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The Cryosphere Discussions

# *Interactive comment on* "Longest time series of glacier mass changes in the Himalaya based on stereo imagery" *by* T. Bolch et al.

**Anonymous Referee #1**

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GENERALS COMMENTS

In their paper, Bolch et al. used several digital terrain models (DTMs) derived (mainly) from satellite optical imagery acquired between 1962 and 2007 to assess the geodetic mass balance of a ~50-60 km$^2$ ice-covered area in the Everest area (Nepal, Eastern Himalaya). They built on and extended the analysis in a previous paper, published in 2008 (Bolch et al., 2008). The novelty here are that some glaciers are entirely covered (whereas the 2008 paper focused mostly on their lower parts) and the important addition of a more precise DTM from 1970 (also derived from Corona Spy satellite imagery) to complement the 1962 one. The authors conclude to negative mass balances with, in particular, a high confidence in the 1970-2007 value. There is less confidence in the estimates for shorter time periods so that the acceleration in the mass loss, al-



though likely, is not statistically significant (yet). The spatial distribution of ice elevation changes is consistent with knowledge of ice dynamics and spatial variability in surface ablation (linked to spatially variable debris thickness). This part of the discussion (to explain the distribution of thinning) is sound, although nothing really new is presented.

This is a well-written and important piece of work that demonstrates the usefulness of satellite spy imagery to extend the geodetic mass balances back in time (60s and 70s) and put the recent glacial mass changes in a multi-decadal perspective. Those 30 to 40 year mass losses are needed to determine whether the ice loss accelerated recently or not. Thus, I suggest publication of the paper in The Cryosphere after minor revision. My main comment concerns the poorly explained error calculation (see P2597 L15 below).

Regarding the previous comment by M. Pelto about the stable terminus of most glaciers. Bolch et al. will probably discuss themselves this issue. However, M. Pelto and other readers must have in mind that (Bajracharya and Mool, 2009) compared middle resolution satellite (Landsat) imagery from year 2000 to 1960s topographic maps (without discussing their relative planimetric adjustment, the precision of the map, etc...) whereas Bolch et al. have a comprehensive, geometrically homogeneous (because orthorectified with the same set of ground control points) series of high resolution satellite imagery...

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SPECIFIC & TECHNICAL COMMENTS

TITLE

The title is not wrong but too vague. You need to indicate that the paper deals with the Everest area (Nepal, Himalaya). A suggestion: "Multi-decadal mass loss of glaciers in the Everest area (Nepal, Himalaya) derived from stereo imagery".

ABSTRACT

It would be good to have somewhere in the abstract the total ice-covered area

P2594 L1: Strictly speaking if glaciers in the Himalayan are currently loosing mass, their contribution to river runoff does not decline but (of course temporary) increase.

P2594 L11: “an increasing rate since at least 1970”. Strange statement given the poor confidence in the 1962-1970 volume change, restricted to a limited area. Did you mean “since at least 2002”? Rephrase.

INTRODUCTION

P2594 L19. Be more cautious. It is indeed more relevant to compare mass balances than length or area changes in different glaciarized areas of the globe but still, keep it mind (or remind to the readers) that the glacier mass balance is highly dependent on the hypsometry of each glacier and, thus, can differ a lot even for glaciers experiencing a similar climate change (e.g., Vincent et al., 2004) or (Paul and Haeberli, 2008, Figure 3 and 4).

P2595 L8. Why “mean” for the 2002 ASTER DEM time stamp?

P2595 L9. “mass balance estimates for a larger sample”

P2595 L11. “the proglacial lake which formed in the 1960s and rapidly grown since”

P2595 L16. Indicate the total area of those 9 studied glaciers

P2595 L20. Meaning of “Cwn”?

DATA & METHODOLOGY

P2596 L8. The justification for not using SRTM is not very convincing given that (L28 of the same page) this is the altimetric reference you used to verify that the 2007 Cartosat-1 DTM is the most precise DTM and can thus be chosen as a reference... Large data gaps in SRTM (are those gaps affecting your glaciers of interest?) is more credible reason to exclude it.



P2596 L10. Regarding the use of Corona data you could also cite (here or, probably better, later at the beginning of the discussion) two recent papers that used those spy imagery in the glaciological context (although the data were not used yet to measure ice elevation changes as you did) (Schmidt and Nüsser, 2009; Surazakov and Aizen, 2010)

P2596 L10. Could you overlay on one of the figures the location of the 14 GPS points? Are they well distributed (spatially and vertically)? Do you have an estimate of their horizontal and vertical accuracy?

P2596 L16. Sensor models (one model for each sensor)

P2596 L19. I think “measure” would be best than “address”

P2596 L22. How many points to estimate those trend surfaces? Why did not you use all the ice free terrain pixels and fit a surface to those?

P2596 L27. RMSE is a combination of mean and standard deviation. As you provide the mean, I think it would be best to provide the standard deviation about the mean and not the RMSE. It is then easier for the reader to “visualize” the distribution of the errors (see also my similar comment about Table 1).

