Interactive comment on "Heterogeneous spatial and temporal pattern of surface elevation change and mass balance of the Patagonian icefields between 2000 and 2016"

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Authors' response to Anonymous Referee #1

Referee comments are shown in **black**, our response in **blue**. Line numbers refer to the manuscript version (pdf) of 23 November 2018.

General comments:

Comment: This manuscript applies advanced SAR processing techniques in order to derive spatially detailed maps of surface elevation change (SEC) of the Northern and Southern Patagonian icefields, NPI and SPI respectively. The text is well written, the figures are of good quality, the tables are clear and informative, the topic is of high interest and the results are very interesting, confirming previous studies showing as a whole a strong negative ice volume change with high spatial variability. The authors analyze in detail different sources of errors and gives precise estimations of uncertainties for every studied glacier, different data sets and analyzed periods.

Response: Firstly, we want to thank the anonymous Referee for the time and effort put in this detailed and thorough review. We carefully evaluated all comments and suggestions, which are extremely valuable in improving the paper. We are very glad about the positive feedback. We particularly value the Referee's appreciation of the error estimation, in which we invested significant effort and which we believe is one of the strong points of this manuscript with respect to previous studies. Throughout this response, as well as in the paper, we refer to the surface elevation change (in m) as "SEC" and to the surface elevation change rate (in m a^{-1} or m d^{-1}) as "SECR".

We recognize that the focus of this review is on the seasonal correction which we apply for filling gaps in the rate of surface elevation change, in particular for the four-year time span of epoch 2012 to 2016. This is an important side issue aimed at reducing the uncertainty in mean annual SECR. The main contribution of the paper is the generation of spatially detailed data sets on surface elevation and volume change of both NPI and SPI for two different epochs, including the assessment of communalities and differences in glacier behaviour between the two ice fields and the two epochs. We are not aware of any other publication showing homogenous high resolution data sets on surface elevation or volume change of both icefields for two different epochs.

Comment: The results are not totally novel, since the data sets employed in this manuscript were recently used in a paper published by Malz et al., (2018) with some variations in dates, error assessments and study area. Unfortunately, the results are not totally comparable between them since the glacier basins and dates are not the same. These differences preclude a precise estimation of discrepancies, but in general the results are statistically similar. The main contribution of Abdel Jaber et al, is their claimed much smaller uncertainties due to several correction that Malz et al didn't applied. After considering the analysis performed by Abdel Jaber et al, I think the error assessment is much more rigorous, effectively addressing many error sources of the data sets, but it is too ambitious when trying to extrapolate parameters from single stations/glaciers for correcting some issues related to the whole icefields. In those cases, is better to live with higher uncertainties and not adding more doubts as I think were added when using Perito Moreno as model for altitudinal gradients for example.

Thanks to the detailed error analysis, this manuscript provides a state-of-the art estimation of surface elevation change of both Patagonia Icefields. Unfortunately, the last data set of 2015 does not come from the end of ablation season, therefore, the authors applied a seasonal corrections to the derived surface elevation changes in order to provide estimates that correspond to full seasonal cycle. This seems to be a weak point of the study design. I guess this was caused by the availability of TanDEM-X imagery, however, employing a more recent datatake from the end of ablation season (later than 2015/16), would have considerably strengthen the importance of this contribution.

Response: While in fact some TanDEM-X raw data (Level-0) used in this study are the same as those used by Malz et al., (2018) we would like to highlight the main differences with respect to the latter publication. Malz et al., (2018) provides a SECR with full coverage of SPI for the epoch 2000-2015/2016 only, from which they derive the geodetic mass balance at an icefield level (with uncertainty) and at a basin level (without uncertainty). They furthermore provide two SECR maps covering the periods 2000-2012 and 2012-2015 which are based on SRTM and on the same pairs of TanDEM-X raw data that we use but they are restricted to the southern part of SPI (~2106 km², ~16% of SPI). Furthermore they do not exploit them to provide any mass balance estimation of the covered glaciers.

