Responses to Anonymous Referee #1 for manuscript (esurf-2018-51) submission to Earth Surface Dynamics:

Measuring Decadal Vertical Land-level Changes from SRTM-C (2000) and TanDEM-X (~2015) in the South-Central Andes

We appreciate the review and the improvements suggested by close reading of the manuscript. Highlighted in **bold are the reviewer comments** followed by our reply. All changes will be made to the final manuscript submission following completion of the interactive review period.

Response to Anonymous Referee #1

The study analyses elevation differences between the SRTM and TanDEM-X DEMs over mountain terrain. The processing procedure to reach maximum accuracy and to remove various horizontal and vertical shifts is sound, but the geophysical results are more sparse than expected. My comments:

General comments

(1) The study is mostly a method presentation, the results are less spectacular than the reader expects ("novel", "first time"). I strongly recommend to tone done the latter type of announcements to make the reader not expect dense measurements over an entire mountain region.

The manuscript primarily focuses on the methods (particularly the SRTM-C correction steps). The river and landslide measurements are used as examples of the method in action. We agree that the results in both cases are sparse and we have made an effort to tone down the language to reflect this. An excerpt of a changed sentence from P1L5-7 in the Abstract:

Before: For the first time we measure land-level changes at the scale of entire mountain belts in the south-central Andes using the SRTM-C (collected in 2000) and the TanDEM-X (collected from 2010–2015), both spaceborne radar DEMs.

After: Following careful corrections, we are able to measure land-level changes in gravel-bed channels and steep hillslopes in the south-central Andes using the SRTM-C (collected in 2000) and the TanDEM-X (collected from 2010-2015) near-global DEMs

(2) Perhaps show and analyse (sediment fluxes) the entire river reach covered not only a subsection.

We appreciate this comment and point out that this was our primary (initial) motivation: to establish a full-catchment vertical land-level dataset. However, during processing we realized the constraints and considered it more useful to elaborate on the methodological processing steps than a sediment budget. Specifically, our analysis is limited by SRTM-C resolution and channel width in the region. The raw signal of the SRTM-C has approximately 30 m ground resolution, however, this degrades to 45-60 m following post-processing in delivered products (see P4L18-20). To avoid the inclusion of non-channel regions (e.g., steep hillslopes) we apply a negative 60 m buffer to the bank-to-bank digitized channel polygon (see P8L22-25). Thus, only center pixels where the local channel width exceeds 120 m are considered in *dh* mapping. Channel widths further upstream of the analyzed reaches, and from their tributaries in the steep catchments that characterize this mountain front, have only sparse pixels meeting this requirement and are thus excluded.

(3) Page5Line5, and else: land level changes are measured for instance using medium resolution ASTER data. Tome down "for the first time" if it refers to medium resolution. Also, are you sure that no landslides etc. have been measured using SRTM and TanDEM-X before? Also, TanDEM-X is in my view a high-resolution sensor, not a medium resolution one.

As noted previously, we have toned down the language throughout the manuscript. Low, medium, and high-resolution terminology is relative and will change from decade to decade. In Passalacqua et al. (2015), the authors define high-resolution topography from sources like lidar and very high-resolution satellites (e.g., Pleiades and WorldView) as meter to sub-meter resolution. With a raw radiometric ground resolution of ~3.3 m, this places the TanDEM-X data outside of this realm. However, these terms are always relative and 10 years ago the 90 m SRTM-C data was considered “high-resolution”. In general, we dislike these relative terms and they certainly add confusion, particularly for future readers. To avoid this, we have carefully gone through the manuscript and removed references to coarse, medium, and high-resolution. Instead we spell out the resolution, referring to Pleiades and WorldView as “sub-meter resolution satellites” and only using terms like “coarser” or “finer” in relative references between datasets. e.g.:

P2L13: “Despite recent advances in meter to sub-meter lidar, satellite, and unmanned aerial vehicle data availability (Passalacqua et al., 2015), these remain limited in spatial and temporal coverage, and sometimes prohibitively expensive. Coarser gridded DEMs from radar and optical spaceborne sensors remain the best, and often only, option in large or remote areas.”

Regarding landslides, we did not find any previous studies that specifically used the SRTM-C and newly released TanDEM-X data for mapping or volume estimation. However, recent work (e.g., Wessel et al., 2018) has begun examining the effect of land-cover on TanDEM-X, which could be useful in volume estimations of biomass and for assessing land-cover changes caused by deforestation, urbanization, and agriculture.

(4) P2L6: be less strict. ASTER timeseries detect a few cm/dm per year over 10-20 years (=dm-m total change)

We argue that ASTER requires either (a) many meters of elevation difference to overcome the large amount of noise in these low quality DEMs or (b) a long enough time series to identify trends in individual pixels. We therefore see no issue with the sentences (P2L4-9):

“Using DEMs from sources like the Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER; Tachikawa et al. (2011)) with higher uncertainties is acceptable for monitoring glaciers and ice sheets (e.g., Brun et al., 2017), where *dh* between even sub-annual time-steps can be tens to hundreds of meters over areas of many square kilometers. On the other hand, *dh* of soil, rock, and unconsolidated sediment are often at the centimeter to meter scale and far more localized over up to a few hundred to thousand square meters.”