P2597 L7. How did you select the 200 points? Randomly? Are they representative of the topography (slope, aspect, altitude range, etc…). Again, why did not you evaluate the DTMs on the whole ice free terrain?

P2597 L15. Provide the formula for the standard error (SE). Your estimate of the error is surprising because the mean elevation difference (MED) should already be included in the SE (or not?); More generally, it is not very clear how you get your error estimate and you should give all the information so that the reader can reproduce your calculation. Currently this is not the case. Are you certain you can readily transpose the 1 out of 20 pixels (to estimate the effective sample size) used by Koblet et al. for aerial photographs? Furthermore, if I read Koblet et al., 2010: “Under the assumption that the auto-correlation of pixels with 100m (or 20 pixels) distance is negligible". So their 20 pixels decorrelation length is in fact an unjustified "first guess". If you use it readily in your paper, it is going to propagate in the literature as a reference/unique value although this length should be estimated in each new case study... Your error bars are reasonable and this is a good thing and I do not challenge them, but I simply suggest that more details are given to the readers.

P2598 L21. "detailed" is too vague. Do you mean "multi-temporal"?

VOLUME CHANGE & MASS LOSSES

P2598 L20. It would be good to show a high resolution (2007?) ortho-image of Khumbu glacier in an additional figure to really locate section A to D. It will give the reader a sense of how the glacier looks like and visually illustrate its different sections.

P2599 L4. I agree that you give good indications of accelerated loss but from the purely statistical point of view the errors bars still overlap...

DISCUSSION

P2599 L10. Do you think a better set of GCPs would permit to limit the distortions in the Corona DTMs? This point needs to be discussed and will help to guide others that would like to use Corona for measuring elevation changes in the future. Compare your results to (Surazakov and Aizen, 2010)

P2599 L15. I do not understand your "supraglacial lake story" and the associated timing. Given the observed thinning between 1970-1984, I would expect the lake to drain during this period (resulting in surface lowering) and then the depression to fill again either by water or ice inflow, leading to the 1984-2002 thickening... Clarify or correct.

P2599 L19. Remind us the value measured by Bolch et al., 2008.

P2600 L10. Indicate that the possible thinning of the accumulation area is observed for



the period 1970-2007.

P2600 L18. "Low velocity". What matters in term of elevation changes is not the absolute ice flux but its change with time. If you want to explain the strong lowering of Imja glacier tongue from the ice dynamic point of view you need to demonstrate first that ice surface velocities (and thus the ice fluxes toward the tongue) have decreased in the last 2-3 decades.

P2600 L26. Why "only partly". I think "as it is not statistically significant yet" would be more reasonable given your error bars. The 2002-2007 time period is short and thus it is very challenging and courageous to measure an elevation change of less than 5-m, in particular using the ASTER DTM... (see also my comment about Table 3)

CONCLUSION

P2601 L18. "careful relative adjustments of the DTMs" seems a better formulation

TABLE

Table 1. I would replace the RMSEz by the standard deviation. For example the RMSEz for the 1962 DTM does not mean a lot because it mainly reflects the (really!) large mean elevation difference. Are those statistics performed on the whole ice free terrain or on the 200 selected points? Could you indicate this info in the caption?

Table 3. Nuptse glacier seems to behave very differently than other glaciers with thickening for the most recent period (2002-2007). Do you trust this thickening? If yes, any explanation for it? More generally, the large scatter of the mass balance for the 2002-2007 period is surprising and worrying (whereas the little scatter for 1970-2007 really gives some confidences in your estimates). The 2002-2007 error bars may be underestimated. I thus suggest revising the error estimate for this period. You will be more "comfortable".

FIGURE

The current color scale makes it difficult to identify region of no (or little) elevation changes. The [-10:10] elevation changes could be shown in white instead of grey to better visualize them.

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Bajracharya, S. and Mool, P., 2009. Glaciers, glacial lakes and glacial lake outburst floods in the Mount Everest region, Nepal. Annals Glaciology, 50(53): 81-86.

Bolch, T., Buchroithner, M., Pieczonka, T. and Kunert, A., 2008. Planimetric and volumetric glacier changes in the Khumbu Himal, Nepal, since 1962 using Corona, Landsat TM and ASTER data. Journal of Glaciology, 54(187): 592-600.

Paul, F. and Haeberli, W., 2008. Spatial variability of glacier elevation changes in the Swiss Alps obtained from two digital elevation models. Geophysical Research Letters, 35(21).

Schmidt, S. and Nüsser, M., 2009. Fluctuations of Raikot Glacier during the past 70 years: a case study from the Nanga Parbat massif, northern Pakistan. Journal of Glaciology, 55(194): 949-959.

Surazakov, A.B. and Aizen, V.B., 2010. Positional accuracy evaluation of declassified Hexagon KH-9 mapping camera imagery. Photogrammetric Engineering & Remote Sensing, 76(5): 603-608.

Vincent, C. et al., 2004. Ice ablation as evidence of climate change in the Alps over the 20th century. Journal of Geophysical Research-Atmospheres, 109(D10).

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Interactive comment on The Cryosphere Discuss., 4, 2593, 2010.