverage and accuracy of the Pléiades DEMs. Statistics for the elevation differences between the Pléiades and Lidar DEMs are computed for ~ 3 000 000 data points on the ice-free terrain around the Tungnafellsjökull Ice Cap (Iceland). The parameter settings tested are: type of terrain = Mountainous (Mtn) or Flat, DEM detail = Low or High, Data gaps = filled or not filled. All Pléiades DEMs are computed using 5 GCPs and with a final pixel size of 4 m. The table provides the horizontal shifts of the Pléiades DEMs and, after horizontal co-registration (i.e. correction of the mean horizontal shift between the Pléiades and the Lidar DEMs on the ice-free terrain), statistics (mean, median, standard deviation and NMAD) of the elevation differences (dh, $Z_{\text{Pléiades}} - Z_{\text{Lidar}}$) outside the ice cap (OFF ice). All values are in meters except the covered area (in %).

Processing parameters	Covered area (%)	Shift Easting	Shift Northing	Mean dh OFF ice*	Median dh OFF ice*	Std dev OFF ice*	NMAD OFF ice*
Mtn, Low, not filled	99.0	1.94	−0.56	0.02	0.03	0.88	0.74
Mtn, Low, **filled**	100	1.89	−0.66	0.08	0.00	2.19	0.92
Mtn, **High**, not filled	92.9	1.91	−0.58	0.02	0.02	0.60	0.71
Flat, Low, not filled	93.6	1.94	−0.44	0.04	0.04	0.51	0.70

* After horizontal co-registration.

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Table 3. Influence of the collection of GCPs and TPs on the accuracy of the Pléiades DEMs. Statistics are computed for the elevation differences (dh) between the Pléiades and Lidar DEMs on the ice-free terrain (except for the last column) around the Tungnafellsjökull Ice Cap (Iceland). The Pléiades DEMs are computed using different numbers of ground control points (GCPs) and Tie Point (TPs). The parameter settings used to generate all the DEMs are: DEM detail = Low, Type of terrain = Mountainous, pixel size = 4 m, Data gaps = not filled. The number of pixels used in these statistics is over 3 000 000. All values are in meters.

Nb of GCPs/TPs	Shift Easting	Shift Northing	Mean dh OFF ice[a]	Median dh OFF ice[a]	Std dev OFF ice[a]	NMAD OFF ice[a]	Mean dh ON ice[b]
0 GCPs/0 TPs	3.16	−1.13	3.07	3.08	0.93	0.84	−1.60
0 GCPs/20 TPs	3.22	−1.33	3.60	3.62	0.92	0.76	−1.57
1 GCP/0 TPs	2.18	−0.56	0.08	0.09	0.90	0.76	−1.60
5 GCPs/0 TPs	1.94	−0.56	0.02	0.03	0.88	0.74	−1.59
19 GCPs/0 TPs	1.86	−0.50	−0.05	−0.04	0.89	0.74	−1.59

[a] After horizontal co-registration.

[b] After horizontal and vertical co-registration, i.e. correction of the mean horizontal and vertical shifts between the Pléiades and Lidar DEMs estimated on the ice-free terrain.

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Table 4. Statistics on the elevation differences between the Pléiades DEMs and the GNSS measurements for all study sites. When a tri-stereo was available, the statistics for the three different image combinations and for a merged DEM are given. For two sites (Agua Negra and Tungnafellsjökull), the statistics are also given separately on and off glaciers. The last column, *N*, indicates the number of points for which elevation differences are computed.

Site	Number of GCPs	Image combination (Tri-stereos only)	Covered area (%)	ON/OFF glacier	Mean (m)	Median (m)	Std dev (m)	NMAD (m)	*N*
Andes – Agua Negra	5	Front/Nadir	96.7	ON & OFF	1.00	1.04	1.06	0.84	2403
		Nadir/Back	96.3	ON & OFF	−0.33	−0.15	1.26	1.10	2343
		Front/Back	93.4	ON & OFF	0.55	0.62	1.02	0.86	2324
		Front/Nadir & Nadir/Back	97.7	ON & OFF	0.37	0.47	1.04	0.83	2403
				ON	0.53	0.64	0.81	0.63	932
				OFF	0.27	0.35	1.16	1.03	1471
	0	Front/Nadir	96.7	ON & OFF	1.33	1.38	1.16	1.00	2389
		Nadir/Back	96.5	ON & OFF	0.99	1.05	1.13	0.85	2329
		Front/Back	93.5	ON & OFF	1.22	1.30	1.10	0.83	2308
		Front/Nadir & Nadir/Back	97.8	ON & OFF	1.17	1.23	1.08	0.84	2388
Alps – Mont Blanc 2012	13		93.1	ON	0.97	0.99	0.69	0.62	491
	0		90.2	ON	6.84	6.84	0.98	0.78	493
Alps – Mont Blanc 2013	11	Front/Nadir	85.5	ON	0.08	0.09	0.55	0.44	460
		Nadir/Back	85.4	ON	0.03	0.07	0.56	0.46	475
		Front/Back	70.9	ON	0.11	0.11	0.56	0.36	479
		Front/Nadir & Nadir/Back	94.2	ON	0.03	0.04	0.51	0.41	479
Iceland – Tungnafellsjökull	5		99.0	ON & OFF	−0.09	−0.08	0.84	0.37	3856
				ON	−0.07	−0.06	0.53	0.37	2764
				OFF	−0.15	−0.12	1.33	0.40	1092
Himalaya – Mera	22 (from SPOT5)		82.0	ON	−0.94	−0.93	1.02	0.92	445
Antarctica – Astrolabe	0		98.5	ON	1.86	1.84	0.72	0.55	170