We argue that one of the strong points of this study is the use of a homogeneous set of methods and data to achieve SECR maps of both Patagonian icefields, featuring a very high coverage, for two similar observation periods. These maps are used to compute the geodetic mass balance (with uncertainty) of all glacier basins larger than 2 km² on NPI and larger than 9 km² on SPI. Hypsometric plots (with uncertainty) for both epochs are also reported for 15 main glaciers of NPI and 24 of SPI.

As correctly noted by the Referee a critical point of our study design is linked to the missing summer days in the "slave" elevation mosaic of the 2012-2015 SEC, caused by its acquisition time in December 2015, whereas February 2016 would have constituted the ideal setup. We hence understand that most of the constructive critique is linked to this issue. We firstly confirm the Referee's presumption: the choice of this dataset was indeed forced by the absence of more suitable coverages of the icefields at the beginning of this study.

As described in the manuscript, the seasonal elevation loss occurring on the icefields during the missing summer days is non-negligible. We show a map of measured seasonal changes on most of the SPI for a different summer, that of 2011/2012 (Fig. 8) which, however, was characterized by the same average air temperature as summer 2015/2016. We are not aware of any published seasonal SECR map of SPI.

Neglecting the impact of summer seasonal elevation variations on the SECR maps and on the corresponding geodetic mass balance would cause some bias, in particular for the second epoch. We hence devise different correction strategies for different sections of the icefields, according to the availability of SECR datasets and complementary data. We are aware of the limitations of such strategies and take into account these limitations in the error budget. Detailed information on the points correctly raised by the Referee is provided below. We are convinced that the seasonal corrections improve the accuracy of the mean annual SECR compared to the approach by filling temporal gaps with average SECR without taking into account the missing days in the melting season.

Comment: Assuming that the surface elevation changes in summers 2011/2012 and 2015/2016 are equal, based on similarity of monthly mean air temperature records in some neighbouring weather stations is very arguable.

Response: We agree that these weather stations, in some distance from the icefields, are not the best choice for checking summer temperature over the icefields. We checked the ERA Interim temperature data, showing agreement within 0.1°C for both summers. The 850 hPa mean summer temperatures (December, January, February) are for point 47.25 S, 73.55 W over NPI: 5.9° C (2011/2012), 6.0° C (2015/2016) and for point 50.25 S, 73.55 W over southern SPI: 3.6° C (2011/2012), 3.5° C (2015/2016).

Comment: The other weak aspects of the manuscript are the assumptions regarding altitudinal gradients only supported by Perito Moreno glacier data. This glacier cannot be considered representative for the entire icefield due to extreme longitudinal gradients of climate and mass balance associated with orographic barrier of the Patagonian Andes.

Response: Here we explain again the strategy and procedures for the seasonal corrections (described in Section 3.1.3 of the manuscript), providing some additional details. The term seasonal correction refers to the difference between mean annual SECR without accounting for seasonal differences in SEC of the missing days and mean annual SECR taking seasonal differences into account. The seasonal correction is assessed separately for the two considered epochs.

Motivations for deriving SECRs over annual periods are: (i) to provide the basis for estimating the annual mass balance (MB), a key climate parameter; (ii) to facilitate comparisons of SECR, volume change and MB from different epochs; (iii) to facilitate comparisons with results of other studies (based on different observation techniques and also on MB modelling).

If repeat observations are not available in exactly annual or multi-annual (365.25xN days) repeat intervals, commonly the mean (average daily) SECR of the (incomplete) epoch is extrapolated to fill the missing temporal gap (or to subtract the contribution of excess days) in order to match annual time spans. This approach introduces a bias in annual SECR in case of seasonal variations. The magnitude of the bias depends on the percentage of missing (or excess) days and the amplitude of the seasonal cycle.

The bias in annual SECR due to deviation from exactly (multi-) annual intervals can be reduced by accounting for seasonal differences in SEC. In our case the temporal mismatch vs. exactly annual repeat observations (time spans of 12 years and 4 years) varies for the two epochs and for different sections of the ice fields. For the 2000 to 2012 time span the mismatch in percentage of the full period is very small. For the different TanDEM-X (TDM) tracks vs. SRTM over SPI the number of missing days corresponds to 0.1 % to 1.0 % of the 12 year period. Nevertheless, for epoch 2000-2012 over SPI we apply a seasonal correction where the temporal mismatch exceeds 15 days. On NPI no seasonal correction is applied because here the number of missing days is only 0.1% of the 12 year period.

