Response to the
Interactive comment on

“Changes in glacier dynamics in the northern Antarctic Peninsula since 1985”

by Thorsten Seehaus et al.

J. Wuite Referee #2
Received and published: 20 April 2017

First of all we want to thank the reviewer for constructive comments on our manuscript. All comments have been taken into account and a list of answers and actions undertaken is given below. Answers are indented and in bold face type and changes in manuscript are indented in *blue*.

General Comments This paper provides an analysis of comprehensive satellite data sets to study changes in glacier area (over the period 1985-2015) and glacier surface velocity (1992-2014) on the northern Antarctic Peninsula, highlighting the complex temporal pattern of glacier retreat and ice flow dynamics in this region. This is a topic of great relevance for exploring factors that are controlling the varying response to climate change for the glaciers in this region. The hierarchical cluster analysis applied for the west coast glaciers is an inventive effort to provide insight into various flow controlling factors. I have, however, some major concerns that would need to be addressed, more specifically there appear to be some serious deficiencies regarding technical matters, as well as in the presentation of the work and discussion of the results, requiring in depth checks and major revisions and/or re-analysis of data.

Referee #1 provides detailed comments and suggestions for improvements regarding the presentation of the study sites, the description of methods, the presentation of results, as well as on the contents in discussion and conclusions sections. Complementary to this careful and well-founded review, I am addressing below additional critical issues with emphasis on analysis, presentation and discussion of velocity data. I am focusing on the glaciers draining into the embayments of the former Larsen-A and Prince-Gustav-Channel (PGC) ice shelves because published data on these glaciers (based on various data sources) enable comparisons and checks of the various results.

The statement (Abstract P1L18, Results P8L11) “In 2014, the flow speed of the former ice shelf tributaries was 16.8% higher than at the beginning of the study period.“ implies that the outlet glaciers into the Larsen-A and PGC embayments are close to balance. This is in contradiction to other observations, showing prevailing large mass imbalance of these glaciers derived from geodetic data, and also to the much higher velocities compared to pre-collapse state. For example Rott et al. (2014) report for the period 2011 to 2013 a rate of mass depletion of 4.2±0.4 Gt/year based on topographic data of the TanDEM-X satellite mission. The largest contribution is supplied by Drygalski Glacier (deficit 2.2±0.2 Gt/year). Scambos et al. (2014) report a mass depletion of 5.6 Gt/year for the same area for the period 2003 to 2008. Analysis of TanDEM-X data from 2013 to 2015 show somewhat reduced mass deficit for these glaciers, but still a large imbalance (Rott et al., 2016), impossible to be maintained by a velocity that is only 16.8 % higher than in the precollapse state.

We understand the reviewer's concerns, but here we present the average of the changes in flow speed of all glaciers in this sector (ignoring the different size or mass discharge). Therefore, this value is biased by the small glaciers, which were not so strongly affected by the disintegration of the ice shelf disintegrated, compared to the larger more inertially glaciers (like Drygalski, DBE, Boydell, Sjögen glaciers). Moreover, the changes in flow speeds do not directly reflect the changes in ice discharge, which also strongly depends on the spatial distribution of the ice thickness at the flux gate. However, a rough approximation of the ice discharge (using our median velocity values and average ice thickness information from Huss and Farinotti 2014 along the profiles) leads to an ice discharge of

~9.4 Gt/a in this sector, whereof 16.8% (our observed average increase of flow speed) correspond to 1.6 Gt/a. This number is lower than the values reported by Rott et al. (2014) or Scambos et al. (2014), but at a comparable level (assuming no change in SMB). Moreover, a recent study by Hogg et al. (2017) points out that only ice discharge across the grounding line can not necessarily explain the deflation. They attribute 35% of the imbalance to increased ice discharge, and hypothesized that ocean driven melting may have forced the dynamical thinning of the glaciers at Western Palmer Land.
The presented study has put the focus on the temporal changes in ice dynamics. However, a detailed study on the changes in ice discharge and mass balance using the "Input-Output" Method or "Flux-Gate" Method is currently in preparation and We change the wording in Section 4.2 to provided additional information to the reader regarding the average flow speed changes.

