Response to Reviewer #1 on "Co-registration and residual correction of digital elevation models: A comparative study"

Comment received: 19 Dec 2022

Key:

Reviewer comment (black)

Response (blue)

Li et al. compared different methods of correcting 3D-shifts and others biases in digital elevation models (DEM) with the ultimate goal to reduce uncertainties in glacier elevation change estimates. They first compared the widely-used Nuth & Kaab (2011) to the less popular Rosenholm and Torlegard (1988) algorithms for DEM coregistration. On top of a simple 3D shift, the latter algorithm also account for any rotation or scale differences between the DEMs. Further, they proposed an improved correction of the structured-biases between the DEMs that have a proper signature in the two directions of image acquisitions (along and across tracks). They go beyond fit by polynomials and sums of sinusoids by proposing a spline-based non parametric model.

I found nothing wrong with this study. However, I am not super convinced that this article, in its current form, fits well in The Cryosphere and its readership. I see two main reasons for that:

1/ DEM differencing is a popular technique to measure glacier changes. However the scope of the present study is really technical with no direct application to glacier changes. The study sites only marginally include glaciers.

2/ The added value of the proposed method is modest. I am not convinced that a gain of 0.2 m (5%) in standard deviation of the residuals between DEMs only covering a single (and not very challenging) test site is sufficient to convince the glaciological community to rethink the way they coregister DEMs. The added value of the spline-based correction of along track residuals is higher but would need to be confirmed in different settings.

Overall the paper is well written, the work is performed seriously but I missed some novel results that would make a real impact on the glaciological community.

Thank you for your constructive comments and suggestions.

In the experimental section of the previous manuscript, only the ASTER DEMs on the margins of the Greenland Ice Sheet (GrIS) were used for two main reasons:

1) There is commonly a large proportion of stable terrain in the scene, which is convenient to visually analyze DEM co-registration residuals.

2) Strong jitter-induced errors remain in the DEM co-registration results, which is desirable for the comparison of different residual correction methods.

Our experiments so far have been carried out on more than 200 DEM pairs from ZY-3, ASTER, SRTM, and Copernicus DEMs in GrIS, High Mountain Asia (HMA), and New Zealand (NZL). The comparative results show that the method of Rosenholm and Torlegard has a greater ability to remove DEM misalignments (83.3% maximum) than the method of Nuth and Kääb. Strong jitters can only be observed from the co-registration results of ASTER DEMs in GrIS. The GAM spline fitting method often yields a higher accuracy than the two parametric regression methods (high-order polynomials and the sum of the sinusoidal functions), but the improvement is relatively modest, because the magnitudes of the errors caused by satellite attitude jitters in ASTER DEMs are typically not significantly greater than those of random errors and unmodeled systematic errors. Considering that the residual correction is just a secondary work in our study, the GAM spline fitting method and related experimental results can be completely removed from the manuscript.

Major comments

1/ Do the conclusions apply in other settings? Map of elevation differences are constructed from several ASTER DEMs in western Greenland with a strong proportion of stable terrain. Ice-covered terrain is restricted to the eastern part of the images/DEM. It seems that images are almost cloud free. This site and the cloud-free images are appropriate to design and test the different methods but are not representative of real case scenario. In my experience, further challenges for DEM coregistration comes from: vegetation (changing with time), large fraction of glacier areas vs. stable terrain, gaps or unreliable data in the DEMs due to clouds, the rough topography leading to higher noise level in the DEMs. Authors did not explore these difficulties and thus their results are not representative of more complex and more realistic situations.

Following your suggestion, DEM co-registration algorithms have been compared in more complex and challenging scenarios of GrIS, HMA, and NZL. We present some representative examples below. Since the three versions of the method of Nuth and Kääb always produce similar co-registration results, we only compare the linear version of the method of Nuth and Kääb (L23 in Table 1) and the method of Rosenholm and Torlegard (L57 in Table 1) to make figures clear.

1) Large fraction of glacier areas vs. stable terrain

We select the DEM pair HMA-5 (Table R1) located in the northern Pamirs, excluding the saturated pixels over the bright snow-covered areas (e.g., upstream of Bol and Oktyabrskiy glaciers). The L57 algorithm can effectively remove the residuals in the east-west direction of the L23 results (Fig. R1a) and improve the co-registration accuracy by 17.5%.

Table R1. Characteristics of DEM pair HMA-5.

Pair ID	Data	Date	Res. (m)	Scene ID	MedAD (L23–L57)
HMA-5	SRTM	11–22 Feb 2000	30	N39E072, N39E073, N38E072, N38E073	9.768–8.060
	ASTER	22 Mar 2005	30	AST14DEM.003:2028219582	(17.5%)

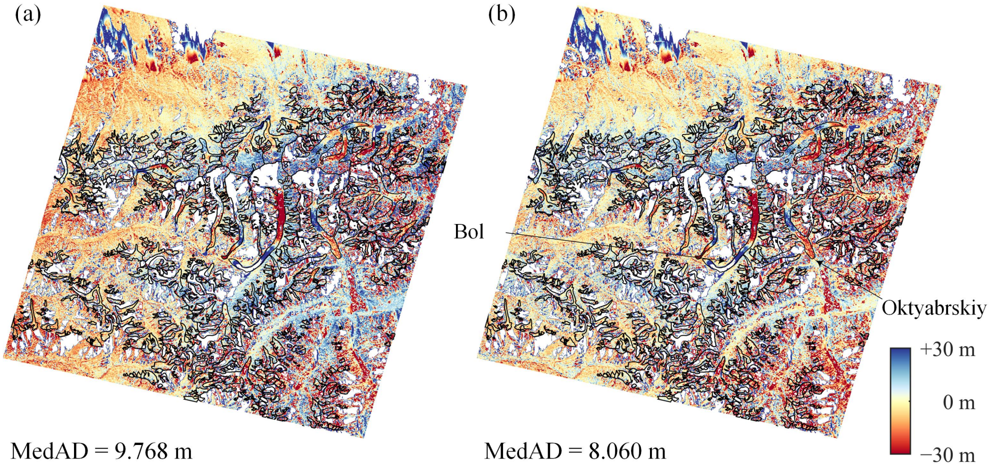


Figure R1. Co-registration results of DEM pair HMA-5: L23 (a) and L57 (b). The black lines mark the glacier boundaries.

2) Gaps or unreliable data in the DEMs due to clouds

As seen in Fig. R2, there are a lot of clouds distributed throughout the center of the ASTER DEM 20050822, and the rotation-induced biases of this image make the glacier in the southeast area of the L23 co-registration results exhibit a positive (Fig. R2a) or negative (Fig. R2b) pattern, which leads to the wrong estimation of the glacier elevation change.

Table R2. Characteristics of DEM pairs HMA-2/3/4.