In the following we provide details for the 2012 to 2016 data because the impact of seasonal corrections is more important due to the shorter time span. For NPI the number of missing days amounts to 3.6 % to 4.8 % of the 4-year time span, depending on the track. For the main sections of SPI the corresponding numbers range from 3.6 % to 5.0 %, except for a small subarea where it is 7 %.

Depending on the availability of additional TDM DEM data, the following procedures for seasonal corrections are applied for different sections of the icefields:

- TDM acquisitions of December 2011 cover the southern, central and north-eastern sections of SPI (59.4 % of the SPI area, manuscript Figure 8). These data are used to compute daily SECR over summer periods 2011/2012 by DEM differencing vs. TDM data of March 2012 (99 days, covering the main part of the SPI area) and vs. TDM data of 31 January 2012 (33 days, for a small section). According to ERA Interim the average temperatures of summer 2011/2012 and summer 2015/2016 agree within 0.1°C (see details above). This means that the SECR maps of summer 2011/2012 (scaled to the length of the missing period) can well be used as substitute for the missing days in summer 2015/2016.
- For glaciers that are not covered by the summer 2011/2012 SECR map we carry out two approaches, explained in manuscript Section 3.1.3 and repeated here. For the majority of these glaciers we use daily SECR in dependence of elevation (aggregated in 100 m elevation bins, Fig. S3) derived from the SECR maps of summer 2011/2012. For the missing part of Pio XI Glacier we use the hypsometric SECR curve of low-loss glaciers (green curve in Fig. S3), based on summer 2011/2012 SECR of Perito Moreno, Grey, Tyndall, HPS 13, Europa, Penguin and Guilardi glaciers. For the rest of SPI (except Jorge Montt Glacier) we use the hypsometric curve of the 99 days (blue curve in Fig. S3). On NPI, except S. Rafael, S. Quintin and (a very small frontal area of) Benito glaciers, we use the hypsometric green curve of Fig. S3 since here calving fluxes are a small component of total mass balance.
- For glaciers that are not covered by the summer 2011/2012 SECR maps and are subject to significant dynamic downwasting (Jorge Montt, S. Rafael, S. Quintin glaciers) we separate the SEC components in the ablation areas related to surface mass balance (SMB) from dynamic downwasting. The seasonal correction accounts for the difference in SMB between summer and the rest of the year for the glacier area below the equilibrium line. For this purpose estimates on the elevation dependence of specific SMB during summer and during the full year are needed. To our knowledge, up to know the only multi-year time series of ablation measurements (including separation of net balance during summer and the rest of the year) on any glacier of SPI and NPI has been performed on Moreno Glacier (Stuefer et al., 2007). We use these data to compute the ratio between daily SECR during summer vs. the rest of the year. Using this ratio, and the hypsometric SMB curve of Moreno Glacier, we estimated the increased contribution due to surface melt during summer relative to the full year up to the equilibrium line and apply this to the missing days. For the dynamic downwasting component we use the average SECR of the full period.

Regarding the validity of the P. Moreno mass balance gradient for Jorge Montt, S. Rafael, S. Quintin and Benito glaciers: We compared published SMB data for the terminus of NPI west coast glaciers with SMB computed with the balance gradient of P. Moreno Glacier, showing good agreement between these two estimates. We computed also mass balance gradients for west coast glaciers using the published balance gradient of Chico Glacier (northern SPI) accounting for the different temperature lapse rates between east and west coast glaciers (Bravo et al., 2019). Notably, these two approaches yield quite similar results, pointing out that use of the Moreno balance gradient is a reasonable choice. See details in the Appendix.

Comment: I would be keen to see maps of systematic error similar to Fig S7 that shows random error. This is specially important for some major outlet glaciers of SPI (Jorge Montt, Pio XI, O'Higgins, Viedma and Upsala) where seasonal correction was in the order of several meters (Fig. S4b).

