Interactive comment on "Evolution of surface velocities and ice discharge of Larsen B outlet glaciers from 1995 to 2013" by J. Wuite et al.

Response to Anonymous Referee #2

COMMENT: This study presents a very thorough and probably the most careful and complete analysis of variations in ice discharge of outlet glaciers into the former and remnant parts of the Larsen B ice shelf so far. Based on satellite measurements of ice dynamics over various time periods and measurements or estimations of ice thickness at flux gates it is a significant and important addition to previous studies which have been primarily or solely based on change in surface elevation. Elevation change methods provide information of total ice mass change, whereas the budget (or input/output) method like the one presented allows much better insight into underlying processes. Although the information on surface mass balance in this area is very limited, I see the outcome of this observational study as an important contribution for a better understanding of changes in ice dynamics during and post ice shelf collapse. The results are clearly summarized and presented in the tables and are likely to find uptake in future studies. The paper is well structured and written. I have three major comments, and several minor comments about the analysis, description of methods, wording, and figures, but recommend full publication once this is considered.
REPLY: We thank the reviewer for his/her comments and suggestions, below you find our response to the review. We hope this and the adjustments in the text clarify the manuscript. The velocity products generated during this study will be made available soon for the wider scientific community through our project website at: http://glacapi.enveo.at/

COMMENT: Major comments: 1/ Baseline for the surface velocity fields are one day repeat pass interferograms in 1995 and 1999. There are meanwhile quite a few examples and theoretical studies that velocities over such short repeat pass intervals are not representative for mean velocities. E.g. Marsh et al. (2013) report that tides produce horizontal velocity variations of > 50% around the mean velocity near the grounding line at the Beardmore Glacier, which are still around 5% about 15 km upstream. However, daily fluctuations rapidly smooth out over time. It seems that the authors did either ignore or did not observe such fluctuations at the Larsen B ice shelf. In any case it needs either to be mentioned (that such fluctuations are ruled out) or at least taken into account in larger errors bars for the ice discharge in 1995 and 1999. The comment on p 6279 (line 25-27) is insufficient, as it is about the uncertainties related to vertical tidal displacements in the interferograms rather than horizontal velocity fluctuations. This could be mentioned in various places, like in section 3.1/3.2, the discussion, or in the introduction.
REPLY: Regarding the 1995 to 1999 velocities on the Larsen-B Ice Shelf and its tributary glaciers, comprehensive work has been performed before at Univ. of Innsbruck, reported in the Ph. D. thesis of W. Rack (Rack, 2000) and other publications (Rack et al., 2000; Rack and Rott, 2004). Therefore emphasis of this paper is on ice flow behaviour of glaciers after Larsen B collapse. The question of possible temporal variations of velocities is certainly important. Therefore we checked again the surface motions at the flux gates, using the following ERS interferograms, acquired from the same view direction (descending orbit) with excellent signal (high coherence): 15/16 Oct. 1995, 31 Oct/1 Nov 1995, 9/10 Nov 1999. The agreement of the motion related fringes in these interferograms at the flux gates is remarkable, in spite of the fact the tidal deformation further downstream, at the transition zone between the ice shelf and glaciers, is quite different on the three dates. The maximum difference in velocity between the 3 dates at any of the gates is < 5%. On the other hand, the Larsen B Ice Shelf has been subject to gradual acceleration during the pre-collapse period, with the acceleration increasing towards the front of the ice shelf (see references above, cited also in the manuscript). The InSAR observations indicate stable conditions of the outlet glaciers, at least until 1999. It should be mentioned that the gates for retrieving the 1995-1999 ice fluxes correspond to the 2008/09 flux gates, and therefore were located in 1995-1999 several kilometres inland of the upper

limit of the tidal deformation zone. We explain this now in the text.