Pair ID	Data	Date	Res. (m)	Scene ID	MedAD (L23–L57)
HMA-2	SRTM	11–22 Feb 2000	30	N39E073	8.598–6.366 (26.0%)
	ASTER	22 Aug 2005	30	AST14DEM.003:2030590191	
HMA-3	ASTER	22 Aug 2005	30	AST14DEM.003:2030590191	8.512–7.561 (11.2%)
	ASTER	7 Sept 2005	30	AST14DEM.003:2030819798	
HMA-4	SRTM	11–22 Feb 2000	30	N39E073	6.334–5.790 (8.6%)
	ASTER	7 Sept 2005	30	AST14DEM.003:2030819798	

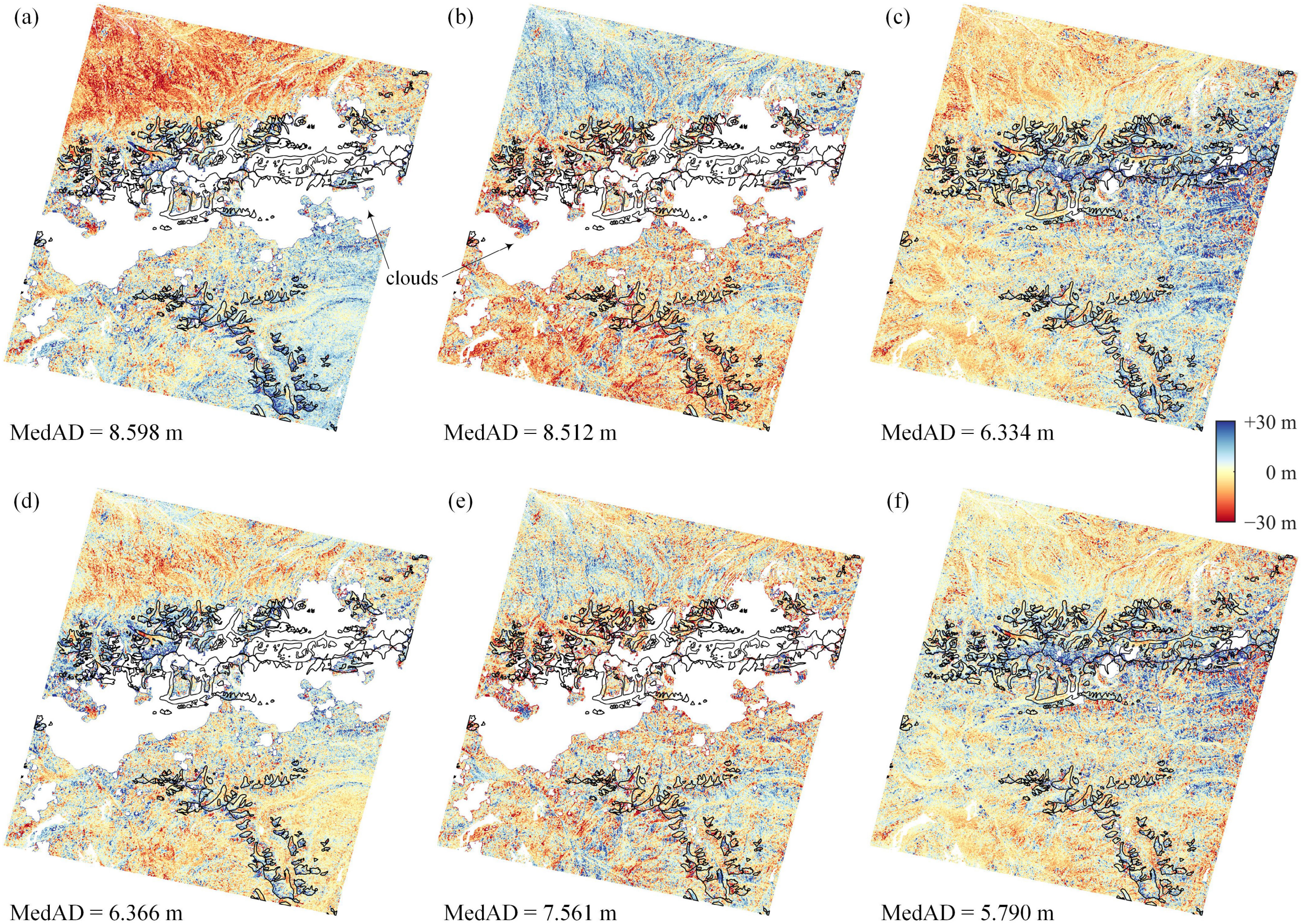


Figure R2. Co-registration results of DEM pairs HMA-2/3/4 based on L23 (top) and L57 (bottom). From left to right: ASTER DEM 20050822 to SRTM DEM, ASTER DEM 20050907 to ASTER DEM 20050822, and ASTER DEM 20050907 to SRTM DEM, respectively.

3) Vegetation

We choose the DEM pair NZL-3 (Table R3) with a large amount of vegetation on the west side (Fig. R3c). After removing the unstable pixels (forest land, water, wetland, and glacier and snow cover), the co-registration results of the L23 method and the L57 method are shown in Figs. R3 a and b. The L57 algorithm can reduce the error in the east-west direction and improve the accuracy by 13.0%.

Table R3. Characteristics of DEM pair NZL-3.

Pair ID	Data	Date	Res. (m)	Scene ID	MedAD (L23–L57)
NZL-3	SRTM	11–22 Feb 2000	30	S44E169, S44E170	7.898–6.871 (13.0%)
	ASTER	24 Feb 2003	30	AST14DEM.003:2011883607	

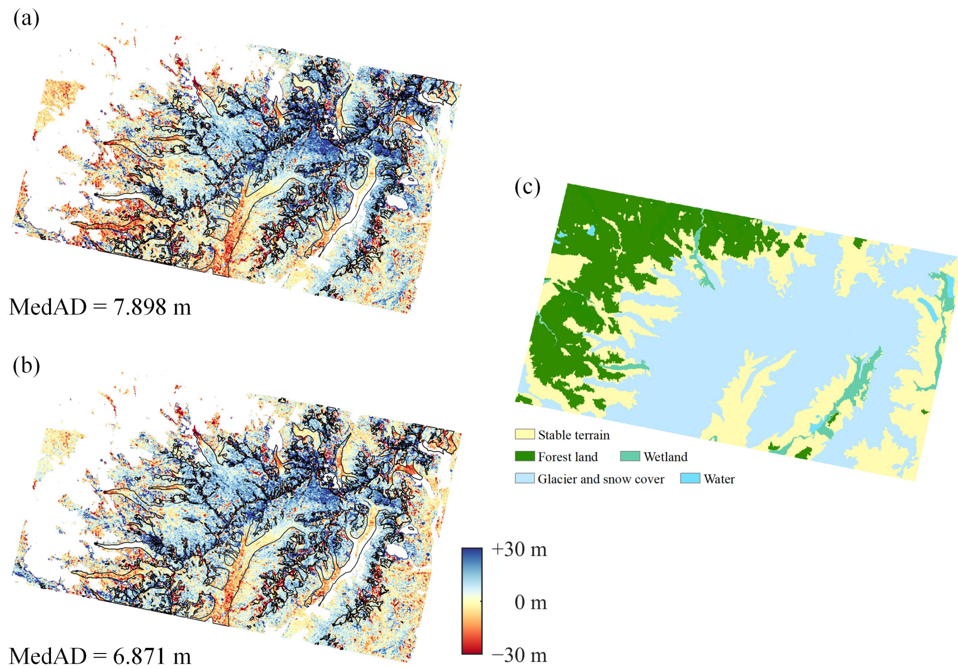


Figure R3. Co-registration results of DEM pair NZL-3: L23 (a), L57 (b), and the land cover map using GlobeLand30 product (c).

