

Interactive comment on “Probabilistic estimation of glacier volume and glacier bed topography: the Andean glacier Huayna West” by V. Moya Quiroga et al.

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Dear editor and reviewers, We deeply value the comments received greatly, as they pointed out a number of issues to be addressed in order to improve the article. The replies to the comments are detailed in the following paragraphs. After general comment 7 we replied all the minor comments. Besides, we provide a shorter but improved manuscript with all the changes and also the new features such as: *•* A Monte Carlo analysis of the volume estimations *•* A Comparison and discussion of the V-A volume estimations using different coefficients *•* A Glacier thickness estimation according to the mass turnover ice-flow mechanics approach We think that the following improve-

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ments improve the manuscript and we hope that it now satisfies the standards for a publication in The Cryosphere. Thank you very much for your kind consideration.

Comment 1: In the present study we do not apply all the volume area relation (V-A) to a single glacier as solution. We applied the V-A volume estimations for comparison and discussion purposes, similar to the comparison of Farinotti et al., (2009). Then we assumed that the V-A relations suggested for tropical glaciers provide reasonable volume estimation; thus, that volume was used to calibrate the thickness estimation. In the new manuscript, we state that currently there is a debate about V-A accuracy (Bahr et al., 2012; Farinotti and Huss 2013). Nevertheless the method is still in use as a first estimation of glacier volume (Baraer et al., 201). Besides, it is also used for validation and comparison of volume estimations (Farinotti et al. 2009). Actually the V-A coefficients for tropical glaciers have a difference about 1.2%. Nevertheless, in the new manuscript we state the fact that V-A estimation has an ill-posed boundary and may easily induce errors about 40%. However, the discussion of V-A errors is a new topic with few publications. Since the main objective of the present study is the volume estimation and glacier bed topography in a tropical glacier considering the uncertainties of the basal shear stress, we assume that V-A coefficients suggested for tropical glaciers provide a good estimation of the glacier volume. Besides that, we also include glacier thickness and volume estimation according to the mass turnover ice-flow mechanics (MTIFM) approach. We calibrate the approach also considering that the V-A suggestion for tropical glaciers provide a reasonable estimation of the volume. The new manuscript has better explanation and better approach. To summarize: *•* First, we performed a Monte Carlo analysis of the volume estimations over the whole range of possible BSS. (New Manuscript Pg5Ln19-22; Pg7Ln10-17) *•* Then, we compare the different confidence of volume estimations with volume estimations from V-A, and discuss why some confidence intervals are related to some V-A coefficients. (New Manuscript Pg7Ln18-Pg8Ln12) *•* Then, assuming that V-A coefficients suggested for tropical glaciers provide a good estimation of the glacier volume, we estimate the BSS that provides such volume. This is the most probable BSS. (New manuscPg8Ln5-12)

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*Besides that, we also include glacier thickness and volume estimation according to the mass turnover ice-flow mechanics (MTIFM) approach. We calibrate the approach also considering that the V-A suggestion for tropical glaciers provide a reasonable estimation of the volume. (New Manuscript Pg6Ln4-17; Pg8Ln21-Pg9Ln16) Comment 2: The Glabtop is a practical approach for estimating glacier volume and glacier bed topography. Its main uncertain parameter is the basal shear stress. Although there is a practical suggestion for estimating BSS as function of the glacier elevation range, tropical glaciers tend to have extremely high mass balance gradients, causing correspondingly high mass turnovers and higher values of basal shear stress for a given elevation range. Thus, the range of probable BSS is much wider. Our main objective was to estimate the glacier volume and glacier bed topography of the tropical glacier Huayna West. For such purpose, we estimated the BSS of a tropical glacier by analysing the whole range of possible BSS values. For such goal we made two assumptions: *The use of the GlabTop approach with the correct BSS should provide a good estimation of the glacier volume. *The use of V-A with correct coefficients should also provide a good estimation of glacier volume. This volume should be equal to the volume estimated by GlabTop. Initially, we did not perform the comparison with the method of Farinotti et al., (2009) because our initial objective was related to the uncertainty of BSS. Besides, the MTIFM approach needs the calibration of the correction factor and it also requires mass balance, which was not available at that time. In the new manuscript we include glacier volume and glacier bed topography estimations according to MTIFM. The correction factor was also calibrated assuming that V-A suggestion from tropical glaciers provide a reasonable estimation of glacier volume. Besides, we improved the abstract (New Manuscript Pg1Ln11-27)

Comment 3: We include a new figure with the flow-lines Equations 2 and 3 estimate the basal shear stress based on statistical analysis of mid-high latitude glaciers. However, since tropical glaciers have higher mass balance gradients, it is reasonable to expect a higher basal shear stress. Since there is no published literature about BSS on tropical glaciers, the present study considered the BSS for maritime glaciers. The explanation