The presented average flow speed change values are based on the observed changes of all glaciers in the respective sector (Table S1), ignoring the different size of the individual glaciers.

In Section 5.1 (Discussion East-Ice-Shelf) the authors discuss possible reasons for differences in velocities of glaciers in this sector compared to velocities reported by Rott et al. (2014). They argue that these differences are due to different approaches for reporting velocities (location in the centre of the glacier near the front vs. the median velocities at cross profiles close to the glacier fronts). Also, they are claiming that "equal temporal trends are observed in both studies" (P9L30). This is incorrect as evident by comparing the velocity data in Table 2 of Rott et al. (2014) for several dates between November 1995 and November 2013. On Drygalski Glacier for example velocity near the centre of the 2013 front is reported to be 280% higher in November 2013 than in November 1995, and on Sjögren Glacier 410%. When referring to the pre-collapse state, the increase of velocity on Drygalski Glacier is even higher, because in November 1995 the lower glacier terminus had already accelerated significantly compared to precollapse state, as the time series of velocities starting in January 1993 shows (Rott et al., 2015). This acceleration 10 months after ice shelf collapse was already reported by Rott et al. (2002). In order to clarify the discrepancies addressed above, it is necessary to better explain the methods used, check and revise the error estimates, and provide full traceability on the geographic location of the selected profiles for velocity retrieval and the epochs, and quantify the impact of using median values for quantifying velocities of glacier fronts for the different sensors. It would for example be very valuable to present cross profiles and/or profile time series used to derive the median values (and not only for East-ice-Shelf), in particular for the earlier pre-collapse estimates.

The difference between measuring velocities at one point at the center of the terminus compared to averaging along a profile at the terminus were already reported in Seehaus et al. (2015) The authors also observed deviations between velocity measurements at the center of the terminus and measurements along profiles across the terminus. They attribute it to the the fact, that highest flow speeds are found at the center of terminus, but this maximum values are suppressed by averaging across the terminus. We added the lit. reference at the description of this issue. See also the figure below. It shows the surface velocity across the terminus of Drygalski Glacier at similar dates as shown in Rott et al. (2015). We observed comparable velocities at the center of Drygalski Glacier's terminus as reported by Rott et al. (2015) (unfortunately the position of the profile is not plotted/provided in this paper). This plot is also added to the "Supplement" and an statement on this issue is added in the manuscript. Regarding the error estimates, geographic location see answers to reviewer comments below.

The velocities reported by Rott et al. (2014) at Sjögren, Pyke, Edgeworth and Drygalski glaciers are generally higher than our findings. The authors measured the velocities at locations near the center of the glacier fronts, where the ice flow velocities are typically highest, whereas we measured the median velocities at cross profiles close to the glacier fronts (Seehaus et al. 2015). The different approaches result in different absolute values, but comparable temporal trends in glacier flow speeds are observed by both author groups. For example Rott et al. (2015) presented surface velocity measured along a central flow line of Drygalski Glacier. Figure S75 shows our *surface velocity measurements across the terminus of Drygalski Glacier. Both studies show comparable values at the center of the terminus.*