Response: The systematic error maps do not feature a strong spatial variation, with exception of regions affected by high probability of signal penetration and regions not covered by the summer 2011/2012 SECR. The systematic error maps are per se not very informative and were hence not included in the Supplement. We instead preferred providing quantitative values of the different systematic error components in Table S7. The systematic error linked to the seasonal correction is considered as a bulk error derived from the systematic error of the summer 2011/2012 SECR (see Sect. 3.3.3 and also the response to specific comment below), which was increased on specific regions to take into account the extrapolation through hypsometric average values on regions not covered by the summer 2011/2012 SECR. The weighting by the number of corrected days was also applied.

We noticed that the description of Figure S4 might lead to confusion and we will change it. Figure S4 represents the rasters (in meters) added during processing to the original SEC rasters (covering the entire observation period) to compensate for the missing/exceeding days.

Comment: This work is largely based on the results and methods reported by Abdel Jaber (2016) PhD thesis. In order to avoid undesirable repetitions, I guess the thesis can be quoted only a couple of times, and then assuming that the results are the one obtained in this manuscript.
In synthesis, I think this manuscript is highly valuable and fits very well with the aim and scope of the journal.

Response: This work is based on methods applied in the Abdel Jaber (2016) PhD thesis which were further developed and adapted to this study. Abdel Jaber (2016) reported SECR maps of NPI (2000-2014) and SPI (2000-2011/2012) with mass balance only at an icefield level. The results presented in this study are completely novel (we note that a limited number of TanDEM-X raw data are in common but were newly processed). For this reason in the manuscript we treat Abdel Jaber (2016) as a separate scientific study. The good agreement between the results of this study and those obtained by Abdel Jaber (2016) by separate processing represents, in our opinion, an added value for both publications.
The only results reported in the manuscript and stemming from Abdel Jaber (2016) are the subaqueous ice volume changes and frontal distance variation of the main SPI glaciers in the epoch 2000-2011/2012 (Table S9) and the icefield-wide subaqueous volume change rate reported in Sect. 4.

Specific comments:

Comment: P1 L20: ... and ..., respectively

Response: Wording changed to: "They stretch from 46.5° S to 47.5° S and from 48.3° S to 51.6° S, respectively, along the…"

Comment: P2 L9: any other reference? this is only review

Response: References added:

Åström, J. A., Vallot, D., Schäfer, M., Welty, E. Z., O'Neel, S., Bartholomaus, T.. C., Liu,, Y., Riikilä, T. I., Zwinger, T., Timonen, J., and Moore, J. C.: Termini of calving glaciers as self-organized critical systems, Nature Geoscience, 7, DOI: 10.1038/NGEO2290, 2014.

Benn, D. I., Warren, C. R. and Mottram, R. H.: Calving processes and the dynamics of calving glaciers, Earth-Science Reviews, 82, 143-179, 2007.

Warren, C. R. and Aniya, M.: The calving glaciers of southern South America, Global and Planetary Change, 22, 59-77, 1999.

Comment: P3 L8-9: You frequently refer to Abdel Jaber (2016), how different is its work from this submission? I presume is roughly speaking the same.

Response: Please see the response to the general comment above.

Comment: P3 L23-24: Later you refer to Abdel Jaber (2016) as a source for subaqueous ice loss estimates

Response: Please see the response to the general comment above.

Comment: P5 L15-20: Crippen et al. (2016) provided only a general description of NASADEM, and as far as I now, its performance has not been thoroughly compared with SRTMGL1. This I guess is one of main differences of this work compared to a very similar study by Malz et al. (2018) - how does it impact your final results? Were there really less voids compared to SRTMGL1?