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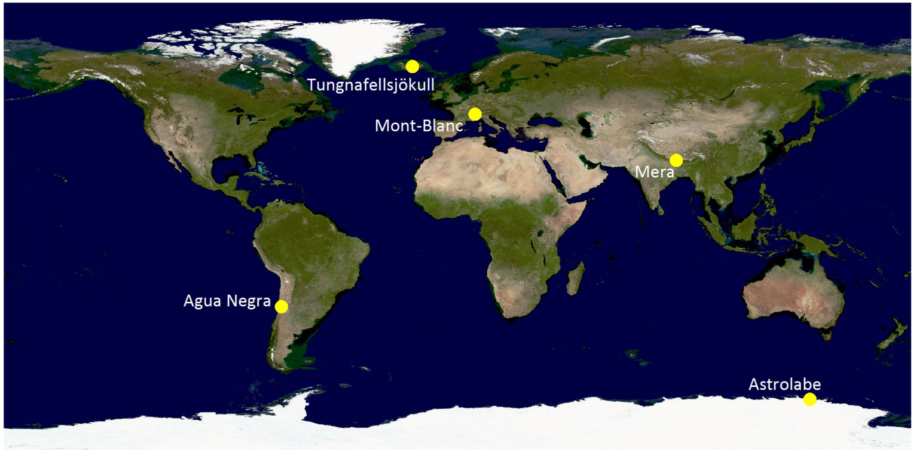

Figure 1. Study sites where Pléiades stereo pairs and tri-stereos were acquired. The background image is a MODIS mosaic from the Blue Marble Next Generation project.

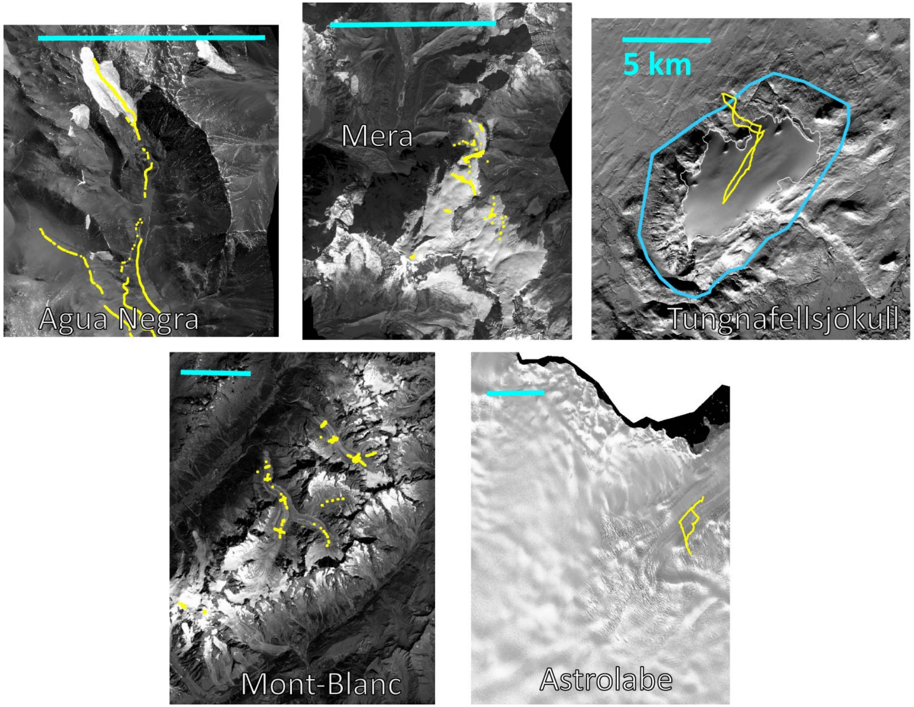

Figure 2. Pléiades ortho-images for the 5 different study sites. Yellow dots locate the GNSS measurements used to evaluate the DEMs. For Tungnafellsjökull, the blue polygon marks the limits of the Lidar DEM. The horizontal blue scale bar has a length of 5 km in each panel.