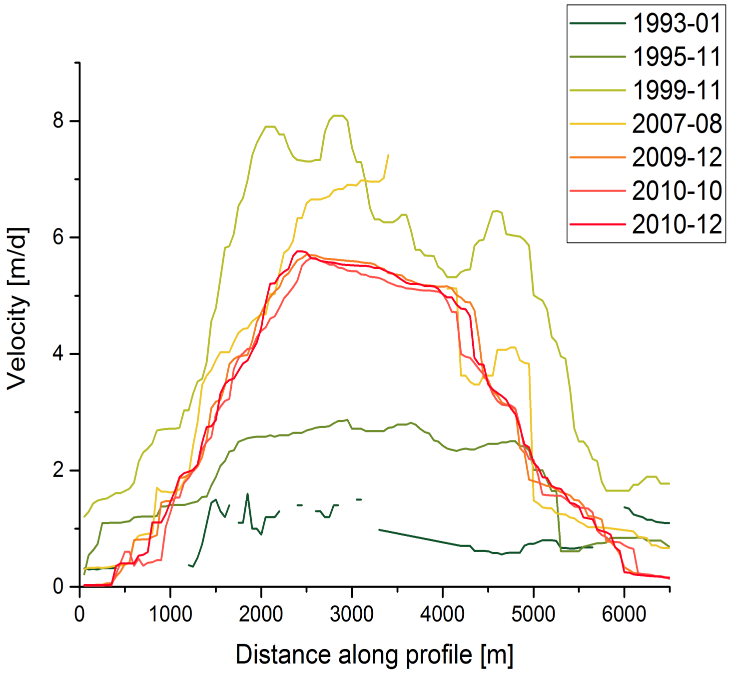

Figure S75: Surface velocity across the terminus of Drygalski Glacier

Regarding velocities, these are the main issues to be checked.
-Cross sections: Cross section poorly defined and not well visible in Fig.1. Possibly define in supplement the coordinates of profile start/end.

**Since some of the profiles are kinked and not straight (coordinates of more than 2 points needs to be provided), we could provide the profiles as shapefiles in the supplement or upload them on PANGAEA (which is planed for some of the obtained results after acceptance of this manuscript)
(as the editor prefers).**

-Median value: How does median compare to velocity profiles of glacier cross section near the terminus. From which statistical sample is the median selected (A certain area close to the front? How far inland? Does it vary with sensor & patch size?). Impact of different sensor resolution, impact of different tracking patches to be checked.

The median is calculated based on the velocity measurements extracted along the profiles, including a 200 m buffer zone around each profile for all sensors. We changed the wording to be clearer.

In order to reduce the number of data gaps along the profile due to pixel size data voids in the velocity fields, the velocity data is extracted within a buffer zone of 200 m around the profiles.

The results of the different patch sizes were stacked (“The results of each image pair are stacked by starting with the results of smallest tracking window size and filling the gaps with the results of the next biggest tracking window size.”) and the step size of the tracking process and the geocoding parameters were adjusted in order to obtain velocity field with

100 m pixel spacing for all sensor. Information on this issue was added.

The results are then geocoded, orthorectified and converted into velocity fields (with 100m pixel spacing for all sensors) by means of the time span between the SAR acquisitions.

-Table 2: Specify patch size on ground (metre), or specify pixel size (range, azimuth) for each sensor.

As also requested by reviewer #1 we added a the nominal ground resolution of the sensors

-Error analysis (Section 3.2 and Supplement Table S2): The procedure applied for estimation of uncertainty seems to refer to the optimum case (smooth velocity fields and good temporal stability of the surface features). A rather generic procedure is applied for specifying the uncertainty of velocity fields, whereas the uncertainty estimates should be provided for the single numbers (median values) presented in the paper. The velocity cross sections near calving fronts outlet often show strong velocity gradients. For these cases large tracking templates (in particular for the sensors with comparatively low spatial resolution) cause increased uncertainty in velocity. The constant factor (C= 0.2) for specifying the accuracy of the tracking algorithm (P5L26) is a value for the optimum case. McNabb et al. (2012) use C = 1-2. The actual values of C can be quite different, depending on time span, spatial resolution of the sensor, and temporal stability of the surface features. Many data sets were acquired during the summer period (Table S2), when surface melt and possibly also temporary refreeze cause changes of amplitude features, impairing the quality of correlation products. Another point to be reconsidered for the uncertainty estimate (Eq. 1, P5L25) is the oversampling factor z which reduces the uncertainty significantly if independence between (partial) overlapping template patches is assumed (which is not the case). This factor is not clearly explained in the paper.

