Rebuttal

Journal:The Cryosphere Discuss., 8, 2425-2463, 2014
Title: Orientation dependent glacial changes at the Tibetan Plateau derived from 2003–2009 ICESat laser altimetry
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Dear Editor,

In this rebuttal, we react on the different comments that we received in the Online Discussion of our manuscript. Below, comments from different people are grouped according to topic. We distinguish between more methodological comments, that are discussed first, and more technical remarks, that are discussed second, followed by minor remarks. Hereby we would like to thank the different contributors to the discussion, which definitely increased our insight in the topic.

With kind regards,

Roderik Lindenbergh, Vu Hien Phan and Massimo Menenti

List of comment reports

- [Nu] Interactive comment by C. Nuth (Referee), Received and published: 18 June 2014
- [Kb] Interactive comment by A. Kaab
- [Ref1] Interactive comment by Anonymous Referee 1.
- We already reacted on initial comments from the Editor.

Methodological comments

1. **Potential biases in ICESat and/or SRTM elevation measurements.**

   [Kb, Nu]: Potential biases in ICESat and/or SRTM elevation measurements could affect the resulting trends. Intercept in e.g. Fig. 4 should be close to zero if extrapolated back to the year 2000 (Acquisition year, SRTM). Therefore crucial assumption: “The average elevation difference dh is considered representative for the height of the glacier above the SRTM base map.”

   Authors: we only use SRTM as a reference surface, but stress here that we don't use SRTM elevations as observations in determining the trend. We do use SRTM for determining local terrain slope and roughness and we use SRTM in determining height differences dh. Therefore, a vertical bias in SRTM w.r.t ICESat elevations will not affect the resulting trends, as long as the bias is the same over one region. As a consequence, it is notably not needed that a *resulting trend intercept is close to zero when extrapolated back to the year 2000.*

We do agree of course, that an intercept that is not close to zero may be caused by vertical misalignments between ICESat and SRTM elevations, or, to a lesser extent, by horizontal misalignments. Actually our statement "The average elevation difference dh is considered representative for the height of the glacier above the SRTM base map." is too strong, we only require SRTM to represent the shape of terrain in the direct vicinity of the ICESat footprints.

