Response to the anonymous referee's comments

Authors' responses are in BLUE color.

General comment

The authors derive surface velocities of glaciers and ice shelves on the Antarctic Peninsula for four 3-year periods between 2000 and 2012, applying feature tracking in medium resolution optical satellite images. The velocity maps presented are very coarse and fragmented, by no means suitable for depicting the complexity of the flow fields of glaciers and ice sheets on the Antarctic Peninsula. Studies on ice motion of Antarctic Peninsula glaciers and ice shelves, mainly based on satellite images, have been reported during the last several years by various authors. Several of these publications are cited, but appropriate discussion of those results and achievements in respect to the work presented by the authors is missing. Compared to the previously published data, the ice motion maps and velocity data presented in the manuscript are of lower quality regarding spatial detail and accuracy. The data presented here are lumping together details of motion fields that are important for documenting and analysing the highly varied behaviour of individual glaciers on the Antarctic Peninsula. Also the analysis of temporal changes of velocity over the four time periods is inconclusive, the presented data being very noisy and lacking the assignment to individual glaciers and ice streams. Glaciological interpretation is missing. In summary, the manuscript does not provide any progress versus the current knowledge on ice motion of Antarctic Peninsula glaciers and ice shelves, and the material presented is not suitable for studies on ice dynamics and glacier evolution in this region. Moreover, the manuscript contains a considerable number of errors, including wrong quotation of information from references.

Response:

The issues you mentioned should mainly be due to the coarse spatial resolution (250m) of MODIS. This is the downside of using MODIS. The advantage of using MODIS is its large coverage of a single image. So the velocity field derived is almost at the same time everywhere. The issue of temporal mismatch is much less severe than mosaicked image from high resolution images acquired at different dates.

1. MODIS L1B data tend to smooth over many small features (< 250m) occurring typically on ground glaciers during the correlation-based feature tracking processing. This is due to the low spatial resolution (i.e., 250m) of MODIS data that is not suitable for mapping the flow fields of the glaciers on Grahm Land. However, MODIS has been successfully applied to map the flow fields of ice shelves.