The reviewer is right, that the error due to the tracking algorithm depends on the template size as well as other parameters and can vary spatially, which is difficult to assess. McNabb et al. (2012)'s analysis is mainly based on optical satellite data and using manual feature tracking, which explains the different value of C. We selected the value of C=0.2 according to personal communication with the software provider (GAMMA Remote Sensing). Rignot et al. (2011) applied a value of “1/128th” (0.0078125) for speckle tracking, which has typically an order of magnitude higher accuracies as intensity tracking (Gray et al. 1998; DOI 10.1080/07038992.2001.10854936). Therefore, our estimate is quite conservative. Wuite et al. (2015) estimated the uncertainty to 0.2 to 0.3 pixels and their resulting uncertainties are quite similar to our estimations (Table 2).
We applied an oversampling factor of two (Seehaus et al. 2015) for the tracking windows (tracking chips), which is suggested by the software provider in order to increase the accuracy of the tracking process. We added a statement on this issue to be clearer.
Finally there is to say, that in several studies in this region no error estimates are provided for glacier velocities. Thus, to provide just “a rather generic” error estimation, addressing the ascertainable values, is better than no estimation (in our opinion).

The accuracy of the tracking algorithm is estimated to be 0.2 pixels and an oversampling factor z=2 is applied to tracking patches in order to improve the accuracy of the tracking process.

-The specified numbers of uncertainty for image coregistration (Table S2) apparently refer to full images, whereas the velocity data are derived from points near the coastline. Due to the lack of points on the ocean the coregistration accuracy near the coast lines might be impaired. The coregistration accuracy should be determined for the relevant image segments near the coast.

we stated in the paper (Section 3.2, P5) “single SAR image tiles acquired during the same satellite flyover are concatenated in the along-track direction.... to further improve the co-registration”. At coastal regions this helps to increase the area land masses used for the co-registration. Moreover, the still remaining co-registration offset is measured on stable ground close to the coastline (glacier fronts) where most of the rock out crops and

nunataks are found. We adjusted the wording to be more precise.

Furthermore, single SAR image tiles acquired during the same satellite flyover are concatenated in the along-track direction. This helps to further improve the co-registration in coastal regions (by including more stable areas in the co-registration process) but also simplifies the analysis of the final results as no mosaicking of the results is needed......
The mismatch of the coregistration σ_v^C *is quantified by measuring the displacement on stable reference areas close to the coast line, such as rock outcrops and nunataks.*

Additional comments:
P1L12 ‘However...missing’ -> the statement as written neglects previous research by various authors

This section was revised and this statement removed. See also comments by reviewer #1

The climatic conditions along the northern Antarctic Peninsula have shown significant changes within the last 50 years. Therefore we present a comprehensive analysis of temporally and spatially detailed observations of the changes in ice dynamics along both the east and west coastlines of this region.....

P1L17 ‘Whereat … trends’ -> the statement as written implies that the ice shelf tributary glaciers also decelerated by something in the same order of 69% since 1992 which is not the case.

We revised this section to be clearer.

A dramatic acceleration after ice shelf disintegration with a subsequent deceleration is observed at most former ice shelf tributaries on the east coast, combined with a significant frontal retreat.

P8L10 ‘On ...1.6%’ -> this is a very surprising number and requires explanation as it implies on average no change at all.

This is because some glaciers/sectors showed significant increase, whereas others showed a decrease. We added a statement, to point out that the changes in the individual sectors were significant. In the next lines the change values of the individual sectors are presented.

On average the ice flow in the study region increased by 1.6%, but the glaciers in the individual sectors showed on average significant change. Along the west coast an average acceleration by 41.5% occurred and the former ice shelf tributaries on the east coast accelerated by 16.8%. In the sector “East” the glaciers decelerated resulting in a mean velocity change of -69%. The presented average flow speed change values are based on the observed changes of all glaciers in the respective sector (Table S1), ignoring the different size of the individual glaciers.

P13L13 ‘Group 3’ -> I assume Group 4 is meant here.

Thank you for this advice. The reviewer is right. We meant group 4 and corrected it.