4) The rough topography leading to higher noise level in the DEMs

We select the DEM pair HMA-7 (Table R4) with a high noise level in Pamir, and the co-registration accuracy of the L57 method is 8.3% better than that of the L23 method.

Table R4. Characteristics of DEM pair HMA-7.

Pair ID	Data	Date	Res. (m)	Scene ID	MedAD (L23–L57)
HMA-7	ASTER	10 Oct 2017	30	AST14DEM.003:2280543414	7.220–6.621 (8.3%)
	ASTER	26 Oct 2017	30	AST14DEM.003:2281248034	

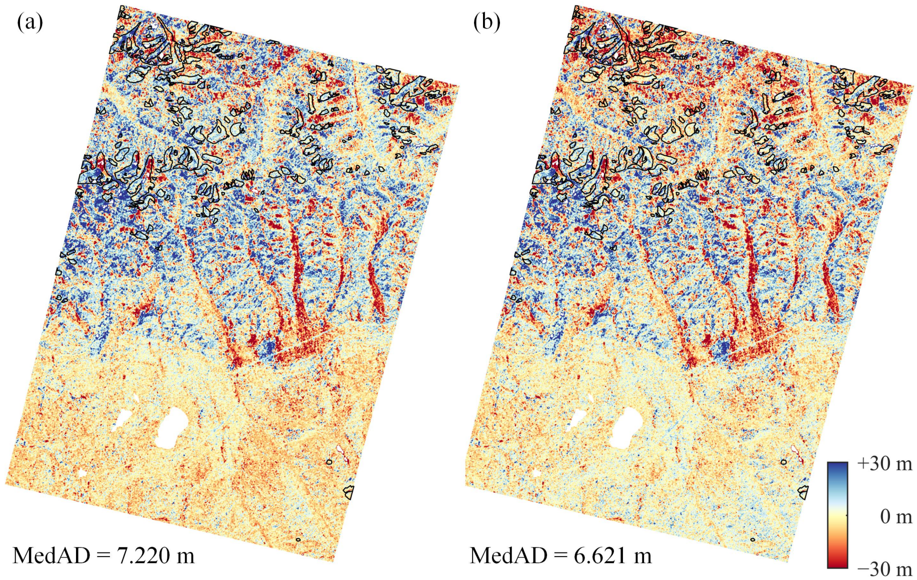


Figure R4. Co-registration results of DEM pair HMA-7: L23 (a) and L57 (b).

For the above scenarios, we only present some representative results in the revised manuscript to keep readability (see Section 4.2. Mountain glacier case study), the rest are provided in the Supplement.

2/ Do the improvements over stable terrain percolate to ice-covered areas? To convince the readers (glaciologists, the readership of TC) of the added values of the proposed methods, authors would need to demonstrate real improvements over glacier terrain.

Such a validation is tricky, I reckon, because glacier elevations are constantly changing. I see two ways for the authors to demonstrate this

(a) apply their methods to DEMs derived from images acquired just a few days apart so that the assumption of no elevation change is almost valid. They would then be in position to coregister and bias correct their DEMs over the stable terrain and then check the improvements on glaciers (where no change should be measured over a few days).

Two DEM pairs have been used for validating the co-registration results over glacier terrain.

The first DEM pair is ZY-3 DEM 20171008 and ASTER DEM 20171010, two days apart (Table R5). The co-registration results of the L23 method show systematic errors in the southwest-northeast direction, resulting in a significantly negative bias (−11.826 m) in the northeast region (within the red circle in Fig. R5a). In contrast, the estimations of glacier elevation changes are much closer to zero in the results of the L57 method.

Table R5. Characteristics of DEM pair HMA-6.

Pair ID	Data	Date	Res. (m)	Scene ID	MedAD (L23–L57)
HMA-6	ZY-3	8 Oct 2017	30	—	6.126–5.063 (17.4%)
	ASTER	10 Oct 2017	30	AST14DEM.003:2280543414	

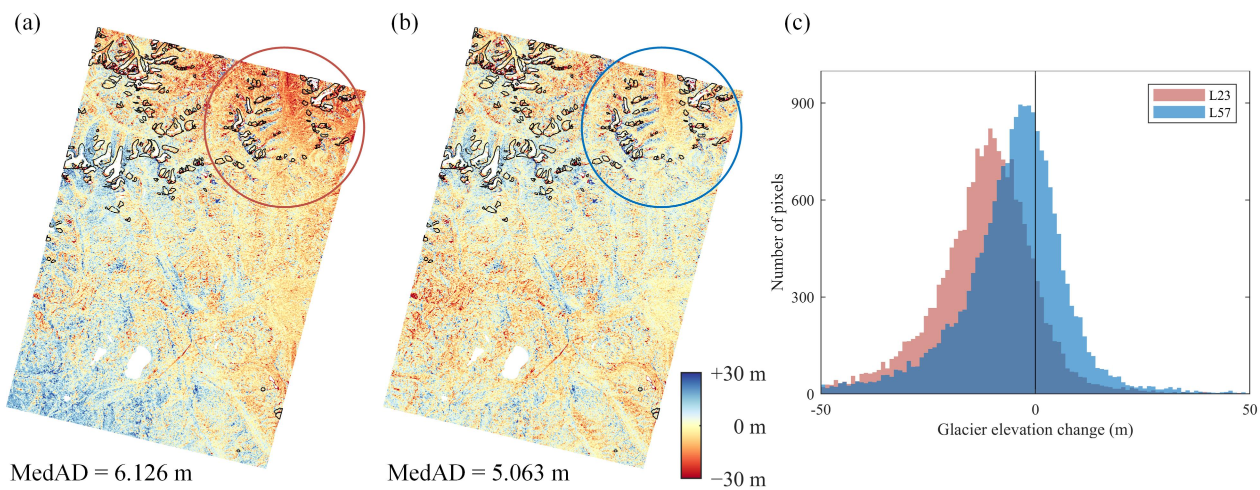
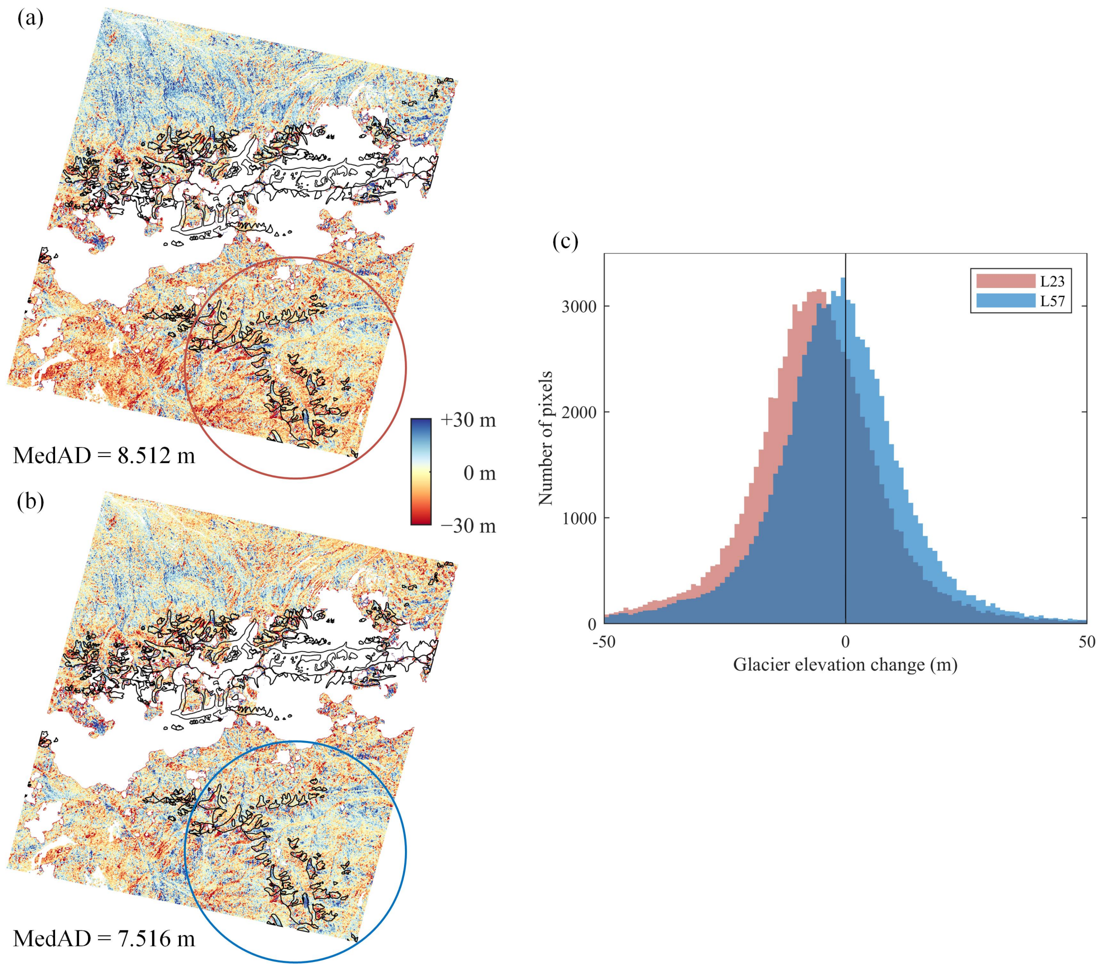