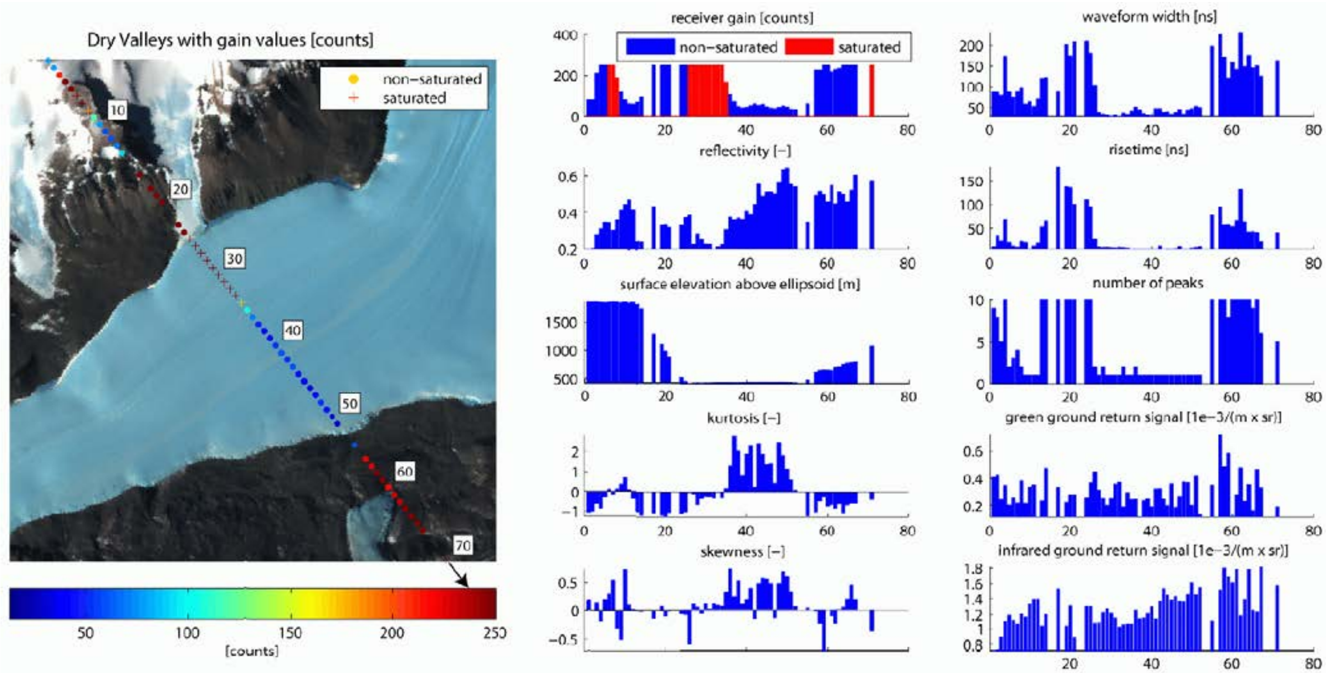

Figure 1: Individual ICESat footprints over a glacier in Dry Valleys, Antarctica, showing how a "slow" gain adaptation results in a number of consecutive saturated waveforms at a land cover transition.(Source: Ramses Molijn, MSc thesis project, Delft University of Technology)

2. ICESat sampling representativity

[Kb, Nu]: ICESat sampling representativity, Data aggregation. Required: much deeper investigation into data aggregation w.r.t the glaciological assumptions. Elevation change trends in Table 3 and 4 are below the significance level. Also density of ICESat points over glacier (Section 4.4) is not an appropriate measurement of ICESat representativity. Better: show that elevations of the ICESat points sampling the group of glaciers considered are sufficiently representative for the actual elevation distribution of these glaciers. There could be a temporal trend in ICESat elevation. (Kaab et al, 2012, supl)

The big issue in this and related studies (Kaab et al, 2012; Neckel et al., 2014; Gardner et al., *2013) is how ICESat elevations, being only sparsely available at Tibetan latitudes, should be used to estimate trends for a certain choice of glacial regions, and how and to what extent these resulting trends can be used to draw conclusions on the state of all glaciers in the full region under study, here the Tibetan Plateau (TP). Notably (Kaab et al., 2012) give a very thorough analysis (in the Supplementary Material) of the way they use ICESat elevations to estimate glacier thickness changes over 2^{o}grid cells. The following steps have to be decided on:*

- *Selecting valid ICESat elevations*
- *Estimating glacier change trends over suitable homogeneous regions*
- *Exaggerating trends to full region of interest*

In order to create a manageable workflow, certain assumptions have to be made, and in our opinion no study yet provided a final approach in which each step is beyond further discussion. We certainly agree with a large part of the criticism on our workflow, see also below, but we also made novel contributions. In selecting ICESat elevation, we require both low terrain slope and roughness, as higher values result in wider GLAS waveforms with lower S/N ratio while simultaneous an elevation error has a bigger effect on a sloped terrain.

What notably surprised us from the methods in the related studies is that less attention is paid to glacial orientation, although this also influences glacial mass balance, compare e.g. (Kutuzov and Shahgedanova, 2009). Related to this one could argue that a division into 2^{o}grid cells (Kaab et al., 2012) is less close to the actual physical processes than the divisions in (Neckel et al., 2014) and our manuscript. The idea to compare the ICESat elevation distribution with the actual elevation distribution is good, and we will definitely adapt that comparison in a future version of the manuscript.

Reviewers somehow question our results and we definitely agree that a more thorough analysis of results should take place, for example by considering shot by shot ICESat/GLAS parameters, SRTM derived parameters (slope, roughness) and appropriate Landsat or maybe MODIS images for some selected case studies. Compare for example Figure 1, showing individual ICESAT/GLAS shots over a snow free glacier in Dry Valleys, Antarctica. This figure also shows that GLAS saturation is not some kind of random effect, but is related to transitions of the ICESat track between land cover. For example after a rock-ice transition, the amount of reflected energy suddenly increases, which will result in saturation of the receiver. It will take a few shots before GLAS is able to automatically lower the gain settings. Over the TP, with quickly changing terrain types, such instrumental effects are quite relevant.

Considering the quality of our results we showed in our manuscript that our results are in good agreement with results by (Neckel et al., 2014) and (Gardner et al., 2013).

Currently we are also correlating our glacier thickness changes to previously derived lake level changes over the TP, (Phan et al., 2012; Phan et al., 2013) by considering which ICESat *sampled glaciers drain exactly into which ICESat sampled lakes on the TP. At this moment, this work is still in progress however.*

2. [Kb, Nu, An] GLIMS outlines, are they really from 2000? Outlines seem extremely outdated. They also have displacements. Others already used Satellite Image data as only proposed here.