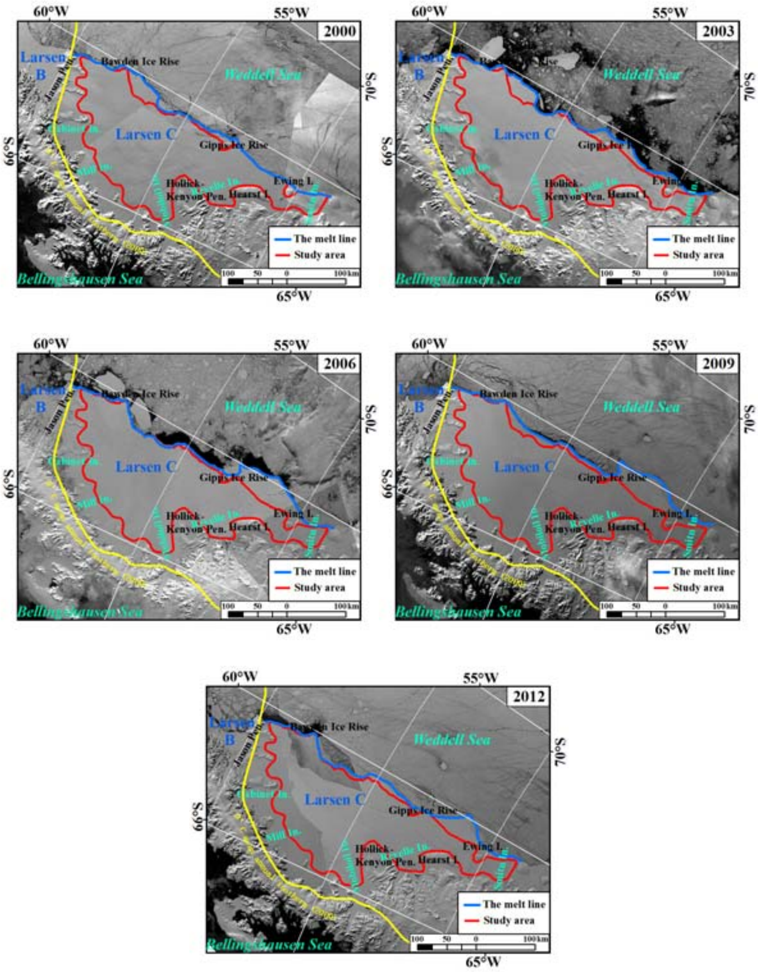

Figure 1. Location of the study area

In the revised manuscript, we only considered the floating ice shelf larger than 10×10 km（Fig.1）by masking out the grounded areas, e.g. glaciers on Grahm Land where the derived velocity may have large errors. Eventually, the study site after the modification has an area of approximately 46,000 km^2, mainly covering the Larsen C Ice Shelf and its far southerly neighbour ice shelf. Also, we used more images with high quality (e.g. little or no clouds) (table1). To be consistent with the changes, we also changed the title of the manuscript to “Spatiotemporal variations in the surface velocities of ice shelves, Northern Antarctic Peninsula”.

The new results show that: (1) The spatial pattern of the velocity field exhibits an increasing trend from grounding line to the maximum at the middle section of ice shelf front on Larsen C with a velocity of approximately 700 m a^{-1}. Ice flows relatively quicker in the outer part than in the inner parts of the ice shelf (Figure 2 as an example). (2) Surface velocity showed a continuous increase from 2000 to 2012. It’s worth noting that, the acceleration rate was relatively higher during 2000-2009 than during 2009-2012. The ice movement on the northeast and southern Larsen C, as well as on Smith Inlet from 2009 to 2012 showed a deceleration. This phenomenon may be related to the reduction of longitudinal stress caused by the rapid thinning of ice shelves.

2. We added more literature review on ice motion of ice shelves, Northern Antarctic Peninsula. We

also revised the discussion on the results and the glaciological interpretation.

3. In short, we focused only on ice dynamics of ice shelves, Northern Antarctic Peninsula in the revised manuscript

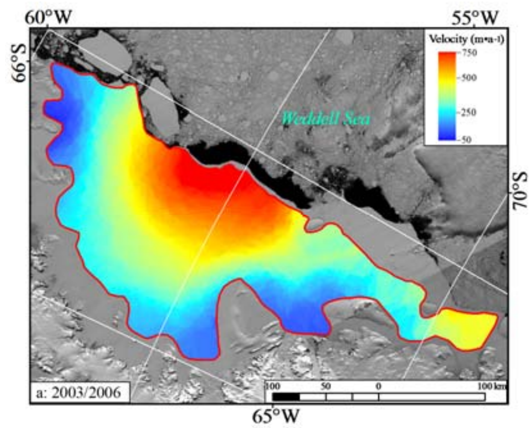

Figure 2. The surface velocity of ice shelves in the northern Antarctic Peninsula (2003-2006).

Details

Introduction (pp. 5877, 5878, 5879):

One page 5877 and 5878 a rather generic overview on satellite methods for ice motion retrieval is provided, not treated in any balanced way, and containing various errors. The topic has been covered well in various review papers; no need repeating this here.

Response:

We revised this paragraph to more concisely illustrate the background of satellite methods (see 1st paragraph of this section in revised manuscript).

Further details:

Page 5878, line 4-6: "It (refers to optical sensors) is therefore more suitable than SAR monitoring methods for estimating the speed of glacial movement and the analysis of relevant spatiotemporal variations over long time series." This statement is plainly wrong. Ice motion maps covering all of Antarctica and Greenland, and many other glacier regions of the world, including time series, are based on SAR data. SAR works with phase information where the lack of features prohibits the application of optical sensors (e.g. interior of Antarctica, Greenland,…), there is no problems with illumination and clouds, etc.

Response:

Agree. We deleted this statement. This type of comparison is not necessary.

Page 5878, line 7-8: " the accuracy of COSI-Corr is primarily determined by the spatial resolution of a pixel "; Spatial resolution is one issue, but as well of importance for use of optical imagery is the availability and quality of features.

Response:

We rephrased the sentence as: "The accuracy of COSI-Corr depends on the spatial resolution of the optical images and the quality (e.g. cloudless and accurate positions) of features used for the correlation analysis."