Figure R5. Co-registration results of DEM pair HMA-6: L23 (a), L57 (b), and the histogram of elevation change for glaciers within the circle (c).

As shown in Fig. R6, the rotation-induced errors in the results of the L23 method can also be observed in the DEM pair HMA-3 (Table R2). We further compared the glacier elevation change estimations of HMA-2 (ASTER DEM 20050822 to SRTM DEM) and HMA-4 (ASTER DEM 20050907 to SRTM DEM). Figure R7 shows that the discrepancy in the co-registration results of the L57 method is smaller than that of L23, with the mean value improving from −5.927 m to −1.669 m.



120 **Figure R6.** Co-registration results of DEM pair HMA-3: L23 (a), L57 (b), and the histogram of elevation change for glaciers within the circle (c).

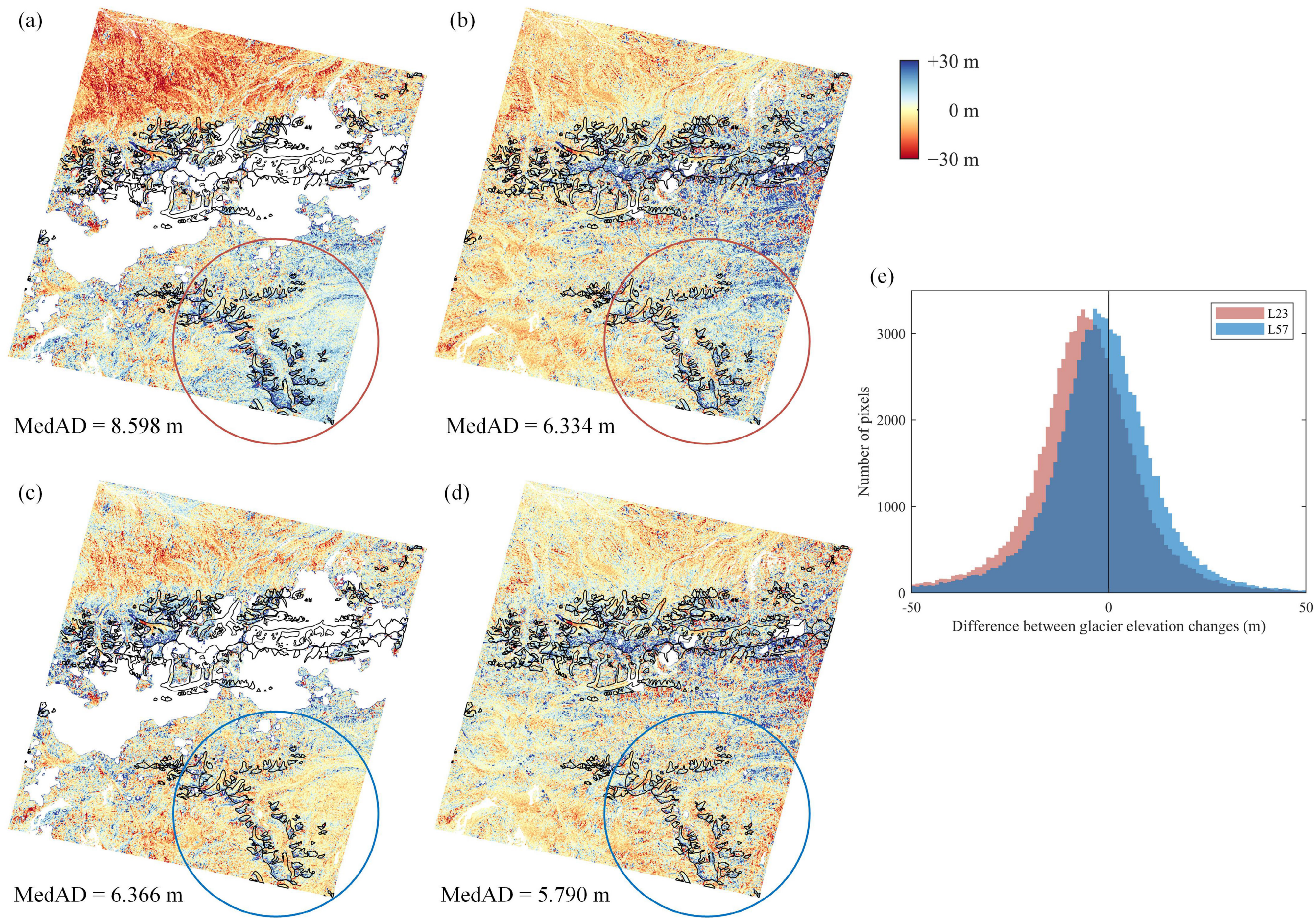


Figure R7. Co-registration results of DEM pairs HMA-2 and HMA-4. HMA-2 (ASTER DEM 20050822 to SRTM DEM): L23 (a) and L57 (c); HMA-4 (ASTER DEM 20050907 to SRTM DEM): L23 (b) and L57 (d); the histogram of the difference between glacier elevation changes derived from the two DEM pairs (e).

(b) find sites where ASTER DEMs are acquired simultaneously to higher resolution DEMs (for example from the Arctic DEM project) so that a reference elevation change map is available. This second solution is more tricky to identify.

To date, we have not found any ArcticDEM data to meet the needs of validating ASTER DEM co-registration.