   You are right, most outlines are actually older. The glacier inventory was based on topographic maps, aerial photography, optical remote sensing images and in situ measurements from 1978 to 2002 (Shi et al., 2009) during several individual periods. Considering (almost) contemporary spectral data to determine glaciers would be better, but is also very time-consuming. It is expected (but not tested) that including probable stable GLAS measurement off the retreated glacier demp a vertical change trend.

3. [Nu]: Major lack of basic glaciological concepts, read Cuffey and Peterson (2010)

   We will read Cuffey and Peterson, we are indeed not glaciologists but mostly Remote Sensing people

4. [Kb, An1] All ICESat campaigns are used, June campaign probably thick snow cover; Winter and autumn trends should be separated

   Of course we could separate trends and determine trends without including the June campaigns. At the same time, precipitation in large parts of the Tibetan Plateau is quite sparse, so thick snow cover is unlikely, compare also (Nickel et al., 2014)

5. [Kb] How do authors decide on Slope and Roughness thresholds?

   This is discussed in the text, notably in Section 3.1.

6. [Kb] Significance of differences between North and South trends. Differences fall within error margins.

   We didn't perform yet a proper testing of the significance of the differences between trends, e.g. using a Chi-squared test as explained in (Teunissen, 2009). We will do so in a future version.

7. [An1] Also add comparisons with field measurement of mass balance [Yao et al, 2012]

   This would definitely be interesting, but would also require strong glacier outlines, knowledge on firn and ice distribution, compare suppl. material of (Kaab et al., 2012).

Technical remarks

1. [Kb, Nu, An1] Assessment of ICESat and SRTM misalignments/co-registration, vertical biases. CGIAR SRTM is e.g. over The Himalayas shifted by 50-200m (Supl. Kaab, 2012)

   We use SRTM version 4. We didn't know about possible horizontal misalignments between ICESat and SRTM and should check this

2. [Nu, Kb] Elevation difference trends on stable terrain are not analyzed

   We agree, it would definitely make sense for validation purposed to apply the same method for stable terrain as well

3. [Nu] ICESat saturation corrections: suggested to be only applicable for GLA06 products, see also Specific Comments from {Nu}

   As far as we understood the saturation correction applies for GLA06, GLA12, 13 14 and 15. We use the saturation flag (i_satCorrFlg) to check if a GLAS signal is corrected, compare http://nsidc.org/data/docs/daac/glas_altimetry/data_dictionary.html#i_satCorrFlg_14

4. [Nu] P2435 L13-19: are larger elevation differences systematically removed? This procedure may remove valid elevation changes at the tongue.

   We agree, this should be checked in some detailed case study by evaluating exactly which differences are exactly removed by the procedure.

5. [Nu] P2436 L1-25, what assumptions are made for the linear regression? Do these assumptions actually hold?

   It is assumed that the vector of observations y, is a random normally distributed vector, that different observations are uncorrelated (as Q_yy is diagonal) and that Q_yy is known. This is ordinary LSQ, only observations are weighted relative to their respected quality as expressed by their variance. Probably the reviewer is right in the sense that observations are not perfectly normal. Still, some type of regression is also used in the related papers, and to us this seems the most reasonable thing to do. Still, this approach could also be better evaluated in a detailed case study.

6. [Nu] P2439, L7-23, Impossible to judge the significance of this result (i.e. final temporal trends)

   The significance of the result is indicated by the given errors, which are computed using LSQ as described on pages 2436 and 2437 (top). Note that we are not interested in the intercept of the trend, the error is the st.dev of the vertical change rate (Square root of entry (2,2) in the Q_{\hat{x}\hat{x}}).

7. [Nu] ICESat track distribution should be shown on Figures 6, 7, 8, more general, spatial

sampling of each of the basins remains questionable. (See also Specific Comments [Nu])

We agree, we should and can add the ICESat footprints to Figures 6, 7 and 8.

Minor remarks

Very minor (but helpful) remarks on e.g. typos are not discussed here.

1. [Nu] Provide refs for P2427 L24 “Recently, however, new remote sensing techniques such as interferometry and radar/laser satellite altimetry have been used for research on glacier and ice-sheet changes.”
   We will in a next version, e.g.
   Quincey, D.J., Luckman, A., Benn, D.: Quantification of Everest region glacier velocities between 1992 and 2002, using satellite radar interferometry and feature tracking. Journal of Glaciology, 55 (192), 596 – 606, 2009.
   Molijn, R., Lindenbergh, R., Gunter, B.: ICESat laser full waveform analysis for the classification of land cover types over the cryosphere. International Journal of Remote Sensing, 32 (23), 8799 – 8822, 2011.