Page 5878, line 26-27: " … few studies have been reported for the Antarctic ice sheet with regard to ice velocities on larger spatial scales over longer time spans." Incorrect, see comment on Page

Response:

We removed this sentence.

Study area (pp. 5879, 5880):

This section refers rather randomly to some previous publications on Antarctic Peninsula glaciers and climate, lacking a clear focus relating the work reported by the authors and containing many errors.

Response:

We revised the section and reorganized and added more literature review on the topic of the present manuscript. More information on ice shelves in the northern Antarctic Peninsula was added (see 1st paragraph of this section in the revised manuscript).

Further details: Page 5879, line 13-14: "The average annual rainfall is up to 500–600mm. " This is certainly not rainfall. Besides, this statement is out of context.

Response:

The sentence was removed.

Page 5879, line 16-17: "Over the period 1952–2000, the Antarctic Peninsula experienced a temperature rise of 5.6 deg C (Turner et al., 2005)". Incorrectly quoted. Turner states: "major warming over the last 50 years, with temperatures at Faraday/Vernadsky station having increased at a rate of 0.56 deg C / decade over the year…"

Response:

This sentence was removed as part of the research background of the Antarctic Peninsula since we now only considered ice shelves where MODIS data are suitable. The coarse spatial resolution of MODIS makes it not suitable to accurately retrieve velocity field for features such as glaciers at the edge of ice shelves.

Page 5879, line 19-20: " the area lost from the Larsen Ice Shelf since 1986 has exceeded 8500 km2 ". The are is >10000 km2, see Cook and Vaughan (2012).

Response:

We revised the sentences as "…the lost area of the twelve ice shelves on the Antarctic Peninsula over the past five decades was more than 28 000 km^2 (Cook and Vaughan, 2010) ."

Page 5879, line 21-22: "The collapse of the Larsen Ice Shelf has caused substantial ice loss in upstream supplies of the Antarctic Peninsula, e.g. up to 6.8±0.3 km3 a-1 in the Fleming Glacier". Fleming Glacier is on the W-coast, does not drain into Larsen Ice Shelf.

Response:

It was removed; see the response to the comment on "Page 5879, line 16-17".

Page 5879, line 23-24: “ Pritchard and Vaughan (2007) monitored the velocities of more than 300 glaciers on the Antarctic Peninsula… acceleration 12 % … “ Incomplete quotation; These are only glaciers along the West Coast.

Response:

It was removed; see the response to the comment on “Page 5879, line 16-17”.

Page 5880, line 26-27: “These authors further estimated the mass output of the Antarctic Peninsula to be 60− 46 Gt a-1 in 2005 Pritchard and Vaughan (2007)” Incorrectly quoted. The “mass output” (calving flux and melt) is much higher.

Response:

It was removed, see above. We added the background of ice shelves (including Larsen C ice shelf).

Page 5879, line 1: “If the marine ice sheet in West Antarctica completely disintegrates, sea level will rise 3.3 m (Bamber et al., 2009).” Incorrectly quoted, 3.3 m do not refer to complete disintegration of WAIS.

Response:

It was removed; see the response to the comment on “Page 5879, line 16-17”.

Page 5880, line 4: “In short, Antarctic Peninsula glacier surface velocities have great implications for estimating Antarctic ice sheet mass balance and the study of global climate change (Skvarca et al., 1999; Osmanoglu et al., 2013).” Osmanoglu et al. report on King George Island, not Antarctic ice sheet.

Response:

It was removed; see the response to the comment on “Page 5879, line 16-17”.

Page 5880, line 9: “ the affiliated islands are neglected in this study to improve the accuracy of computation.” How can excluding an area improve the accuracy elsewhere?

Response:

We clarified this point by revising the paragraph as: “…It is required that the window size used for cross-correlation calculation should be large enough and with adequate number of pixels. Each of these affiliated islands occupies a very limited number of pixels, whereas the required window size for cross-correlation calculation is larger than each island.” In the revised manuscript, we only considered the ice shelves by excluding the affiliated islands and the glaciers of Graham Land. Thus, this sentence was removed.

Page 5880, line 10, 11; Fig.2: cannot see any “melt lines” on the ice shelves. The message of this Figure is unclear.