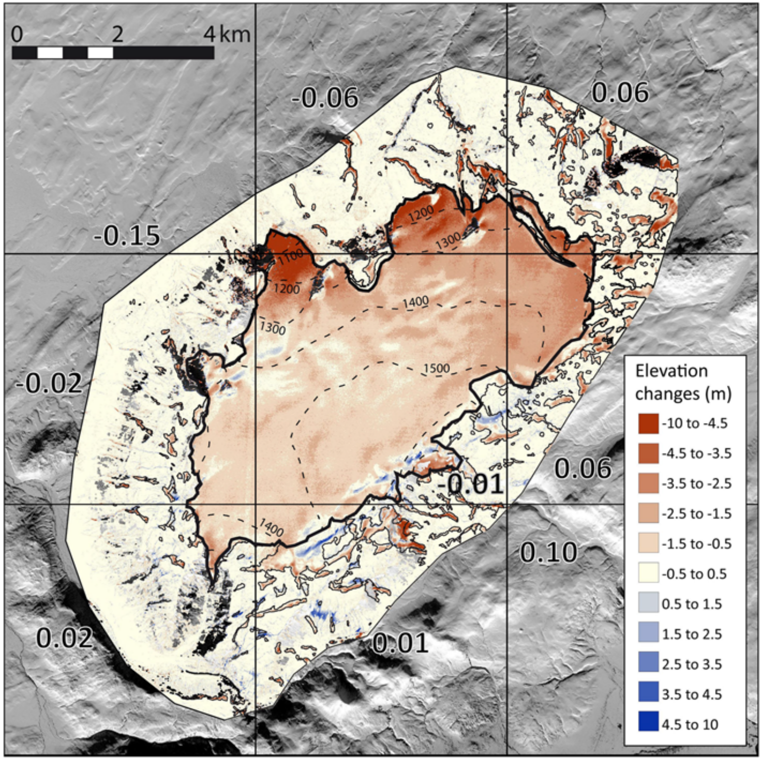

Figure 3. Map of the elevation differences between the Lidar DEM (7–8 August 2011) and the Pléiades DEM (9 October 2013) of the Tungnafellsjökull Ice Cap. The limit of the ice cap is shown by a thick black line and snowpatches are outlined with a thinner black line. On the ice cap, the elevation contour lines are drawn as thin dashed lines every 100 m (from 1000 m to 1500 m). The study area has been divided into 3 by 3 tiles in which the median of the elevation differences on the ice-free terrain only is reported (in meters). Background: Pléiades image (© CNES 2013, Distribution Airbus D&S).

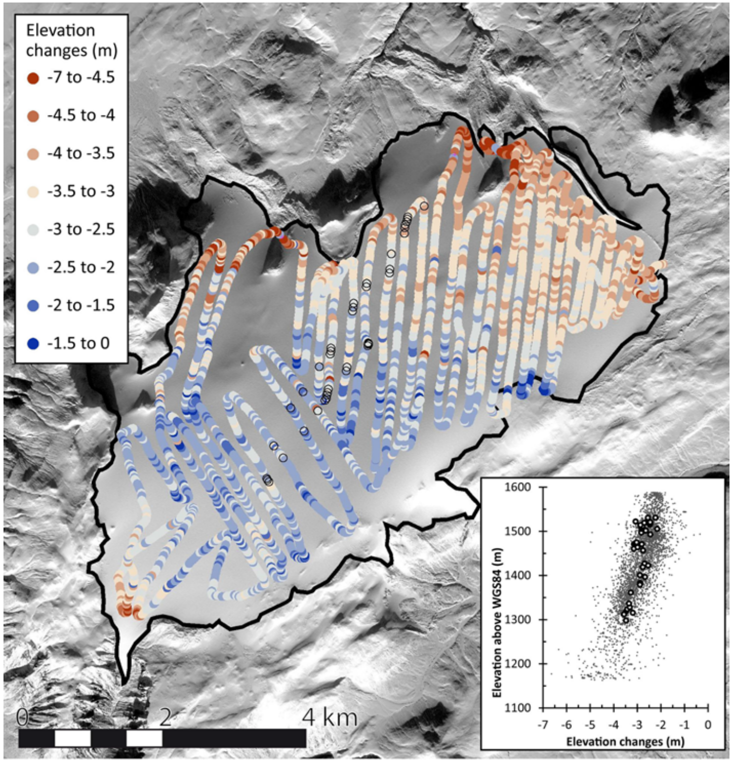

Figure 4. Elevation differences between the kinematic GNSS data (2 May 2013) and the Pléiades DEM (9 October 2013) on the Tungnafellsjökull Ice Cap. Black circles indicate the locations where elevation differences have been measured using repeated GNSS surveys (2 May 2013 and 18 September 2013). Inset: distribution of these elevation differences with altitude, with repeat GNSS surveys shown as larger dots. Background: Pléiades image (© CNES 2013, Distribution Airbus D&S).