Response: Voids, mostly caused by phase unwrapping errors, were filled using ASTER GDEM2 in the SRTMGL1 dataset (SRTM version 3). In the NASADEM (available in its void-filled and SRTM-only versions) voids were not very critical on great part of the icefield. We agree with the Referee that the performance of NASADEM has not been assessed yet. We hence performed our own assessment with the main focus being on sources of systematic errors, and particularly long-wavelength elevation biases. While not perfect (particularly around NPI) we concluded that NASADEM is certainly a step forward in this regard compared to SRTMGL1. We hence proceeded with this dataset for the production of the SECR maps and the computation of the mass balance. SECR maps based on SRTMGL1 were not produced; a quantitative comparison of volume change rates is hence not available.

Comment: P6 L25: How different were your glacier outlines from those used by Malz et al? The Randolph inventory is known to have problems in many places. Maybe you can discuss about this.

Response: Assuming reference to P5 L25. For the glacier outlines of NPI and SPI we use the Randolph Glacier Inventory in its latest version 6 with our own modifications. In RGI v6 significant changes compared to the previous version are found on NPI, where a complete new set of outline was introduced based on those published by Rivera et al. (2007), while no changes are found on SPI. We are aware of the limitations of the RGI outlines, particularly in the definition of the internal divides between adjacent basins. We improved the external borders of the glacier outlines as described in Sect 2.3, whereas we did not modify the internal divides. The TanDEM-X DEMs have potential for such an improvement but this exceeded the scope of this study. We preferred to use the latest RGI for comparability of results, limiting changes to the termini.

The SPI outlines of Malz et al., (2018) are reportedly based on RGI version 5 with refinements based on optical images. Some non-negligible differences between our and their glacier outlines can be appreciated by comparing our Figure S9a with their Figure 2b. In particular differences are visible on Bernardo, Tempano, Occidental, Greve glaciers (the latter three appear as a single basin in their paper). Other differences are found on Chico/Viedma glaciers, Europa/Guilardi glaciers, and on smaller glaciers.

Comment: P7 L10: There is a problem when quoting equations along the whole manuscript. Only Eq. 2 is mentioned in the text and some equations are between lines without label numbers, don't helping in the fluent reading process. You refer here to Eq. (2) well before introducing it (and before Eq. (1))

Response: Agreed, many equations were written inline in order to reduce space and provide a flowing narrative. We will improve the manuscript on this issue.

Comment: P8 L20. The temperature and balance altitudinal gradients in the SPI are highly different between east-west margins or northern - southern parts etc. Maybe you can check a recent paper by Bravo et al in JGR (DOI: 10.1029/2018JD028857) and comment on this.

Response: Many thanks for referring to this recently published paper providing very valuable data for advancing the modelling of surface/atmosphere exchange processes and surface mass balance across the icefield. We performed computations on mass balance gradients using different lapse rates on east and west coast glaciers and comparisons with Moreno balance gradients. See details above and in the Appendix.

Comment: P8 23-36: Can you please clarify this part? For example Perito Moreno and Jorge Montt have very different climatic setting (Lenaerts et al., 2014), I wonder if Perito Moreno is a best choice for a reference in this case.

Response: See the detailed description on the seasonal correction above and the Appendix.

Comment: P8 L30-32: Again, issue of transferability of parameters of Perito Moreno to entire SPI. Why was it not necessary for NPI, because of the day of datatake, I guess?

Response: The 2000-2012 SECR of NPI was not corrected because the SRTM and the TanDEM-X data takes were acquired approximately in the same days of February. The seasonal changes on the scene with index 1, not involving summer days, were deemed to be negligible and much less than the systematic errors on a 12-year time frame. See also the detailed description on the seasonal correction above and the Appendix.

Comment: P8 L36-37; Fig S4: There are sharp boundaries between zones corresponding to different time spans, do they propagate to the final product introducing discontinuities?

Response: The discontinuities are caused by the different Δt in days to be corrected between adjacent master-slave pairs. These do not propagate in a noticeable way to the final SECR product. In fact light discontinuities might already be present in the uncorrected SECR, the correction would, at least in theory, reduce such discontinuities by compensating different amplitude of seasonal changes according to the actual Δt in days.

Comment: P9 L19: Uncertainty bound on glacier-wide density seems to be too low. Cogley (2009) refer to Sapiano et al. (1998) 6% estimate as reasonable. In similar work, Malz et al. (2018) provide three scenarios of different densities, it is their main source of uncertainty for the final results.