Response:

In the previous version, the “melt lines” on the ice shelves were not marked in Fig.2. But they were added as blue lines in Fig.1for different years in the revised manuscript.

Page 5880, line 14: how are “the minimum freeze/melt lines of sea ice” linked with retrievals of ice velocity.

Response:

We revised the sentence as "Mismatches can occur during the process of correlation calculation for feature tracking because of the great differences of reflectance between floating ice areas and ocean areas in images. Hence, we extract the minimum freeze/melt lines of sea ice during five different periods as the scope of cross-correlation calculation,"

Page 5880, line 16: "mainly covering Graham Land and the Larsen Ice Shelf (10.5km2)." Area inorrect by at least 3 orders of magnitude.

Response:

Agree, we corrected it. The sentence now reads "…Finally, the study region encloses an area of approximately 46,000 km^2."

Data (pp. 5880, 5881):

Concluding from the rather low quality of the velocity data, it seems that the selected data sample for velocity retrievals (only 5 images spread over 12 years) is inadequate. There are certainly many more MODIS images available.

Response:

This is a good point. For the results to be conclusive, we added more images with good quality (e.g. little or no clouds) (table1) for the velocity retrieval.

Table 1. Images with good quality used for velocity retrieval.

period1	period2	period3	period4	period5
27-MAR-2000(13:15)	10-FEB-2003(12:45)	5-JAN-2006(14:45)	8-APR-2009(14:15)	19-JAN-2012(13:25)
29-MAR-2000(13:05)	20-MAR-2003(13:45),	7-JAN-2006(14:20)	1-JAN-2009(13:10)	25-JAN-2012(12:50)
24-AUG-2000(14:15)	8-APR-2003(14:15)	10-NOV-2006(12:35)		21-FEB-2012(14:10)
26-AUG-2000(15:40)	18-APR-2003(14:50)			19-AUG-2012(13:50)
24-SEP-2000(11:55)	11-DEC-2003(14:50)			23-AUG-2012(13:25)

Further details:

Page 5881, line 8: The split in "geographic data" and "scientific data" is a bit confusing.

Response:

We clarified this point by revising the paragraph as: "MODIS L1B product consists of calibrated radiance at different resolutions (i.e., 1km, 500m, and 250m) and onboard calibrator/engineering data. These data are "scientific data". The position information for each pixel is "geographic data". We separate geographic data from the scientific data so that the scientific data images can be manipulated while keeping the geographic data intact. "

Page 5881, line 11: " …data products (Geolocation 1 km) for geocoding prior to cross-correlation calculations. " Geolocation accuracy of 1 km is not sufficient for retrieval of ice velocity.

Response:

There was a misunderstanding. The geolocation accuracy of MODIS L1B product is 50 m at nadir. 1km is the spatial resolution. To make it clear, we modified the paragraph as: "The geolocation accuracy of MODIS L1B product is 50 m at nadir (Wolfe et al. 2002)".

Page 5881, line 11: " During calibration, the pixel values are synchronically converted from reflectance to DN values, ultimately producing images with precise geographic coordinates." How can conversion from reflectance to DN improve geolocation accuracy.

Response:

This sentence does not make much sense. We removed it in the revised version. We replaced DN values with reflectance values in COSI-Corr.

Page 5881, line 18 to 30: The standard ASTER GDEM has large errors on the Antarctic Peninsula. Cook et al. (2012) produced an improved DEM for the Antarctic Peninsula that is freely available.

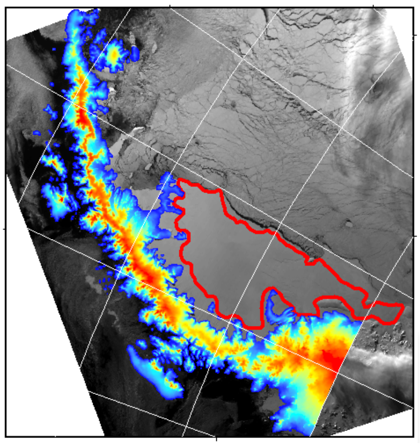

Figure 3. A new DEM based on ASTER GDEM by COOK.

Response:

We did not use the DEM data by Cook (since his DEM does not cover our study area (Fig.3). ASTER GDEM seems to be one of the few options that we can select.