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was included in the new manuscript. (New manusc Pg5Ln1-14) Minor Comments Pg 3932. New abstract was provided in answer to comment 2. (New Manuscript Pg1Ln11-27) Pg 3933. Ln22; Pg 3933. Ln25; Pg 3933. Ln29. The introduction was replaced by a shorter clearer introduction. First we introduce GPR and RES field measurements and V-A method (New Manuscript Pg2Ln8-22) Then, we introduce the analytical approaches of GlabTop (New manusc Pg2Ln24-Pg3Ln6) and MTIFM (New manusc Pg3Ln7-14) Pg 3934. Ln1. The word popular was removed. Now we state that V-A a popular and practical approach (New manusc Pg2Ln8-19) Pg 3934. Ln8 and Ln10. Same as above Pg 3934. Ln18 and Pg3934. Ln 21. We mentioned those references just to show the importance and the need of glacier bed topography estimations. However, since those studies are not relevant, they will be summarized in one sentence (New manusc Pg2Ln19-22). Pg 3935. Ln18. The sentence was deleted Pg 3935. Ln 26. The coordinates of the glacier ($16^{\circ} 16' S$ $68^{\circ} 10' W$) and its area are included in the new manuscript. (New manusc Pg3Ln27-28) Pg 3936. Ln 4. Since it is not relevant for the study, it was removed Pg 3936. Ln8. The new phrase is: "The melting water from Huayna glacier flows towards the Tuni reservoir and plays an important role for the water supply of La Paz" (New manusc Pg4Ln1-6) Pg 3936. Ln 19. The sentence was removed Pg 3936. Ln 22. Actually we verified the latest version of GLIMS. However, the copyright of GLIMS states that we must reference the publication of Raup et al., 2007. Pg 3937. Ln 5. The name of the algorithm is TauDEM, which is implemented in the mentioned GIS software. The details of the algorithm are explained by Tarboton 1997. However, this is not relevant. We only wanted to make a detailed description of the methodology Pg3937Ln11. Thank you for the correction. Pg 3937. Ln 8 and Ln.9 Actually the topography and basin delineation does not change. With this figure we only wanted to show the accuracy of the used DEM. However, since the basin delineation is not relevant, the figure will be replaced by a figure showing the flow-path lines Pg 3937. Ln17. Equation 2 and Equation 3 for basal shear stress are obtained from (haeberli and Hoelze 1995). However, it is important to that tropical glaciers tend to have extremely high mass balance gradients, causing correspondingly high mass turnovers and shear

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stresses for a given elevation range. Thus, we also considered the BSS suggested for maritime glaciers. (New manusc Pg5Ln1-14) Ref: Haeberli, W. 1985. Global land-ice monitoring: present status and future perspectives. In United States Department of Energy, Glaciers Ice Sheets and Sea Level: Effect of a CO2 induced climatic change, report of a workshop held in Seattle, Washington, September 13-15, 1984. Report DOE/EV 60235-1 Pg 3937. Ln 24. Thank you for the suggestion. We were using past tense in the whole manuscript, trying to describe the process already done. Pg 3938. Ln1. Thank you for the suggestion, Glacier density is replaced by Ice density. (New manusc Pg5Ln2) Pg 3938. Ln16. Thank you for the suggestion. As you pointed, the averaging process is quite straightforward and could be understood without equation 6. However, since density is not the main objective, in order to avoid confusion the variable density was removed. Pg 3939. Ln 2. Same as above Pg 3939. Ln5. Same as above Pg 3939. Ln14. Thank you for the comment. The V-A explanation and discussion were improved (New manusc Pg2Ln12-20; Pg7Ln14-31). Pg 3939. Ln25. We misused the word "method". In the previous manuscript we only wanted to show the coefficients of the thickness-area relationship. However, it led to confusion. In the new manuscript we only introduce the V-A coefficients Pg 3940. Ln2. Same as above Pg 3940. Ln15. The statistical approach was replaced by a Monte Carlo analysis of the possible volume estimations. (New manusc Pg5Ln19-22; Pg7Ln10-17) Pg 3940 Ln18 and Ln19. Same as above Pg 3940 Ln21. Same as above Pg 3942. Ln17. Same as above Pg 3942. Ln21. Thank you for the suggestion. The new version mentions that the basal shear stress is used to estimate the glacier thickness. (New manusc Pg8Ln13) Pg 3942. Ln23. The reviewer is right. GBT was already defined. We wanted to make the difference between GBT and GBTE. However, as mentioned by the reviewer GBT is enough. We made the correction. (New manusc Pg6Ln17) Pg 3943. Ln2. The paragraph was improved. (New manusc Pg7Ln2-9) Pg 3943. Ln26. In the new manuscript the discussion was improved. (New manusc Pg7Ln14-Pg8Ln12) Pg 3943. Ln28. Thank you for the comment. We truly apologize. We carefully checked that all unit are in the manuscript Pg 3945. Ln6-21. The reviewer is right. This paragraph only repeats the values from the

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table. The new manuscript replaced the statistical analysis by a Monte Carlo analysis of the whole range of volume estimation (New manusc Pg7Ln14-Pg8Ln12) Pg 3946. Ln12. Thank you for the comment. The conclusions were not properly explained. The new manuscript has shorter but clearer conclusions. (New manusc Pg10Ln13-30) Pg 3947. Ln12. The reviewer is correct. This is not a conclusion of the present study, but a reasonable assumption. Thus, this conclusion will be deleted. Pg 3963. The new figure has graphical scale Pg 3964. The figure was replaced by a figure of the glacier with the flow-lines Pg 3965. The size of the letters is increased, and the caption was improved with a brief explanation. The manuscript has a complete explanation. Pg 3967. The size of the letters was increased.

To conclude, we just want to thank again the reviewer.

Please also note the supplement to this comment:

<http://www.the-cryosphere-discuss.net/7/C2240/2013/tcd-7-C2240-2013-supplement.pdf>

Interactive comment on The Cryosphere Discuss., 7, 3931, 2013.

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