Besides, we observe good agreement between GPS velocity measurements at two stations of British Antarctic Survey on Flask Glacier, 12 km and 16 km above the grounding, and our velocity analysis with TerraSAR-X. Velocities of 0.95 m/d, respectively 0.71 m/d, were measured by GPS at the two stations over an annual interval (9 Nov 2009 to 5 Nov 2010). The TerraSAR-X velocities at these stations, derived from an image pair spanning 2 July to 13 July 2010, are 0.91 m/d and 0.71 m/d. Because of the different time periods the GPS data cannot be used for direct validation of the satellite measurements. However, this agreement is another indication for rather stable velocities, as observed by TerraSAR-X during the 2009 to 2013 time period on Flask Glacier.

The retrieval of 2D velocities on grounded ice uses points on ice free surfaces near the glacier margins as reference for zero velocity. On floating ice points without horizontal motion are used, so that the observed reference signal corresponds to the tidal displacement. In our analysis for Larsen-B ice motion the reference points are located at the margins of the Seal Nunataks and at several points in small coves along the ice shelf margin of Jason Peninsula. The agreement of the tidal deformation at these points confirms that the vertical displacement is representative for the ice shelf. Uncertainty in tidal deformation plays mainly a role in the velocity retrievals from 1-day repeat pass ERS InSAR data. With the estimated uncertainty in tidal deformation at the reference points of 0.5 fringes (corresponding to 3.6 cm projected onto a horizontal surface) and an uncertainty of 0.2 fringes for a velocity point, the resulting total uncertainty for ERS InSAR derived horizontal motion is 3.9 cm. For grounded ice the estimated uncertainties are 0.2 fringes for the reference points and 0.2 fringes for the velocity point, resulting in total uncertainty of horizontal displacement of 2.0 cm.

COMMENT: 2/ As the authors describe, there has been a significant change in surface topography post ice shelf disintegration, and the DEM used in the interferometric analysis is therefore not representative. What is the introduced error in the InSAR analysis?
REPLY: The geocoding of the 2D velocity vector (retrieved in radar geometry) is performed for each displacement value independently. We use the 100 m Digital Elevation Model derived from the ASTER GDEM and available through the NSIDC database (Cook et al, 2012a), which is the most detailed available DEM for the total study area. This DEM is compiled from ASTER scenes from a range of dates between 2000 and 2009 which are unspecified in the final product (Cook et al, 2012b). Part of this period is pre-collapse and part is post-collapse. In general absolute errors in the DEM lead to very small errors in velocity. In order to estimate the impact of a change in surface slope we estimate the introduced error for a hypothetical test case with 100 m surface lowering over 15 km, which is comparable to the amount of surface lowering observed on the lower terminus of large outlet glaciers. Even in this case the induced error in velocity is well below 1%.

Cook, A. J., T. Murray, A. Luckman, D. G. Vaughan, and N. E. Barrand.: A new 100-m digital elevation model of the Antarctic Peninsula derived from ASTER Global DEM: Methods and accuracy assessment, Earth System Science Data Discussions, 5 (1), 365–403, doi:10.5194/essdd-5-365-2012, 2012a.

Cook, A. J., T. Murray, A. Luckman, D. G. Vaughan, and N. E. Barrand.: A new 100-m digital elevation model of the Antarctic Peninsula derived from ASTER Global DEM: Methods and accuracy assessment, Earth Syst. Sci. Data, 4, 129-142, doi:10.5194/essd-4-129-2012, 2012b.

COMMENT: 3/ It would be good to show the velocity differences as a figure (the difference between Figure 2 left and right) to illustrate how far upglacier velocity acceleration was detected.
REPLY: We have added a third panel to Figure 2 showing the difference in velocities between the two epochs in m/d. The figure illustrates the extent of the velocity changes due to the collapse. We also added extra info to the text.

COMMENT: Minor comments: 6272, Abstract, SCAR Inlet: I suggest capital letters for SCAR (often neglected in the literature, but it is an acronym for the Scientific Committee for Antarctic research, it has nothing to do with a scar) like in the heading for 3.2, but be consistent throughout the manuscript.
REPLY: All occurrences have been capitalized in the updated manuscript.