Response: The main scope of this study is to provide reliable volume change rate estimates at a basin scale (Tables 2, 3, S8). These can then be converted to mass change rates using a constant density assumption and a corresponding error of choice. Furthermore we also wanted to provide a reference mass change rate at an icefield level. For this purpose we decided to use the common scenario of glacier-wide density of 900 kg m^{-3} facilitating the comparison of results with other studies. We agree that the assigned error of 17 kg m^{-3} is a small one (1.8%) for firn areas. However, the main mass losses on the Patagonian icefields refer to ice areas. For the accumulation areas assumptions on changes of the vertical profiles of snow/ice density would be speculative. Furthermore, the core of the error estimation of this study focuses on the volume change rate estimates.

Comment: P10 L7-10: Please back it up with some reference

Response: References added:

Garreaud, R., Lopez, P., Minvielle, M., and Rojas, M.: Large Scale Control on the Patagonia Climate, J. Climate, 26, 215–230, 2012.

Schaefer, M., Machguth, H., Falvey, M., and Casassa, G.: Modeling past and future surface mass balance of the Northern Patagonian Icefield, J. Geophys. Res.-Earth, 118, 571–588, doi:10.1002/jgrf.20038, 2013.

Comment: P10 L24: Finally, what exactly was the criterion for masking regions prone to penetration? Was it only manually outlined based on expert knowledge?

Response: In each DEM mosaic, regions prone to signal penetration were not masked-out, instead they were manually outlined and assigned a certain penetration bias, which was then used to compute the corresponding systematic error component of the SECR (Sect. 3.3.3). The penetration bias was assigned based on the average σ^0 within the region. Measurements of signal penetration in TanDEM-X data over NPI at varying σ^0 are reported in Abdel Jaber (2016). These, together with expert knowledge on relations between X-band σ° and signal penetration were used to assign the penetration bias values. During summer the top snow layers on the main ice plateau are either wet (low σ°) or include melt/freeze metamorphic layers with rather small penetration for X-band signals also in frozen state (Reber et al., 1987).

Reber, C., Mätzler, C., and Schanda, E.: Microwave signatures of snow crusts, modelling and measurements, Int. J. Remote Sensing, 8 (11), 1649 – 1665, 1987.

Comment: P11 L8-9: See comment above.

Response: The average σ^0 of the SRTM acquisitions were analyzed to reach this conclusion. This is another novel aspect of this publication; we are not aware of an empirical assessment of the backscatter of C-band SRTM to assess possible signal penetration in glaciological remote sensing studies. Furthermore, the good agreement between our volume change rates 2000 to 2012 over NPI and the results of Dussaillant et al. (2018) based on optical data confirm the validity of our approach regarding signal penetration. See also their conclusion: " our study confirms the lack of penetration of the C-band SRTM radar signal into the NPI snow and firn except for a region above 2,900 m a.s.l."

Comment: P11 L11: Bippus (2007) assumed this lapse-rate for summer season on Perito Moreno, however as far as I know this value was not based on measurements. Additionally, she accounted for an off-glacier location of AWS, resulting in additional temperature offset. Maybe you can compare your numbers with Bravo et al 2019

Response: Thank you for this input. However, we want to stress that the conclusion about signal penetration is primarily based on the backscatter assessment. Regarding penetration see also the comment above.

Comment: P12 L26: Is 0.1 m based on literature?

Response: The bulk systematic error of 0.1 m for the remaining pixels above 1000 m a.s.l. accounts for undetected regions (a very small percentage of the total area) and possible small offsets on refrozen upper layer of snow and firn, affecting only very small areas; see response above. The typical X-band one-way penetration depth of frozen crust is 0.1 m (Reber et al, 1987).

Comment: P13 L1-5: I think that the error linked to the seasonal correction may be underestimated as it does not seem to cover all uncertainties related to the transferability of hypsometric averages shown in Fig. 8 (see previous comments).