Methods (pp. 5882 - 5886):

This section reports (verbosely) on standard procedures for velocity retrievals using optical satellite images. As these are routine procedures, most of the text, the equations, and Figs. 3, 4, and 5, can be omitted. On the other hand, the parameter settings which the authors used should be specified precisely, as well as the impact on retrieval performance. E.g., it is rather doubtful if good correlation peaks can be obtained with 10m x 10 pixels template size.

Response:

Agree. We removed Figs. 3, 4, and 5, Eq.2, 3, 5, 6, 7 and 8. The routine procedures were now briefly introduced, with an emphasis on precise specification of the parameter settings. The size of window should be small enough to avoid ice displacements being included in the same window. In the previous version of manuscript, the windows were set to 10 x 10 pixels so that the ice flows of ground glaciers can be monitored.

However, in the revised manuscript, we only focus on ice shelves. While the highest velocity of ice shelves in the northern Antarctic Peninsula is approximately 700m a^{-1}. We can thus set the reference window size for cross-correlation to 36 × 36 pixels. Correct matches have generally produced a much stronger correlation peak than incorrect matches. We modified the paragraph to make the point clearer (see 3st paragraph of this section in the revised manuscript).

Spatial distribution and temporal variations of velocities (pp. 5886 - 5889): The velocity maps presented in Fig. 6 are very coarse and not suitable for supporting studies on ice dynamics in this region. The motion fields of individual glaciers are not resolved. Even on Larsen-C ice shelf, a large homogeneous area, the motion field is coarse and noisy, not reproducing the actual spatial pattern of ice motion mapped with high resolution sensors (see Fig. 2 of Khazendar et al., 2011). Also the temporal trend, presented in Figs. 9b and 10 b, is very noisy, varying form one point to another from acceleration to deceleration. The amplitude of the temporal changes greatly exceeds the values in Fig. 3 of Khazendar et al. (2011). Besides, it seems that there is major trend of overestimating velocities on Larsen-C.

Response:

In the submitted version of the manuscript, we only showed the overall characteristics of the surface velocities of Antarctic Peninsula glaciers. However, the motion fields of individual glaciers could not be resolved due to the coarse resolution of the MODIS images. The consequence is that Fig. 6 looks coarse and noisy. Also, the representativeness of the velocity field on ice shelves may be compromised due to the small number of images used and the possible interference by the cloud cover (up to 20%) in some of the images used in COSI-Corr.

In the revised manuscript, we used more MODIS images of less cloud cover and thus of higher quality to generate the velocity field over only for ice shelves (Fig.2). The velocity field generated overall agrees well with that shown in Fig. 2 and Fig. 3 reported by Khazendar et al. (2011).

50 sample points were selected for quantitative analysis and they were marked in Fig.4. Fig.5 shows the velocity values derived for various time periods at each location. From Fig.5 we can see that at most locations, the ice moving speed increased from 200-2003 to 2009-2012, although the absolute velocity value at those locations varies greatly from a little bit over 141 m/a at one location to over 736 m/a at another location. This indicates the heterogeneity of the spatial distribution of the speed field of the ice shelves.

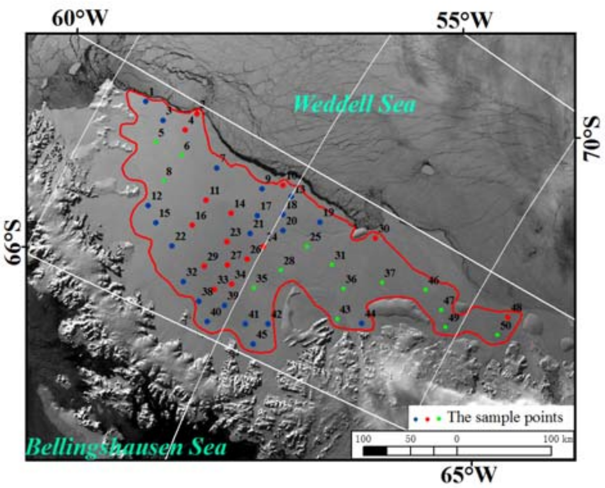

Figure 4. Sketch map of the 50 sample points. The ice at the sample points in blue showed a continuous acceleration; at the sample points in red did not show any significant change in velocity; and at the sample points

in green showed a deceleration from the period 2006-2009 to the period 2009-2012.