We have added the experimental results and relevant description of the DEM pairs HMA-2/3/4 in the revised manuscript to investigate the influence of the DEM co-registration method on glacier surface elevation changes estimation (see Section 4.2.2. DEM co-registration). HMA-6 is appended to the Supplement.

3/ The discussion is rather weak. There is a long part about the "extrapolation error" that is mostly unrelated to the rest of the article.

In the experiment section, we tested the DEM pairs with good geometric conditions only. Under real conditions, DEMs with poor geometric quality that require data extrapolation sometimes need to be processed as well. We discussed this issue in the discussion section of the previous manuscript.

As shown in Fig. R8, when stable regions are located on one corner of the DEM, the method of Rosenholm and Torlegard is prone to producing incorrect predictions over glacier covered regions. Similar problems exist in all the application scenarios required large extrapolations, e.g., the residual regression example in Fig. 10.

In the revised manuscript, we present examples of DEM co-registration and residual correction for scenarios with poor geometric conditions, giving some suggestions for the choice of different methods.

Table R6. Characteristics of ASTER DEM 20190725 and ASTER DEM 20190826.

Data	Date	Res. (m)	Scene ID	MedAD (L23–L57)
ASTER	25 July 2019	30	AST14DEM.003:2344943025	4.237–3.657 (13.7%)
ASTER	26 Aug 2019	30	AST14DEM.003:2346334895	

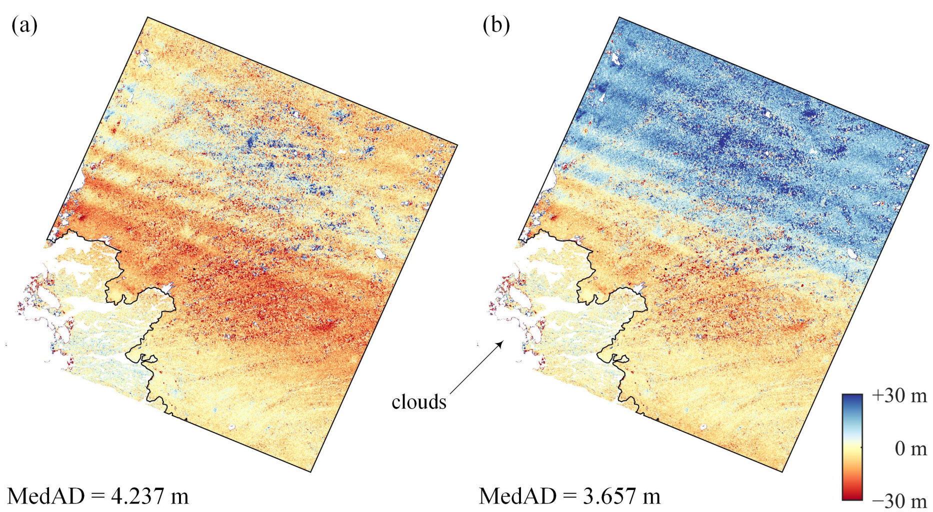


Figure R8. Co-registration results of ASTER DEM 20190725 (Scene ID: AST14DEM.003:2344943025) and ASTER DEM 20190826 (Scene ID: AST14DEM.003:2346334895). (a) The linear versions of the method of Nuth and Kääb. (b) The method of Rosenholm and Torlegard.

4/ I was also a bit disappointed to see that the techniques are only apply to ASTER DEMs. This also reduce the scope/relevance of the results.

We have conducted the tests on a variety of DEMs, including ZY-3 DEMs, ASTER DEMs, SRTM DEMs, and Copernicus DEMs. Representative experimental results have now been added to the revised manuscript and Supplement.

Specific comments

L30. I find it unbalanced that three out of four references on the use of DEMs for glacier elevation change mapping are from Chinese colleagues. Others more seminal papers on the topic could be cited here.

We have replaced the references Lin et al. (2017) and Ke et al. (2022) with Gardelle et al. (2013) and Pieczonka et al. (2013).

References:

Gardelle, J., Berthier, E., Arnaud, Y., and Kääb, A.: Region-wide glacier mass balances over the Pamir-Karakoram-Himalaya during 1999–2011, The Cryosphere, 7, 1263–1286, https://doi.org/10.5194/tc-7-1263-2013, 2013.

Pieczonka, T., Bolch, T., Junfeng, W., and Shiyin, L.: Heterogeneous mass loss of glaciers in the Aksu-Tarim Catchment (Central Tien Shan) revealed by 1976 KH-9 Hexagon and 2009 SPOT-5 stereo imagery, Remote Sens. Environ., 130, 233–244, https://doi.org/10.1016/j.rse.2012.11.020, 2013.

L31. Leprince et al., is about mapping surface displacements (using Cosi-Corr), I am not sure this reference is appropriate for DEM errors. Can authors double check?

We have removed this reference.

L50. What are these "scenarios"?

We have changed it to "images".

L71. Authors need to explain why they need to revisit the Nuth & Kaab's method and why they present in details these flavours of their method. It is not straightforward for the reader what is the aim here. Also because in the end the results are almost identical...

The following sentences have been added at the beginning of Section 2.

> “In this section, we will demonstrate that the method of Nuth and Kääb (2011) and the method of Rosenholm and Torlegard (1988) are theoretically compatible, and the latter can be viewed as an extension of the former by additionally modeling the scale and rotation errors. As the original algorithms in the works of Nuth and Kääb (2011) and Rosenholm and Torlegard (1988) were presented in distinct forms, we will present detailed derivations of the equations used in their algorithms and variants.”

Figure 1. I did not really understand the figure because I did not understand what were representing the different letters/segments. Annotation to be clarified.

The meanings of θ, ψ, a, b, c have been annotated in Fig. R9 (highlighted in the green rectangle), X, Y, Z represent the axes along the three dimensions, O,E,G... are points in 3D space, and dH_{XY} and dH_{Z} are the elevation differences induced by a horizontal shift and a vertical shift, respectively.

Figure R9b (i.e., Fig. 1b in the manuscript) was redrawn from Figure 2 (i.e., Fig. R10) of Nuth and Kääb (2011). It is easy to read but only illustrates the special case when $b = \psi$, where b and ψ are the aspect of the shift vector and the terrain aspect, respectively. Figure R9a presents a 3D illustration of a general case when $b \neq \psi$, which is of importance to interpret the $\cos(b - \psi)$ term in Equation 2 of Nuth and Kääb (2011).

