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The Cryosphere Discussions

Interactive comment on "Spatial and temporal variations of glacier extent across the Southern Patagonian Icefield since the 1970s" *by* A. White and L. Copland

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The authors would like to express their appreciation for the detailed comments provided by B. Davies. Below are the responses to all comments.

RESPONSE TO B. DAVIES

COMMENT: 1.1 Originality and novelty The most obvious problem to be addressed is the fact that the manuscript repeats a lot of the work and detailed analysis published recently by Davies and Glasser (Davies, B.J., and Glasser, N.F., 2012. Accelerating shrinkage of Patagonian glaciers from the Little Ice Age (AD 1870) to 2011. Journal of Glaciology 58 (212), 1063-1084). If the Copland and White article is to be published in

TC, the authors need to read and cite this paper, and write a section of text explaining how the findings of their research differ from those already published.

The authors should consider how the study by Davies and Glasser (2012) could be built upon or extended and should focus on novel and new findings. Areas that this could cover could include ELA and mass-balance estimates of the glaciers (subject to the provisos below), analysis of ELA change, debris cover, accumulation area ratio change or structural glaciology, or further analysis of precipitation and temperature records. Alternatively, the authors could draw out changes in the glaciers prior to the 1980s (the Davies and Glasser 2012 paper averages change from 1870-1986 for the SPI), perhaps focussing on change from the 1940s onwards, using satellite images or published maps (e.g., Gordon et al., 2008; Berthier et al., 2010). This would highlight interesting glacier dynamical behaviour over a decadal timescale. However, this is all subject to the authors being able to address the methodological comments below, and the gathering of additional data.

We are aware that all of these things require substantial amounts of work, but the paper is not suitable for publication without substantial additional original data, analysis and discussion.

RESPONSE: Our study was submitted on Nov. 19, 2012, prior to the publication of the paper by Davies and Glasser (2012) in Dec. 2012. We were therefore unaware of it when our paper was submitted, but we have included reference to it now. Our study does not duplicate the Davies and Glasser paper, but rather provides a more comprehensive, independent dataset that builds upon the study by Aniya et al. (1999) by extending observation of area changes from the 1970s to late-2000s. Our paper focuses on determining how glacier areas have changed over three periods of study, analyzes how these changes are distributed across the icefield, and their potential links to climate.

COMMENT: 1.2 Methodological issues The most important methodological difficulty is the analysis of glacier area and glacier area change. All the change rates are given in absolute rates (km2 per year), rather than relative measures.

RESPONSE: We have updated our results to provide both relative and absolute measures in the text, figures and in Tables 2 and 3 for all of our measured glacier changes

COMMENT: Related to the above point is the assessment of annual rates of change. How have the authors accounted for the different lengths of time between inventories, related to the availability of cloud-free satellite images (cf. Abermann et al., 2009)?

RESPONSE: We agree that availability of cloud-free images limits choice of satellite imagery. In this study each of our time periods covered a few years (1976 to 1979, 1984 to 1986, 2000 to 2002, and 2008 to 2010) so that we could include as complete an assessment of the SPI as possible. To determine the amount of area change per time period for each glacier (e.g. 1970s to 1980s), the exact difference in dates between each satellite image pair was used. For example, Lucia Glacier decreased in area by 1.02 km2 between February 25, 1979 and January 14, 1986. To enable the reader to identify the exact date used for each glacier, an 'analysis ID' has been added to Tables 2 and 3 to indicate which satellite image was used for the analysis from Table 1.

COMMENT: The methods used need more clarification. It is difficult upon reading to ascertain exactly how area changes were measured, and whether length changes were measured.

RESPONSE: Lines 16 to 24 explain exactly how measurements were conducted. We have reworded this section to make it clear that area changes were recorded, rather than length changes.

COMMENT: The method for defining the ablation area is not clear. The area change measurements do not apparently conform to GLIMS guidelines, which are also not cited (Kargel et al., 2005; Rau et al., 2005; Raup et al., 2007a; Raup et al., 2007b; Racoviteanu et al., 2009; Raup and Khalsa, 2010). The authors should reference the

GLIMS literature and explain their methodology in more detail, stating why it deviates from established methods.

RESPONSE: Our measurements were completed in a way that best allowed area changes to be calculated between time periods for the SPI. This project was not completed as part of the GLIMS project in the way that Davies and Glasser (2012) was, but we have modified the text to state how our measurements differ from the GLIMS guidelines.

COMMENT: Standard glacier names and IDs are available in the GLIMS database - why were these not used? There is no need to assign new and confusing names or numbers.

RESPONSE: The GLIMS glacier IDs were not included in the original manuscript as we followed the naming conventions of earlier studies, and our paper was submitted prior to the publication of Davies and Glasser (2012). However, the GLIMS IDs have now been added to Table 1 and an explanation has been added to the section describing naming conventions.

COMMENT: How are east-west and north-south gradients accounted for in the analysis of climate data?