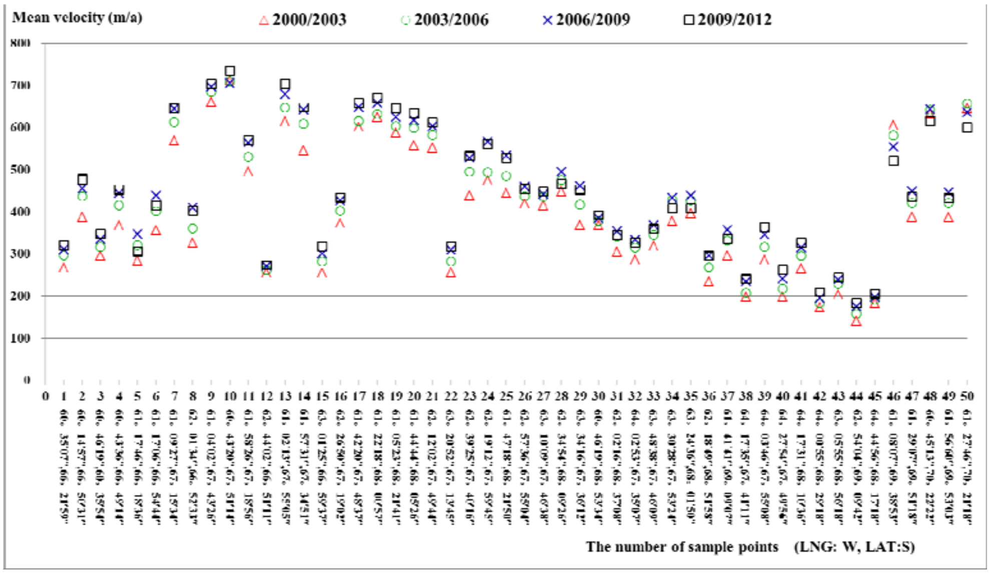

Figure 5. Average velocity of the 50 sample points.

Zooming into the velocity map (e.g. as shown in Fig. 7, for Cabinet Inlet on Larsen-C and some of its tributary glaciers) shows the weakness of the velocity products: motion vectors show up also on stable surface (mountain ridges); the high velocities on the narrow glacier channels (Eden Gl., Morrison Gl.) are not resolved, whereas the velocity on Cabinet Inlet is overestimated. Adjacent velocity vectors on the ice shelf are angling off by up to 90 degrees, contradicting laws of mass continuity and ice flow. Also the velocity time series for individual points on outlet glaciers (Figs. 9a and 10 a) are very noisy. There are many points (out of the total sample of the 50 points) showing two- to three-fold (and even higher) increase of velocities from 2000 to 2012. Actually, among the 50 points analysed only 3 are located on glaciers that showed such high acceleration rates (those are draining into Larsen-B embayment). It seems that many of these "temporal changes" are actually artefacts of velocity retrievals and geo-referencing.

Response:

Agree. The issues with velocity retrieval for small glaciers using MODIS data has been discussed in responses above. In the revised manuscript, temporal changes in surface velocities show continuous acceleration from 2000 to 2012. The acceleration rate during 2000-2009 was observed to be higher than that during 2009-2012. However, the velocities on the northeast and southern Larsen C, as well as on Smith Inlet from 2009 to 2012 showed deceleration (see Fig.4 and 6).