(5) P2L14: what about ArcticDEM, HighMountain Asia DEM, ALOS PRISM AW3D? I wouldn’t call them limited spatial coverage.

Arctic and High Mountain Asia DEMs are non-global datasets. ALOS PRISM is available at 5 m resolution for much of the globe, though major holes remain in high mountain regions. Furthermore, the quality of this data is suspect (please refer to our previous publication: Purinton and Bookhagen, 2017) and does not match the quality expected from sub-meter sensors like WorldView or Pleiades. Furthermore, both the TanDEM-X and SRTM-C MEASURES DEM (the SRTM-C version used in this study) have been extensively referenced to ICESat measurements (see P6L8) and are referenced to the same geoid. Thus these datasets (in addition to lower quality ALOS AW3D and ASTER GDEM2 DEMs) represent unique DEMs, which may be widely applied by other scientists in diverse regions around the globe.

(6) Section 3 (Correction...) is rather part of the methods.

We agree with the suggestion and have moved this section to the beginning of the methods, thus removing Section 3.

(7) Fig 8 and 9: you also need to show the results outside the masks in order to let the reader judge the statistical significance.

In Figure 9 we are showing the full, un-masked *dh* map using statistical thresholding in slope-height-error-consistency bins (please refer to P9L7-12). Only *dh* values that are in the bottom and top 5% of pixels in their respective bins are mapped. For Figure 8 we are only considering the channel pixels. By restricting measurement to only the low-slope, vegetation-free, buffered channel pixels we ignore increased uncertainties from higher slopes and areas with dense vegetation and anthropogenic tampering on banks and nearby farmlands that would hide the significantly changing channel pixels within the statistical cutoffs. We argue that the lack of statistically significant pixels being mapped on the low-slope, vegetation-free, arid Altiplano-Puna Plateau region in Figure 9A is evidence that the method returns primarily true change pixels, while ignoring statistically insignificant changes. We hope that the points made in the discussion at P20L26-30 clearly point out the caveats of the method regarding this change detection:

“Given remaining noise in the datasets, change mapping is limited to large areas of coherent change (e.g., massive landslides) or specific low-slope, sparsely vegetated areas of interest such as wide gravel-bed rivers. In either case, field knowledge or auxiliary data (even in the form of GoogleEarth^{TM}) is necessary for accurate assessment of true change signals versus noise. In any case, the magnitude of change must be significantly above the expected uncertainty between

DEMs, which in the case of SRTM-C and TanDEM-X is as low as ~3 m on flat, partially vegetated terrain, and increasing with slope and topographic complexity."

(8) Fig 8: I guess these magnitudes of changes would also be visible in ASTER time series, or ASTER versus SRTM (for instance;Castro et al. 2016 (Nature Comm Art 13585), Brun et al. 2017 (in your list), Girod et al. 2017 (doi: 10.3390/rs9070704), Wang et al. 2015 (doi: 10.3390/rs70810117))

Actually we have experimented with ASTER DEMs in the area, but scene quality is very low and obscured in most cases by heavy cloud cover (this is an orographic barrier experiencing heavy precipitation in much of the downstream reaches at the mountain front). We were unable to find a good collection of ASTER scenes with which to assess the MICMAC methods of Girod et al. (2017) or regressions of Wang et al. (2015). Regarding the magnitudes of change, likely only the very large anthropogenic piles would be visible in an ASTER time series, given the > 5 m vertical uncertainty typically associated with even carefully hand-clicked ASTER DEMs in high relief areas, and worse still in lower quality ASTER DEMs (Purinton and Bookhagen, 2017). We added the following sentence at P4L8:

"Additionally, a dearth of cloud-free, high-quality ASTER imagery covering the study area precludes the automated DEM generation of Girod et al. (2017) and regression techniques of Wang et al. (2015)."

(9) Fig 9: The landslide dh would also be visible without your processing, I guess. You could use this (and the river) to visualize the importance of your processing in more detail (before-after processing).

Given the sparse pixels mapped, we have found that visual representation of the pre- and post-processed *dh* change maps are not so helpful. However, we think that this has been addressed textually in the case of the channels in the discussion at P19L6-10:

"Downstream of the knickpoint, Río Toro is in a net aggradation state with a corrected *dh* volume of $0.81\pm0.15\times10^6$ m^3, whereas, for Río Grande the net state is incision with a volume of -$0.69\pm0.15\times10^6$ m^3. In comparison, the pre-correction volume in each case is -$1.18\pm0.12\times10^6$ m^3

and $2.80\pm0.11\times10^6$ m^3 for Río Toro and Río Grande, respectively, thus indicating a flip in sign and reduction of magnitude following careful corrections applied prior to differencing."