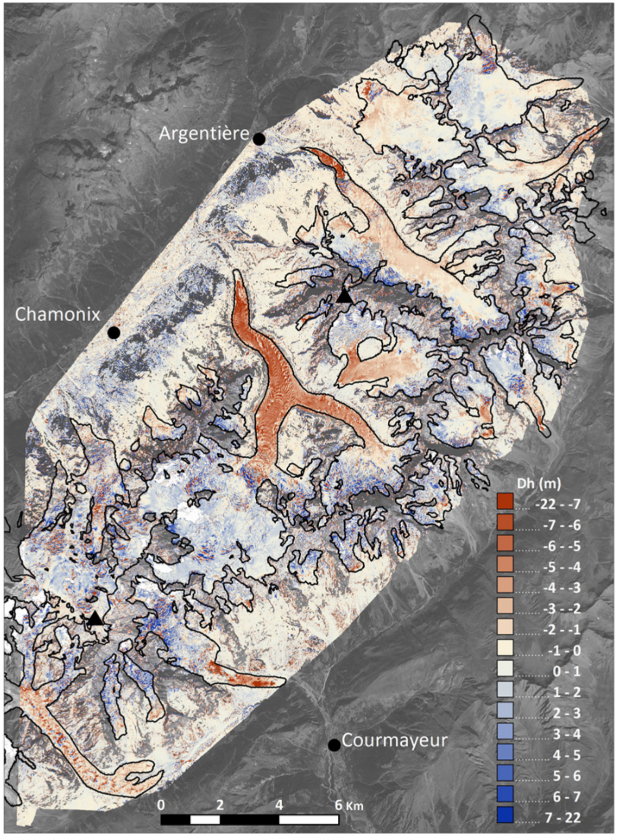

Figure 5. Elevation differences between the Pléiades DEMs of 21 August 2012 and 20 September 2013 over the Mont-Blanc area. The outlines of glaciers in August 2003 are shown as black lines. The southernmost triangle locates the summit of Mont Blanc (4810 m a.s.l.) and the northernmost triangle the summit of Aiguille Verte (4122 m a.s.l.). Background: SPOT5 image acquired 19 August 2003 (© CNES 2003, Distribution Spot Image).

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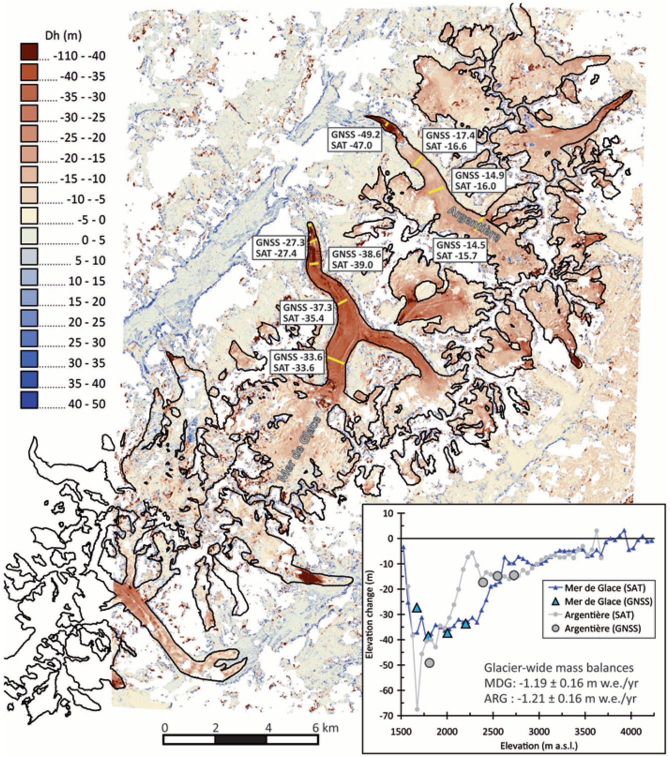

Figure 6. Elevation differences between the SPOT5 DEM from 19–23 August 2003 and Pléiades DEM from 21 August 2012 over the Mont-Blanc area. In yellow, the location of the transverse profiles where elevations are measured every year using differential GNSS. The field (noted GNSS) and satellite (SAT) 2003–2012 elevation differences averaged along these profiles are indicated. Inset: satellite-derived (SAT, small symbols) and field (GNSS, large symbols) elevation changes as a function of altitude for the Mer de Glace (blue) and the Argentière (grey) glaciers. Large symbols correspond to the field measurements.