COMMENT: Change wording in last sentence, use e.g.: In 2013 their discharge was 38% (Flask Gl.) and 45 % (Leppard Gl.) higher than in 1995.
REPLY: Sentence is adjusted

COMMENT: 6272, 26: remove 'calving'
REPLY: Deleted

COMMENT: 6273, 4/5: change wording, maybe: . . . and its interaction with grounded ice.
REPLY: Sentence is adjusted

COMMENT: 6: 'Larsen Ice Shelf' as it is a geographic name change to capital letters throughout the manuscript.
REPLY: All occurrences have been capitalized in the updated manuscript.

COMMENT: 18: wording. Maybe change to: ". . . tributary glaciers continued at almost the same rate over the period. . ."
REPLY: Sentence is adjusted

COMMENT: 21: use past tense in 'inferred'.
REPLY: Changed

COMMENT: 6274, 14: . . ., defined by the ASTER. . .
REPLY: Changed

COMMENT: 16/17: . . .vectors are provided in South polar stereographic . . .
REPLY: We prefer to keep it Antarctic polar stereographic projection

COMMENT: 6275, 5: . . .from the velocity vectors . . .
REPLY: Changed

COMMENT: 17/18: . . .with a typical accuracy of 0.1 fringes . . .
REPLY: Changed

COMMENT: 19: For a one day . . .
REPLY: Changed

COMMENT: 22: . . . uncertainty for the retrieval of the displacement is in the order . . .
REPLY: Changed

COMMENT: 6276, 3 (equation (1)): instead of an integral I suggest using a summation sign (with i=0,N) and discrete step size with (greek) delta y, as the authors were summing up a finite number of pixels across the flux gate.
REPLY: Changed

COMMENT: 8-10: based on Paterson (1994), what are the assumptions made to come up with the value 0.95?

REPLY:
We use parameters specified by Hulbe et al. (2008) for estimating the sliding velocity of outlet glaciers to Larsen-B. The laminar flow approximation for ice deformation is applied, with flow-law exponent n = 3 and the rate factor A = 2.0 $\times 10^{-24}$ Pa^{-3} s^{-1}. The deformation velocity is computed by:

$$u_{def} = \frac{2A}{n+1}\left(f\rho g \sin\alpha\right)^n h^{n+1} \quad \text{and} \quad u_{mean} = u_{surf} - u_{def}\frac{1}{n+2} \quad ,$$

where α is the surface slope. The value of the shape factor f (depending on glacier width and depth) is derived for a parabolic cross section according to Patterson (1994), Table 11.3. The results show moderate values of deformation velocities for all of the glaciers. The resulting u_{mean} - values for the glaciers with accurately know cross sections are: Starbuck: u_{mean} = 0.95 u_{surf}; Flask (1995, 1999): u_{mean} = 0.95 u_{surf}; Flask (2009): u_{mean} = 0.96 u_{surf}; Crane (1995, 1999): u_{mean} = 0.96 u_{surf}. For flux computations we use for Crane (1995, 1999) u_{mean} = 0.96 u_{surf}, for the other glaciers u_{mean} = 0.95 u_{surf}. For gates at calving fronts we assume full sliding.

Reference: Hulbe, C. L., Scambos, T. A., Youngberg, T., and Lamb A. K.: Patterns of glacier response to disintegration of the Larsen B ice shelf, Antarctic Peninsula, Global Planet. Change, 63, 1–8, 2008.

COMMENT: 24: clarify if the 5% uncertainty is for the satellite measured surface velocity or the vertically averaged ice velocity. It is probably OK for the measured velocity, but because of additional assumptions likely too conservative for Um in equation (1).
REPLY:
See reply to comment 8-10 above. According to these results the uncertainty in deriving u_{mean} from u_{surf} is quite small. The total error for the flux estimates is dominated by the assumptions on uncertainty of the cross sections (for which we are using conservative estimates of uncertainty).

