Reply to the comments by Mauri Pelto on the TDC manuscript entitled

"**Longest time series of glacier mass changes in the Himalaya based on stereo imagery**"
by T. Bolch, T. Pieczonka and D.I. Benn

The reviewer's comments are given in *italic* and our response in **bold**

SC: That debris cover plays a key role and the greatest thinning is some distance above the terminus as a result. To gain full value from this valuable data the authors must expand their discussion and visual presentation on debris cover as this variable is key.

AR: We agree that debris-cover is of high importance. However, we do not want to repeat the former study (Bolch et al. 2008b) where we addressed the changes in debris-cover area in detail including a figure of Khumbu Glacier and its surrounding (Figure 3) which clearly shows that the debris-covered area expanded at the upper elevation of the debris-covered area. In this paper we also summarize and discussed the previous studies on glaciers in the investigated region. All the very valuable references of the study area suggested (except Bajracharja and Mool, 2009 which was not published at that time) were addressed in this publication. Nevertheless, we put now a greater attention to the debris cover.

SC: They must reconcile the brief mention of nearly stable terminus position with previous work by Bajrachaya and Mool (2009).

AR: The earlier data by Bajracharja and Mool (2009) rely on topographic maps. Maps of this area are valuable information. However the delineation of the glaciers is partly speculative. This issue is partly discussed by Salerno et al. (2008) for Khumbu Himalaya and elsewhere (e.g. Bolch et al. 2010, Bhambri and Bolch 2009). Hence, maps should only be the second choice if no suitable imagery is available. We used high resolution imagery to delineate the glaciers. We show an example in Bolch et al. (2008b) and include now a zoom of the 1970 image and the 2007 image. In addition, the following image show the terminus of Khumbu Glacier of the year 1984, 1992 and 2001.

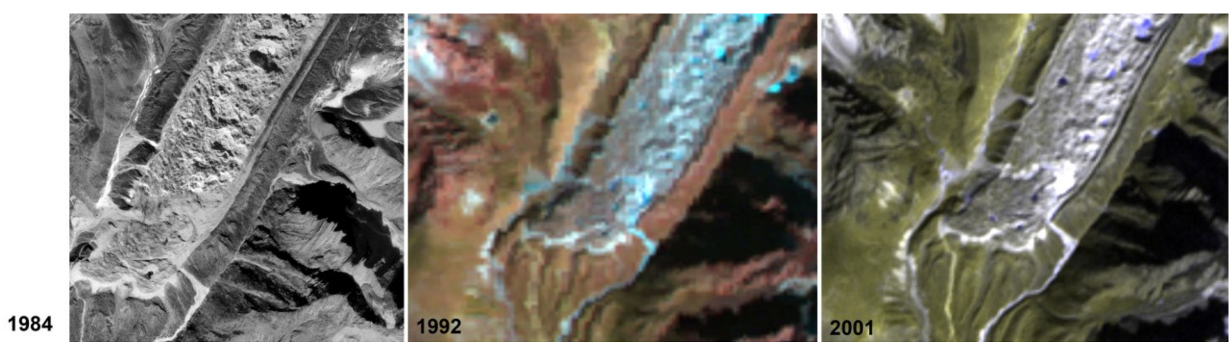

Figure: The terminus of Khumbu Glaciers based on the 1984 aerial image, 1992 Landsat TM, and 2001 ASTER Data.

It can be seen that there is not retreat of the distal part of the terminus. However, one can see the beginning of an erosion at the side about 1.5 km upglacier from the distal part. This erosion increased and there is now a lower eroded part across the terminus which was chosen by Bajacharja and Mool at as the current terminus position. The erosion indicates that there is likely stagnant ice at the front. However, the situation did not change significantly since the 1960s and 70s as the imagery shows. Existing remote sensing based velocity measurements (Bolch et al 2008a, Quincey at al. 2009) indicate

that a larger part of the terminus is stagnant or has only a low velocity which was already mentioned by Inoue (1977). Kadota et al. (2000) did a detailed investigation on Khumbu Glacier and describe the area about 1 km upglacier of the distal part as "fossil or stagnant ice area" but found a lowering between 1978 and 1995 and included this section also into the glacier area and did not mention any retreat. Hence, we do not agree with the delineation of Bajracharja and Mool (2009) as it is highly speculative. In addition, dead ice which is in contact with the glacier ice would be included into the glacier from a glaciological point of view. Detailed field investigations would be necessary for clarification.
This issue shows again that especially for debris-covered glaciers more studies on volume changes are needed rather than on area changes. We included a short statement on this issue in the discussion.

SC: 2594-20: This study focuses primarily on the ablation zone, a reference would be valuable supporting the idea most of the volume change should be occurring in this region of the glacier and your limited accumulation zone data supports this.
AR: It is typical for mountain glaciers that most of the volume change occurs in the ablation zone. For the Indian Himalaya, Berthier et al. 2007 obtained similar results. We include this information in the discussion and write: "Highest mass change was found for all glaciers in the lower elevations, which is in typical for retreating mountain glaciers and was also found in the Western Himalaya (Berthier et al. 2007)."