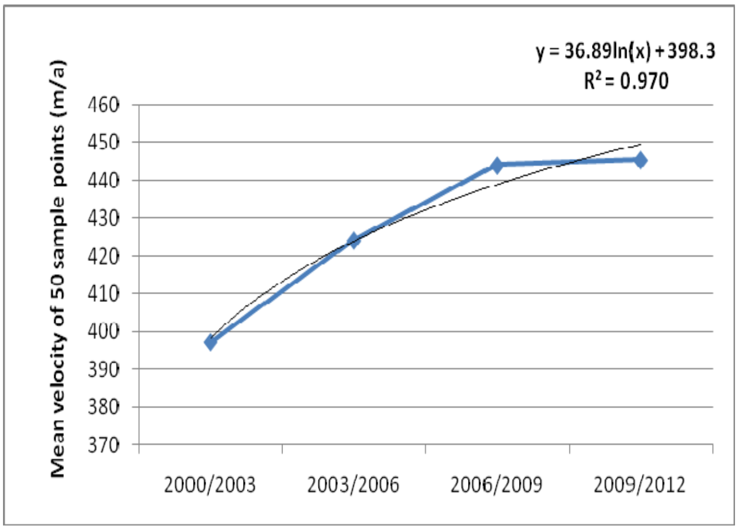

Figure 6. The variation of average velocities of 50 sample points

Error analysis (pp. 5889-5890):

In this section the authors compare some of their results with previously published velocity data and mention various factors that are commonly affecting the quality of ice motion products derived from optical satellite imagery. A rigorous assessment of error sources and the quantification of errors of the ice motion products presented in the manuscript is completely missing. The “comparison” with published velocity data (1st paragraph of this section) is not meaningful, because data of different epochs are compared and no attention is paid to the spatial congruence.

Response:

We reorganized this section and added more error analysis. There were no stable bare rocks in the study area, thus testing objects outside the study region were selected for the error analysis. To quantify the uncertainty of the results in applying COSI-Corr to MODIS L1B data, 25 matching points were selected and investigated, the RMS of the matching measurements in both W-E and S-N directions over stable bare rocks is given in (Table 2).

Table 2. The uncertainties of stable bare rocks outside the study area

Image pairs	RMSE-W	RMSS-N
2000/2003	54	62
2003/2006	46	56
2006/2009	61	71
2009/2012	47	52
Mean	52	60

Further details:

Page 5889, line 8 - 10, and Fig. 11: The motion field of Crane Glacier, presented in Fig. 11, does not agree with high resolution velocity data. Rott et al. (2011) present velocity data of Crane Glacier and several other glaciers of the Larsen-B embayment for various epochs between 1995 and 2008 based on SAR data. For Crane glacier see also Rignot et al. (2004), Hulbe at al. (2008); Scambos et al. (2011).

Response:

It was removed; see the response to the comment on “Page 5879, line 16-17”.

Page 5889, line 12 - 15, and Fig. 12: The velocities presented here for five points on a single line across the remnant part of Larsen-B ice shelf are not representing the“average velocity of the Larsen-B ice shelf”. This section of the ice shelf shows a rather complex field of ice motion and deformation (Rack et al., 2000).

Response:

Since “the remnant part of Larsen-B ice shelf “ is no more within the study area, it was removed; see the response to the comment on “Page 5879, line 16-17”..

Page 5889, line 16: Incorrectly quoted. Scambos et al. (2004) do not provide velocity data for any point on Larsen ice shelf

Response:

Corrected.

Additional References:

Cook, A. J. and Vaughan, D.G.: Overview of areal changes of the ice shelves on the Antarctic Peninsula over the past 50 years. The Cryosphere, 4, 77–98, 2010

Cook, A. J. et al.: A new 100-m Digital Elevation Model of the Antarctic Peninsula derived from ASTER Global DEM: methods and accuracy assessment, Earth System Science Data. 4, 129-142, doi:10.5194/essd-4-129-2012, 2012.

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.

Rack,W., Doake, C. S. M., Rott, H., Siegel, A., and Skvarca, P.: Interferometric analysis of the deformation pattern of the Northern Larsen ice shelf, Antarctic Peninsula, compared to ï ˘ n ¸Aeld measurements and numerical modeling, Ann. Glaciol., 31, 205–210,2000.

Rott, H., Müller, F., Nagler, T., and Floricioiu, D.: The imbalance of glaciers after disintegration of Larsen-B ice shelf, Antarctic Peninsula, The Cryosphere 5 (1), 125–134,2011.

Scambos, T. A., Berthier, E., and Shuman, C.A.: The triggering of subglacial lake drainage during rapid glacier drawdown: Crane Glacier, Antarctic Peninsula, Ann.Glaciol., 52(59), 74-82, 2011.

Response:

We read these references and cited them in the revised manuscript.