COMMENT: 6277, 21 (wording): . . .break up of increasingly large areas. . .
REPLY: Changed

COMMENT: 6277 (27-28)-6278 (1-2): I do not see the connection between the mass turnover and sensitivity; the cited reference (Rott et al., 2011) is also unclear about this and inadequate. If this is true, why do the authors assume that the mass turnover of e.g. Mapple Glacier is different to e.g. Punchbowl Gl.? The catchment basins look very similar in size and distance from the plateau (Fig. 1).
REPLY: Specific surface mass balance and mass turnover of Mapple Glacier, Punchbowl Glacier, Starbuck Glacier are similar, as indicated by slow velocities at the frontal flux gates, and reduced surface accumulation compared to the glaciers originating at the main ice divide (discussed in the paper). The name of Punchbowl Glacier slipped in by mistake into p6278, line 7 and does not correspond to the glaciers with large mass turnover (Crane, Jorum, HG).
Thanks for pointing this out. Corrected now.

COMMENT: 6278, 3-12: why is e.g. Punchbowl so different to Mapple Gl. ? See also previous comment.
REPLY: See reply to 6277 (27-28)-6278 (1-2).

OMMENT: 13-23: in this paragraph any observations of daily variations are missing, see also major comments.
REPLY: Further info is provided now. See response to Reviewer No. 1.

COMMENT: 6279, 27: I agree to exclude the velocities at the grounding line, but also for other additional reasons; see also major comments;
REPLY: Ok

COMMENT: 6280, 24: Because of the retreat. . .
REPLY: Changed

COMMENT: 6281, 8: . . . inland of the ice front. . .
REPLY: Changed

COMMENT: 10: Change 'For June. . .' to e.g. 'Based on the June 2007 analysis . . .'. This sentence is not correct, as the flux is given for a whole year.
REPLY: Changed

COMMENT: 23: . . . difference compared to 1995.
REPLY: Changed

COMMENT: 6282, 1-3: Is the value of 0.78 Gt a-1 for both glaciers? Change wording (see also comment in the abstract for the usage of 'respectively').
REPLY: Changed to: **"**In 1995 and 1999 the velocities in the centre are 1.31m d^{-1} (478 m a^{-1}) and 1.36 m d^{-1} (496 m a^{-1}) respectively, resulting in an ice discharge of approximately 0.78 Gt a^{-1} for both years."

COMMENT: line 26 to 6283, 1-2: how far upglacier and how fast (implied by 'moving upward') was the acceleration detected? This could be nicely evaluated and illustrated by a figure showing the difference in velocities. See also major comments. Reword the sentences; e.g. '. . .caused flow acceleration moving upstream. Our analysis of new velocity data also shows that . . .'
REPLY: See response to major comment 3. Rewording done.

COMMENT: 9: '. . . for six periods between . . .'
REPLY: Changed

COMMENT: 15: '. . . the ratio between driving stress and lateral shear. . .'
REPLY: Changed

COMMENT: 6285, 15-19: Reword and shorten this sentence. It is especially unclear what is meant by '. . . shear zones vs. slowly moving ice. . .'.
REPLY: **"**vs. slowly moving ice" deleted

COMMENT: Figures:Figure 1: change 'coastline' to 'ice edge' or 'ice front'
REPLY: Changed to 'ice front'

COMMENT: Figure 3: increase font size
REPLY: The font size is increased

COMMENT: Figure 4: use different color (preferably white) for flux gate lines;
REPLY: Changed to white

COMMENT: Figure 5: What are the yellow arrows? Increase font size. Yellow sections of ICESat track hardly visible.
REPLY: Figure adjusted

COMMENT: Figure 6: move arrow up too the curve, increase font size;
REPLY: Figure adjusted

COMMENT: Figure 7: increase font size;
REPLY: Font increased

COMMENT: References: Marsh, O.J., W. Rack, D. Floricioiu, N.R. Golledge, and W. Lawson. (2013). Tidally induced velocity variations of the Beardmore Glacier, Antarctica, and their representation in satellite measurements of ice velocity. The Cryosphere 7: 1375-1384. doi:10.5194/tc-7-1375-2013.
See response to main comment 1