Response: See also the response to the general comment and Sect. 3.3.3. The systematic error linked to the seasonal correction is derived from the systematic error the summer 2011/2012 SECR used for the correction on most of the glaciers. This systematic error was increased to account for the different year to correct, although summer air temperatures were nearly the same (see response above). It was also increased on regions where the summer 2011/2012 SECR has no coverage (NPI, north-west SPI and many gaps throughout SPI) in order to account for the transferability of hypsometric averages. Such increases might even lead to an overestimation of this error source; this is accepted as it tends towards a more conservative error budget.

Comment: P15 L26: It that is true than your seasonal correction should use lower density in accumulation area.

Response: P15 L26 does neither refer to seasonal correction nor to density in the accumulation area. Regarding the comment above concerning seasonal correction, there is no point for using snow density, because the correction refers to seasonal differences (summer vs. rest of the year) in surface elevation.

Comment: P15 L30: Perito Moreno glacier

Response: Corrected.

Comment: P16 L28: Results were recently published in Frontiers - Langhammer et al. (2018)

Response: Thank you; we will include the reference to this publication.

Comment: P16 L37: Again, I doubt that Perito Moreno is representative for entire SPI and SPI, Steufer (2007)

Response: There seems to be some misunderstanding regarding the use of Perito Moreno seasonal balance gradients. This is not used for entire SPI and NPI, but to estimate the impact of seasonal differences in surface lowering due to ablation for altogether only four glaciers of the two icefields and only for the epoch 2012-2016. See also the detailed description on the seasonal correction above and the Appendix.

Comment: P17 L26: This issue is a critical factor in the whole analysis of the elevation changes in the high plateau of the icefields. We know that the accumulation is extremely high, an in between few days you can have huge accumulation events. I think this high temporal variation of snow fall must be taken into account. See Schwikowski et al 2013 for snow accumulation on the SPI.

Response: At first, we want to point out that we are well aware on the spatial and temporal variability of accumulation on SPI. The work reported in this paper does not deal with single events, but addresses the retrieval of spatially detailed maps on changes in surface elevation and volume over SPI and NPI, providing mean values over epochs of 12 years and 4 years. The contribution of single events during this period is implicitly included in this analysis. Regarding spatial variability, this is fully taken into account by the high spatial resolution of the TanDEM-X elevation data and the high percentage of spatial coverage (Table 3). Regarding the summer periods 2011/2012 vs. 2015/2016, there is no indication on exceptional events as according to ERA Interim there is perfect agreement for air temperature and the difference in precipitation over SPI between these two summers is 15 % (probably within the uncertainty of precipitation estimates for this region).

Comment: P18 9? What analysis? It is missing in methods and results sections. Maybe you wanted to quote Abdel jabber 2012?

Response: Assuming reference to P18 L4. Agreed, the sentence is not well-formulated. The analysis refers to ice flow velocity results external to this study and based on TerraSAR-X. We will reformulate.

Comment: P18 L25: See comment above P33 Fig.4: Why is there a sharp transition in the terminal part of the glacier on panel a? Frontal retreat I guess?

Response: Yes, exactly. The sharp transition is in fact a physical signal in the elevation difference between the glacier front in 2012 (abrupt step in elevation) and what in year 2000 was the glacier surface (smooth increase in elevation).

New references mentioned in this review:

Bravo, C. et al (2019) Air Temperature Characteristics, Distribution and Impact on Modeled Ablation for the South Patagonia Icefield. JGR, DOI: 10.1029/2018JD028857

Langhamer, L., Sauter, T., & Mayr, G. J. (2018). Lagrangian Detection of Moisture Sources for the Southern Patagonia Icefield (1979-2017). Frontiers in Earth Science, https://doi.org/10.3389/feart.2018.00219

Lenaerts, J. T., Van Den Broeke, M. R., van Wessem, J. M., van de Berg, W. J., van Meijgaard, E., van Ulft, L. H., & Schaefer, M. (2014). Extreme precipitation and climate gradients in Patagonia revealed by high-resolution regional atmospheric climate modeling. Journal of Climate, 27(12), 4607-4621.