2. [Nu, An] Derivation slope and roughness parameters is to detailed; Remove 3x3 kernel picture; Remove Figure 2

   We will shorten the derivation in a next version

3. [Nu, An1] ICESat elevations are given w.r.t TOPEX/POSEIDON. Were elevations converted to WGS84? How was the datum converted?

   ICESat/GLAS data was converted to the WGS84 ellipsoid using the IDL Ellipsoid Conversion tool provided by the NSIDC (http://nsidc.org)

4. [Nu] 100 m threshold between ICESat and SRTM. Why 100 m? Too small?

   Others use 150m (Kaab et al., 2012; Neckel et al, 2014). In a detailed case study at footprint level (as mentioned above) it could be assessed if 100m is indeed too small.

5. [Nu] Don't use velocity for glacial thickness changes (People think of glacial flow); Introduce TP once, and use TP instead of Tibetan Plateau thereafter.

   Agree

6. [An1] TP boundary used?

We use the TP boundary as provided by the FP7 project CEOP-AEGIS (http://www.ceop-aegis.org/). This boundary is illustrated in Figure 2.

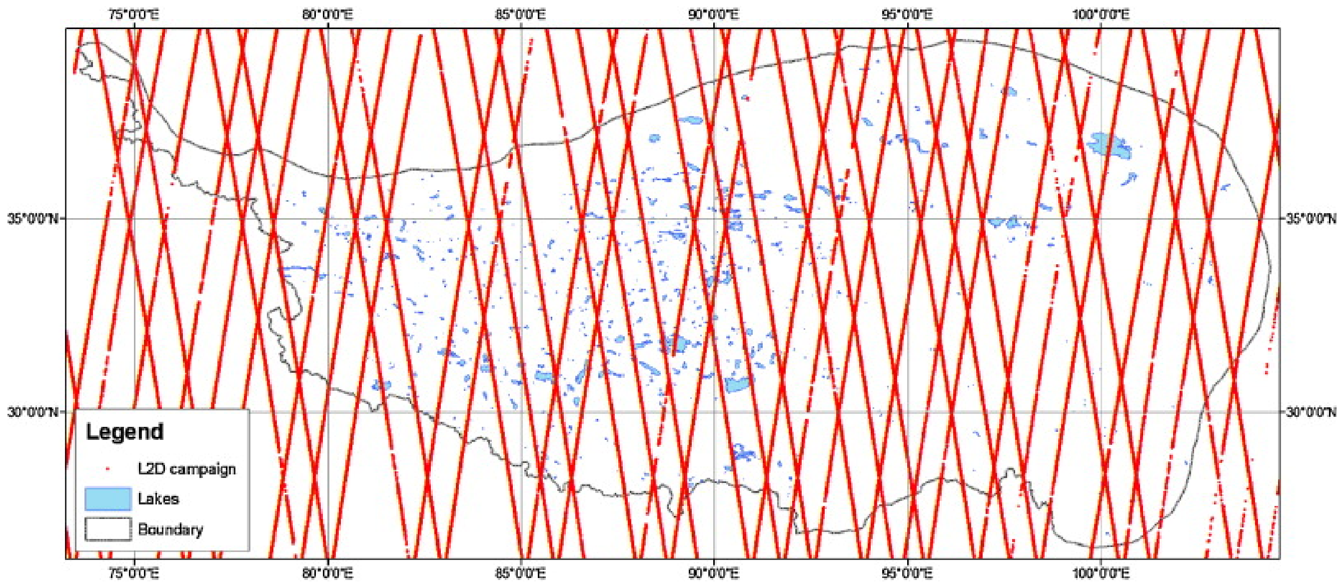

Figure 1: The black line indicates the boundary of the TP as used in this study (Source: Phan et al., 2012)

Additional References

1. Glacier retreat and climatic variability in the eastern Terskey–Alatoo, inner Tien Shan, between the middle of the 19th century and beginning of the 21st century, Stanislav Kutuzov and Maria Shahgedanova, Global and Planetary Change 69 (2009) 59–70
2. Testing theory, An Introduction, P.J.G. Teunissen, Delft University Press, (2009)