SC: 2593-22: Can a typical AAR be given for the Khumbu or Imja Glacier at least. Given the high avalanche accumulation and debris cover one would expect a different equilibrium AAR than typical for alpine glaciers.
AR: We do not address the ELA in this study. This would require further and different investigations which are beyond the scope of the study.

SC: 2595-24: What is the percent increase in the debris covered area? Use Nakawo (1999) here, or at 2599-24, to elaborate on the change in debris covered area.
AR: The increase of debris-covered area is about 2.5% for 1962 until 2005 as shown by Bolch et al 2008 which was cited here. We include this number now in brackets.

SC: 2593-25: The brief comment on the almost stable terminus position does not agree with the work of Bajrachaya and Mool (2009) who in examining most of the same glacier noted a 1976-2000 retreat rate of -10 to -59 m/a (Table 1). Further in Table 1 they provide 2000-2007 terminus retreat rates and the elevation range for these glaciers.
AR: See our comments above. I disagree with these numbers except for Imja Glacier where the tongue terminates in the lake.

SC: 2600-4: Given the importance of debris cover it is imperative that the reader be given a measure of how this changes spatially and temporally. This should be done visually with a satellite image of the lower Khumbu and or Imja Glacier. A profile of the increase in thickness or percentage coverage of the debris cover on Khumbu Glacier should be provided. Additionally it was noted that the debris cover had expanded, was this largely at the upper elevation of the debris covered region? Nakawo (1999) explored this. Since debris cover is the key variable cited for the change in thinning, it needs greater attention.
AR: See our main reply above.

SC: Kadota and others (2000) should be cited as it supports the findings here. They surveyed the Khumbu glacier in 1995 and compared the results with those of the 1978 survey. They found that the surface of

the glacier lowered about 12-15 meters over most of the length but by only 6-8 meters near the terminus.
AR: We agree and cite Kadota and others (2000). However, they do not mention a lowering of about 12-15 meters.

SC: Takeuchi and others (2000) should be utilized more extensively as they noted that for Khumbu Glacier debris cover less than 5 cm increases ablation, debris greater than 5 cm in thickness reduces ablation. On Khumbu Glacier their ablation measurements indicate that ablation is reduced 40% from that of clean ice when the debris cover is 10 cm thick. Thicker debris cover reduced ablation even more, but only slightly. At what elevation is the ice no longer clean? At what elevation is the thickness more than 5 cm? How does this fit with the thinning?
AR: Takeuchi and others (2000) present measurements on few points only. To our knowledge there has been no detailed investigation about the debris thickness of whole Khumbu Glacier. Analysis of the distributed debris thickness would exceed the scope of this study. Hence we can only present general tendencies and no detailed analysis.

SC: Expand on your point of support with Naito et al. (2000, as this enhances the value of the paper. They developed a model coupling mass balance and flow dynamics of debris covered glaciers and applied it to the Khumbu Glacier. The model predicts formation and enlargement of a depression in the lower ablation area about 5 km upstream of the terminus.
AR: Naito et al. (2000) do not predict a lake 5 km upstream of the terminus but at "x=5.5 km" which is when looking at Figure 4a 3-3.5 km upstream. We write "Very low slope angles in the 2007 longitudinal profile (Figure 5B) indicate that a glacial lake could develop about 1.5 to 3 km upstream of the terminus, similar to that predicted in simulations based on a 1D-coupled mass balance and flow model by Naito et al. (2000)."

SC: 2601-1-12: Move this section earlier to the other portion on Khumbu Glacier.
AR: We prefer to leave it separate as we address here the mass balance and compare it with other glaciers and other regions.

SC: 2601-20: I would suggest this is an appropriate to reiterate that the greatest thinning is in the areas of thinner debris cover.
AR: We think most important is the conclusion that the glaciers are significantly losing mass despite thick debris cover. The profile Fig. 5A shows a surface lowering where thick debris cover can be estimated at about km 9 which is similar to those areas with thinner debris cover at km 3.5.

SC: Further an important conclusion from this, is that the greatest thinning is not associated with an area of a glacier where black carbon would play a significant role. Ramanthan and Cunningham (2008) and others have noted the potential role of black carbon in volume losses. With respect to the heavily debris covered monsoon dominated glaciers of Nepal, evidence of thinning distribution does not support this. Given that debris cover areas would not be sensitive to black carbon deposition, nor the accumulation zone where the summer monsoon is also the main accumulation season, this is not a surprise.
AR: We agree and include the following sentence in the discussion: "The influence of black carbon (BC) as summarized by Ramanathan and Carmichael (2008) cannot be excluded but is probably negligible for the ablation zones with debris-cover as debris is not sensitive to black carbon deposition nor can significant albedo changes be expected in the accumulation zone where the summer monsoon is also the main accumulation season. " and "The influence of black carbon is probably low for the investigated glaciers." in the conclusions.

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