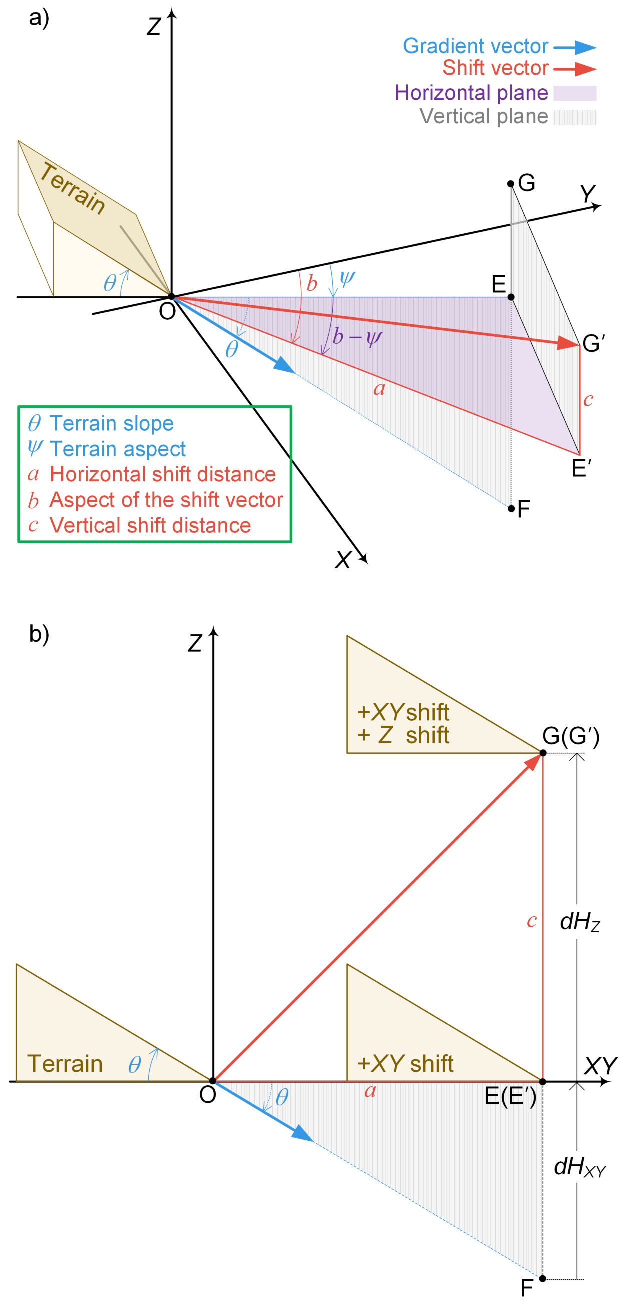


Figure R9. Elevation differences induced by DEM shift: **(a)** 3-D view when $b \neq \psi$. **(b)** 2-D view when $b = \psi$.

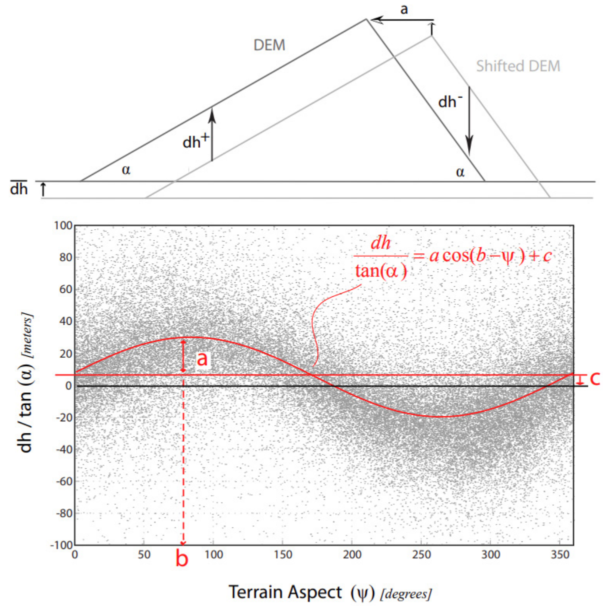


Figure R10. The Figure 2 of Nuth and Kääb (2011).

Figure 2. the terminology "master" and "slave" are not very the best ones for ethical reasons. "Reference" and "secondary" DEMs are better.

We have replaced the two words with "reference" and "secondary".

L204. I do not understand why 23 DEM pairs are first mention and then only 2 DEM pairs are presented in detail in Table 2. Rather include an appendix with the dates and ID of all the DEMs so that the study can be reproduced. Also, as you read in my general comment, a more extensive study using a variety of study sites would be more convincing.

We only displayed the results of 2 DEM pairs to improve the manuscript's readability. In the revised version, we have provided information of all DEM pairs in the Supplement.

L208. The NDBI index is not often used in the glaciological community so need to be explained a bit more.

As listed in Table R7 (The Table 1 of Nguyen et al., 2021), there are more than 10 bareness indices available in literature. The NDBI index used in this work was adapted from Deng et al. (2015) by replacing the SWIR2 band by SWIR1. Our experimental results show that the revised index performs slightly better than Deng et al.'s version (i.e., the NDSI2 in Table R7) in terms of enhancing bare soil from other land cover features around the periphery of GrIS.

Table R7. The Table 1 of Nguyen et al. (2021).

Table 1. Bare soil indices derived from Landsat imagery.

Index	Data	Formula	Case Study	References
Bare soil index	Landsat TM, ETM, 8 (OLI)	$BSI = \frac{(SWIR2+R)-(NIR+B)}{(SWIR2+R)+(NIR+B)}$	The Swiss Plateau, Switzerland	[48]
Bare soil index 1	Landsat TM	$BSI1 = \frac{(SWIR1+R)-(NIR+B)}{(SWIR1+R)+(NIR+B)}$	Guangdong, China	[34]
Bare soil index 2	Landsat TM	$BSI2 = 100 \times \sqrt{\frac{SWIR2-G}{SWIR2+G}}$	South Africa	[47]
Bare soil index 3	Landsat TM, ETM	$BSI3 = \frac{(SWIR1+R)-(NIR+B)}{(SWIR1+R)+(NIR+B)} \times 100 + 100$	Iran	[45]
Normalized difference soil index 1	Landsat TM	$NDSI1 = \frac{SWIR1-NIR}{SWIR1+NIR}$	–	[46]
Normalized difference soil index 2	Landsat TM	$NDSI2 = \frac{SWIR2-G}{SWIR2+G}$	Milwaukee and Waukesha, US	[50]
Normalized difference bareness index	Landsat TM, ETM	$NDBaI = \frac{SWIR1-TIR}{SWIR1+TIR}$	Northern coastal China	[52]
Bareness Index	Landsat TM	$BI = (R + SWIR1 - NIR)$	Beijing, China	[44]
Enhanced built-Up and bareness index	Landsat ETM	$EBBI = \frac{SWIR1-NIR}{10\sqrt{SWIR1+TIR}}$	Bali, Indonesia	[31]
Modified normalized difference soil index	Landsat 8 (OLI)	$MNDSI = \frac{SWIR2-PAN}{SWIR2+PAN}$	Dehradun, India	[54]
Normalized difference bare land index	Landsat TM, 8 (OLI)	$NBLI = \frac{R-TIR}{R+TIR}$	Wuhan, China	[53]
Dry bare-soil index	Landsat 8 (OLI)	$DBSI = \frac{SWIR1-G}{SWIR1+G} - \frac{NIR-R}{NIR+R}$	Kurdistan, Iraq	[49]

R: red wavelength, G: green wavelength, B: blue wavelength, NIR: near-infrared, SWIR1: shortwave infrared band 5 (Landsat TM/ETM) and band 6 (Landsat 8), SWIR2: shortwave infrared band 6 (Landsat TM/ETM) and band 7 (Landsat 8), PAN: panchromatic band 8 (Landsat ETM/8), TIR: thermal infrared band 6 (Landsat TM/ETM) and band 10 (Landsat 8).

References:

Deng, Y., Wu, C., Li, M., and Chen, R.: RNDSI: A ratio normalized difference soil index for remote sensing of urban/suburban environments, Int. J. Appl. Earth Obs. Geoinf., 39, 40–48, https://doi.org/10.1016/j.jag.2015.02.010, 2015.