Sapiano, J.J., W.D. Harrison and K.A. Echelmeyer. 1998. Elevation, volume and terminus changes of nine glaciers in North America. Journal of Glaciology, 44(146), 119- 135.

Schwikowski, M., M. Schläppi, P. Santibañez, A. Rivera and Casassa G. (2013): "Net accumulation rates derived from ice core stable isotope records of Pío XI glacier, Southern Patagonia Icefield". The Cryosphere 7, 1635-1644. doi.org/10.5194/tc-7- 1635-2013

APPENDIX

Estimation of mass balance gradients for Jorge Montt Glacier and for the NPI glaciers S. Rafael. S. Quintin and Benito

In the current version of the paper (Abdel Jaber et al., 2018) the mass balance (MB) gradients of Moreno Glacier are used to estimate the seasonal difference of surface lowering in the ablation area related to the surface mass balance (SMB) for J. Montt Glacier and for three glaciers on the west coast of NPI. In the review the use of the Moreno MB gradient for these glaciers is questioned, pointing out the different temperature lapse rates between the east and west side of SPI measured along a transect crossing the northern section of the icefield (Bravo et al., 2019). Taking this into account, we computed the MB gradient for west side glaciers based on the MB gradient for a glacier on the east side of the norther section of SPI, accounting for the different lapse rates.

Mass balance gradients:

- For Chico Glacier Rivera (2005) shows a MB gradient based on modelling. The (close to linear) value in the ablation area is: $\Delta b_n/\Delta z = 0.015$ m w.e./(m a).

- The ratio of the west/east temperature lapse rate (LR) at the transect Occidental to O'Higgins glaciers is: LR(west) = 0.76 LR(east) (Bravo et al., 2019):
- Chico Glacier is adjacent to O'Higgins Glacier. Using the balance gradient of Chico Glacier and the west/east ratio of LR results in the MB gradient: $\Delta b_n/\Delta z$ (west) = 0.0114 m w.e./(m a)
- For comparison: The MB gradient for Moreno Glacier: $\Delta b_n/\Delta z$ (Mor) = 0.0122 m w.e./(m a)

Specific mass balance on the terminus of tidewater calving glaciers at 50 m a.s.l.:

- Equilibrium line altitude (ELA) is used as reference for specific mass balance $b_n = 0$ at ELA.
  Mean ELA NPI west (S. Rafael. S. Quintin): 1200 m (Rivera et al., 2007).
  Mean ELA J. Montt Glacier: 1100 m (Rivera et al., 2012)
- The resulting b_n at 50 m a.s.l using $\Delta b_n/\Delta z$ (west) is: NPI west b_n = 13.11 m w.e. a^{-1}; Jorge Montt b_n = 11.97 m w.e. a^{-1}.
- The resulting b_n at 50 m a.s.l using $\Delta b_n/\Delta z$ (Moreno) is : NPI west b_n = 14.03 m w.e. a^{-1}; Jorge Montt b_n = 12.81 m w.e. a^{-1}.
- Comparison with published (modelled) b_n for NPI western outlet glaciers (on the terminus near the glacier front): 14 m w.e a^{-1} (Schaefer et al, 2013).

Conclusion:

The computed b_n for the terminus of NPI western outlet glaciers, using the Moreno Glacier MB gradient, shows good agreement with b_n reported by Schaefer et al. (2013). This confirms the use of the Moreno Glacier MB gradient as a reasonable option for computing the seasonal correction for these glaciers. For b_n on the terminus of J. Montt Glacier we did not find any published data. However, considering the comparatively short distance to NPI (300 km) it can be assumed that the MB gradient is rather similar. Therefore (and for better traceability) we use the Moreno MB gradient for estimating the SMB-related seasonal correction also for J. Montt Glacier. The use of the MB gradient for west coast glacier, derived from the Chico Glacier MB gradient, would not cause any significant difference for the seasonal correction. , backing up this solution.

Error estimate: for b_n ±20 %; for the ratio b_n summer vs. full year $b_{n,S}/b_{n,yr}$-±20 %; combined ±28 %.

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