And for the landslide we have added a clarification to the volume estimation at P20L8:

"These magnitudes of change show little difference in the pre- and post-corrected mapping, indicating (a) this is a localized region of good agreement between SRTM-C and TanDEM-X and (b) this large landslide can be identified in uncorrected difference maps."

(10) P19L7-8: How are uncertainties computed? StDeviation, StError (if StError, how computed?). How aggregated and how voids filled?

Error bars in Figure 7 are the RMSE taken from low-slope (< 5°) stable terrain. This is noted in the text and is also used as the level of detection cutoff following statistical outlier identification to further remove any suspect pixels well within expected TanDEM-X / SRTM-C noise. The uncertainties for volume estimation on P19L7-8 are clarified with the addition of this sentence in the methods at P9L5:

"Volume changes are calculated from the sum of pixel area (900 m^2) multiplied by vertical change with uncertainties taken as the level of detection RMSE and propagated via equation (15) in Lane et al. (2003)."

(11) P30L31: it is not that easy to account for radar penetration! It exceeds often the actual elevation change signal, and the correction magnitudes applied here. See above ASTER studies, and others.

Duly noted, we soften this section by changing it to the following:

"We posit that these correction steps may also be applied to cryospheric studies, however, radar penetration would need to be carefully considered first as this may exceed *dh* signals."

Detail Comments

page 1, line 2: rewrite 1st sentence. "Vertical change is measured in the cryosphere...". I understand what you mean, but what is "measuring in the cryosphere"?

Before: Vertical change is often measured in the cryosphere via digital elevation model (DEM) differencing to assess glacier and ice-sheet mass balances.
After: It is common to measure vertical changes of ice-sheets and glaciers in the arctic and high mountains via digital elevation model (DEM) differencing.

P1L4: typically much smaller (landslides, as the one you show later, are a frequent exception with vertical changes on the same order of magnitude as glaciers).
Before: On the ice-free earth, land-level change is much smaller in magnitude and thus requires more accurate DEMs for differencing and identification of change.
After: Excluding large landslides, on the ice-free earth land-level change is smaller in magnitude and thus requires more accurate DEMs for differencing and identification of change.

P18L15: leaves stripes noise at the expense of preserving ... ? Other way round?
Before: This leaves some stripe noise at the expense of preserving topographic signal.
After: This conservative approach retains the true topographic signal at the expense of remaining stripe noise.

Sincerely,
For both authors,

Ben Purinton
Universität Potsdam, Germany
purinton@uni-potsdam.de

References

Bagnardi, M., González, P. J., and Hooper, A.: High-resolution digital elevation model from tri-stereo Pleiades-1 satellite imagery for lava flow volume estimates at Fogo Volcano, Geophysical Research Letters, 43, 6267–6275, https://doi.org/10.1002/2016gl069457, 2016.

Brun, F., Berthier, E., Wagnon, P., Kääb, A., and Treichler, D.: A spatially resolved estimate of High Mountain Asia glacier mass balances from 2000 to 2016, Nature Geoscience, https://doi.org/10.1038/ngeo2999, 2017.

Girod, L.; Nuth, C.; Kääb, A.; McNabb, R. & Galland, O.: MMASTER: Improved ASTER DEMs for Elevation Change Monitoring, Remote Sensing, 704, 2017.

Lane, S. N., Westaway, R. M., and Murray Hicks, D.: Estimation of erosion and deposition volumes in a large, gravel-bed, braided river using synoptic remote sensing, Earth Surface Processes and Landforms, 28, 249–271, 2003.

Passalacqua, P., Belmont, P., Staley, D. M., Simley, J. D., Arrowsmith, J. R., Bode, C. A., Crosby, C., DeLong, S. B., Glenn, N. F., Kelly, S. A., Lague, D., Sangireddy, H., Schaffrath, K., Tarboton, D. G., Wasklewicz, T., and Wheaton, J. M.: Analyzing high resolution topography for advancing the understanding of mass and energy transfer through landscapes: A review, Earth-Science Reviews, 148, 174–193, https://doi.org/10.1016/j.earscirev.2015.05.012, 2015.

Purinton, B. and Bookhagen, B.: Validation of digital elevation models (DEMs) and comparison of geomorphic metrics on the southern Central Andean Plateau, Earth Surface Dynamics, 5, 211, https://doi.org/10.5194/esurf-5-211-2017, 2017.

Tachikawa, T., Kaku, M., Iwasaki, A., Gesch, D. B., Oimoen, M. J., Zhang, Z., Danielson, J. J., Krieger, T., Curtis, B., Haase, J., et al.: ASTER global digital elevation model version 2-summary of validation results, Tech. rep., NASA, 2011.

Wang, D. and Kääb, A.: Modeling glacier elevation change from DEM time series, Remote Sensing, 10117-10142, 2015.

Wessel, B., Huber, M., Wohlfart, C., Marschalk, U., Kosmann, D., and Roth, A.: Accuracy Assessment of the Global TanDEM-X Digital Elevation Model with GPS Data, ISPRS Journal of Photogrammetry and Remote Sensing, 139, 171–182, 2018.