Nguyen, C. T., Chidthaisong, A., Kieu Diem, P., and Huo, L.-Z.: A Modified Bare Soil Index to Identify Bare Land Features during Agricultural Fallow-Period in Southeast Asia Using Landsat 8, Land, 10, 231, https://doi.org/10.3390/land10030231, 2021.

L215. I do not understand how this 3-sigma rule is applied to check outliers from the classification. Authors need to elaborate more.

We have edited this sentence as follows:

" …and a three-sigma rule (i.e., more than three times the standard deviation) was employed on the elevation differences between two DEMs to remove erroneous data caused by misclassification of unstable terrain areas."

Figure 4 does not really bring much. I think it will be pretty obvious to most readers and can be explained in a few sentences in the text.

We have removed this figure.

L239. Example of why the application of the algorithm to a greater diversity of images is needed.

So far, the simplified and standard versions of the method of Nuth and Kääb have been compared with more than 200 DEM pairs from different sources, and the experimental results show that their performance is always close to each other. However, we still cannot reach a more definitive conclusion, because it lacks theoretical grounding.

L302. English is not really correct I think. Check

We have replaced "checked" with "check".

L320. This statement (and the rest of the paragraph) about extrapolation error and elevation error as a function of altitude comes a bit out of nowhere. Why discussing extrapolation when this was not mentioned before.

Please see the response to the third question of Major comments.

L328. This is exactly what the revised study should do: include cases where bare terrain is rare and see how the different methods compare.

There are two cases where bare terrain is rare:

1) Stable regions are fairly evenly distributed throughout the image

Compared to the L23 method, L57 usually yields a higher co-registration accuracy by additionally modeling the scale and rotation errors (refer to Fig. R3).

2) Stable regions are located on one side or even on one corner of the image

Due to data extrapolation, both the L23 and L57 methods are prone to yield unreliable co-registration results (refer to Fig. R8).

L349. I found the improvements rather modest. "outperformed" is a bit overselling.

The additional test results for HMA and NZL showed that the L57 algorithm could improve the co-registration accuracy by up to 83.3% more than the L23 method. Here we illustrate two examples in HMA (Figs. R11 and R12), where the DEM information used is shown in Table R8.

Table R8. Characteristics of the two DEM pairs.

Pair ID	Data	Date	Res. (m)	MedAD (L23–L57)
HMA-1	Copernicus	2011 to 2015	30	4.680–0.780 (83.3%)
	ZY-3	8 Oct 2017	30	
HMA-10	Copernicus	2011 to 2015	30	2.476–1.429 (42.3%)
	ZY-3	2 Dec 2016	30	

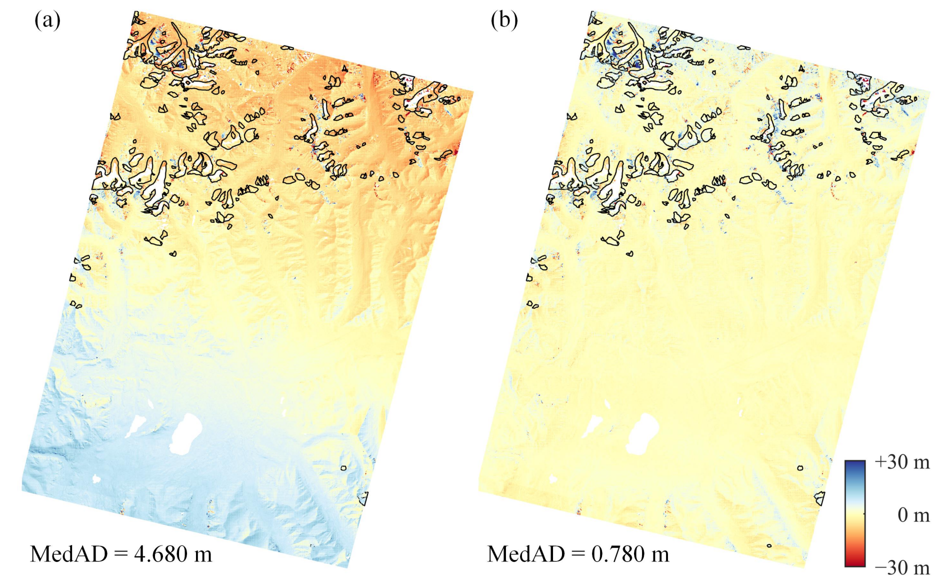


Figure R11. Co-registration results of DEM pair HMA-1: L23 (a) and L57 (b).

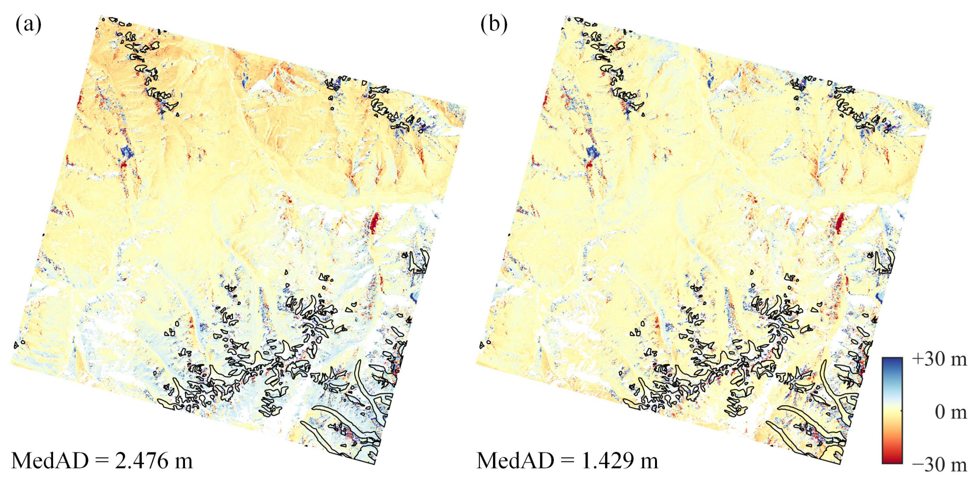


Figure R12. Co-registration results of DEM pair HMA-10: L23 (a) and L57 (b).

Response to Reviewer #2 on "Co-registration and residual correction of digital elevation models: A comparative study"

Comment received: 11 Jan 2023

Key:

Reviewer comment (black)

Response (blue)

This paper deals with the co-registration of DEMs for determining surface elevation changes by DEM differencing. The differences between DEMs are affected by random measuring errors and various systematic errors due to imperfections of the sensors. The success of the simple differencing method depends on how well the systematic errors can be determined and be removed. The paper begins with comparing 3 variants of the Nuth and Kääb method with the lessor known method proposed by Rosenholm and Torlegard. The authors then introduce a non-parametric residual correction model and present results from a few experiments with ASTER DEMs of Western Greenland.

Thank you for your constructive comments and suggestions.

Major Comments

I agree with the authors that the Nuth and Kääb method is predominently used for co-registering ASTER DEMs by the cryospheric research community. The method has been improved over the years, particularly with handling systematic errors of ASTER DEMs (see reference Luc Girod et al., 2017). If one wants to correct Aster DEMs, as the authors do, then I think one should start the process on the level of 2017 (see reference above) and not on the original level of 2011. The main reason is that in the 2017 version a new DEM is computed (MMASTER) with superior image matching that increases the reliability of the DEMs.

The research objects of our work are the DEM co-registration and residual correction methods utilized by cryospheric research for DEM differencing. In the previous manuscript, we chose the ASTER DEMs as a test dataset, which existed obvious complex systematic errors induced by satellite altitude jitter, enabling us to simultaneously design co-registration and residual correction methods. In the additional experiment, we tested DEMs widely used by cryospheric research, including ZY-3 DEMs, SRTM DEMs, and Copernicus DEMs (please see the response to Reviewer #1 for specific experimental results).

The research of Girod et al. (2017) includes two points: the process from a single stereo pair (one ASTER L1A scene) to an ASTER DEM and the correction of DEMs differences (dDEMs). Since we are not involved in the ASTER L1A data processing, the first point is not compared. For the dDEMs process, Girod et al. (2017) first adopted the DEM co-registration method described by Nuth and Kääb (2011), then proposed a parametric regression model (the sum of the sinusoidal functions) to correct the jitter-induced bias, which we have compared in the previous manuscript (Sect. 3.1. Parametric regression).

Another comment is related to the 'master/slave' concept to co-register DEMs. As is apparent from Table 2, the authors use as a master another ASTER DEM. That makes all computations relative to the master (which is essentially affected by the same systematic sensor errors as the slave) and thus precluding comparisons to an accepted ground reference system. In the area of the test site in Greenland are alternative sources that would be much better suited for serving as a master DEM (e.g. ICESat-2, World View DEMs, ATM airborne laser altimetry).

We agree that refined ASTER DEMs, ICESat-2, and ArcticDEM would be better alternatives for the accurate estimation of glacier changes. However, it should be noted that the main goal of this work is not to assess the accuracy of new DEM datasets but to compare different DEM co-registration algorithms. So far, our experiments have been carried out on four different DEM sources, including ASTER, ZY-3, SRTM, and Copernicus DEMs. The georeferencing errors in these DEMs are commonly larger than those in up-to-date data, but much smaller than those in historical data before 2000, which is adequate for the comparative analysis of different DEM co-registration methods.

The research results presented in this paper include a comparison between the methods proposed by Nuth/Kääb and Rosenholm/Torlegard. The results of these comparisons can be found in Table 3. The numbers confirm what other researchers have found. The question I have is the definition of AverageMed which is used throughout the paper. How does it compare with more traditional statistical error measures such as mean, median, standard deviation?

The mean and median are measures of location, while the standard deviation is a measure of scale (Rousseeuw and Hubert, 2018). There are two versions of MedAD (the median of all absolute deviations, also abbreviated as MAD) used in literature, i.e., MedAD around the median (Mcmillan et al., 2019) and around zero (Shen et al., 2021).

The MedAD around the median is a measure of scale and can be seen as a robust version of the standard deviation. It is calculated as follows:

$$\text{MedAD} = 1.4826 * \underset{i=1,\dots,n}{\text{median}}\left(\left|x_i - \underset{j=1,\dots,n}{\text{median}}(x_j)\right|\right) \quad (1)$$

where $x = H_{\text{Master}} - H_{\text{Slave}}$ in our manuscript. The constant 1.4826 is a correction factor which makes the MedAD consistent with the standard deviation at Gaussian distributions (Rousseeuw and Hubert, 2018).

In our manuscript, the MedAD is calculated around zero, and the constant 1.4826 is omitted:

$$\text{MedAD} = \underset{i=1,\dots,n}{\text{median}}\left(\left|x_i\right|\right) \quad (2)$$

This form of MedAD is a combined measure of location and scale, and it can be used as a robust alternative to the Root-Mean-Square Deviation (RMSD).

As shown in the last four rows of Table R9, the ratio of the standard deviation (Std) to the MedAD around zero is very close to 1.4826 in our experiments, because the distribution of DEM co-registration residuals is often nearly Gaussian with a zero mean.

Table R9. Co-registration results obtained with the 23 DEM pairs.

Method	ID	Average Median (m)	Average MedAD (m)	Average Mean (m)	Average Std (m)
Before co-registration	—	−3.391	12.043	−3.504	12.604
Nuth and Kääb standard version	N23	0.045	7.170	−0.014	10.910
Nuth and Kääb simplified version	N13	0.036	7.163	−0.017	10.913
Nuth and Kääb linear version	L23	0.045	7.170	−0.014	10.910
Rosenholm and Torlegard	L57	0.005	6.839	0.002	10.484

References:

McMillan, M., Muir, A., Shepherd, A., Escola, R., Roca, M., Aublanc, J., Thibaut, P., Restano, M., Ambrozio, A., and Benveniste, J.: Sentinel-3 Delay-Doppler altimetry over Antarctica, The Cryosphere, 13, 709–722, https://doi.org/10.5194/tc-13-709-2019, 2019.

Rousseeuw, P. J. and Hubert, M.: Anomaly detection by robust statistics, WIREs Data Mining and Knowledge Discovery, 8, e1236, https://doi.org/10.1002/widm.1236, 2018.

Shen, X., Ke, C.-Q., Yu, X., Cai, Y., and Fan, Y.: Evaluation of Ice, Cloud, And Land Elevation Satellite-2 (ICESat-2) land ice surface heights using Airborne Topographic Mapper (ATM) data in Antarctica, Int. J. Remote Sens., 42, 2556–2573, https://doi.org/10.1080/01431161.2020.1856962, 2021.

Another conclusion the authors make is that GAM spline fitting can be used to reduce complex systematic errors that are still present after geo-referencing. These research results are OK but limited to a specific sensor (ASTER, 25 years in space, outdated technology, complex suite of systematic errors that change in time). Moreover, since GAM spline fitting seems to play an important role in this paper I would strongly suggest to cover it in more detail and provide readers with explanations why you choose it.

Thank you for your suggestion. We have added the technical details of the GAM spline fitting algorithm in the revised manuscript (see 3.2. Non-parametric regression).

Our experiments so far have been conducted on more than 200 DEM pairs from four different sources including, ASTER, ZY-3, SRTM, and Copernicus DEMs, located in the Greenland Ice Sheet (GrIS), High Mountain Asia (HMA), and New Zealand (NZL). The experimental results show that strong jitters can only be observed in the ASTER DEMs of GrIS.

Though the paper is written well I have doubts that it is suitable for publishing in this journal in its current form. The methodology presented in this paper should be made more relevant to cryospheric research or might be better suited for a journal that is more focused on new methods and algorithms.

The paper of Nuth and Kääb (2011) was originally published in "The Cryosphere". Their algorithm is currently the most commonly used DEM co-registration method in glacial studies, but it has not been widely adopted in other geoscience applications. Our work aims to present a deep investigation on the algorithm of Nuth and Kääb, and, therefore, we submitted our manuscript to the same journal, "The Cryosphere".

As suggested by you and Reviewer #1, we have provided more experiments to investigate the choice of DEM co-registration algorithms of glacier change estimation in the revised manuscript and Supplement. For more details, please see our replies to Reviewer #1.

Reference:

Nuth, C. and Kääb, A.: Co-registration and bias corrections of satellite elevation data sets for quantifying glacier thickness change, The Cryosphere, 5, 271–290, https://doi.org/10.5194/tc-5-271-2011, 2011.