RESPONSE: We have omitted our climate analysis from the study.

COMMENT: GLIMS also uses glacier designations (glacieret, valley glacier, etc) to define glaciers, and this may also influence its behaviour. This data is all available within the GLIMS database, but it is not referred to or used.

RESPONSE: With the GLIMS glacier IDs now added to Table 1, the designations for the glacier types can be accessed from the GLIMS website.

COMMENT: The error analysis needs further work. Uncertainty in glacier inventories comes from many sources (Davies et al., 2012), not just from orthorectification and georeferencing of satellite images (cf. Granshaw and Fountain, 2006), but also from human error, slope (Jiskoot et al., 2009) and the quantification of change of debris-covered snouts (Bolch, 2007; Davies and Glasser, 2012). One method of quantifying mapping accuracy is to blind-map the same glacier 5-10 times and assess differences in area mapped (Stokes et al., 2007). In any case, further discussion of the mitigation of these uncertainties is required. How can the authors assess if the observed annual rates of change are significant? Ideally, measurements of change should have uncertainties attached.

RESPONSE: The error analysis section of the paper has been updated and expanded to include a more detailed analysis of potential sources of human error. Blind-mapping was performed five times each on three different glacier sizes (small, medium, and large), for each time period. The highest mean error from this analysis was then used to define whether measured glacier changes were significant. All change values have been updated throughout the paper to exclude shrinkage rates less than the total estimated error.

COMMENT: Finally, the terminology is incorrect. It is difficult to know throughout the manuscript whether length or area changes are being dealt with. Glacier inventories should use "shrinkage" when dealing with glacier area change, as glacier area can change in all regions, including around nunataks in the accumulation zone. For clarity, "recession" should be used only when discussing length changes (Bolch et al., 2010; Davies et al., 2012; Davies and Glasser, 2012).

RESPONSE: Terminology throughout the manuscript has been changed to use the term 'shrinkage' rather than retreat, and the methodology has been updated to clearly state that only area changes were measured. In the background, however, the term retreat is still used when discussing previous studies which used this term.

COMMENT: 1.3 Glacier dynamics and climate change Perhaps one of the most fundamental issues that the authors need to address is the relationship between climate and glaciers. The climate analysis is very brief and does not refer to other regional records

(e.g., Giese et al., 2002; Bown and Rivera, 2007; Aravena and Luckman, 2009), or include important data on precipitation (Bolch, 2007), which may well influence the glaciers on the SPI, where there is a strong east-west precipitation gradient (Masiokas et al., 2008). Furthermore, the authors categorically state in their conclusions that more precipitation is falling as snow, but this is only inferred and implied in the discussion. The authors provide no clear evidence for declining precipitation.

RESPONSE: Previous research on climate (temperature and precipitation) and relationships with glacier changes in southern South American has been incorporated into the background. This includes multiple references recommended in the reviewer's comments.

COMMENT: It is very dangerous to make sweeping statements about glacier response to climate change without establishing clear mass-balance records (Bolch, 2007; Hoelzle et al., 2007) or without taking into account response times (see Bamber and Rivera, 2007; Möller et al., 2007; Oerlemans, 2007; Möller and Schneider, 2008).

Important factors concerning glacier dynamics are not considered. Glacier change is rarely a linear and simplistic response to changing atmospheric conditions, as is implied in this study. Glacier response time is controlled strongly not only by precipitation, but also whether it is calving, floating, or on land; its hypsometry, size, altitude and steepness; and its orientation or aspect, and amount of debris cover (Granshaw and Fountain, 2006; Bolch, 2007; Paul et al., 2007; Gordon et al., 2008; Jiskoot et al., 2009; Paul and Svoboda, 2009; Raper and Braithwaite, 2009; Jiskoot, 2011). Glacier recession directly as a result of changing precipitation and temperature can generally only be inferred from small, land-terminating glaciers (Oerlemans, 2005). Most of the glaciers in this study area are calving, and therefore react non-linearly to climate and are driven primarily by internal factors (Warren and Aniya, 1999; Benn et al., 2007a; Benn et al.,2007b). Glacier recession of calving glaciers can therefore not be simplistically related to changing atmospheric temperatures

The authors should consider showing scatter plots of normalised annual rates of recession versus glacier size, altitude, hypsometry and other variables. Although much of this information is readily available in the GLIMS database or through simple analysis of a DEM (Frey and Paul, 2012), none of these factors are considered in this study, and we strongly recommend analysing as a minimum the effect of calving, size and orientation when investigating recent glacier change. Overall, the analysis of the variation in recession rates across the SPI is only weakly analysed, does not use all the available data, and is not considered acceptably in the manuscript. In general, it is not justifiable to simply and simplistically argue for reduced precipitation and its effects on the glaciers of the SPI without showing this and providing convincing evidence. If more robust evidence is not available, this section should be omitted.

RESPONSE: We acknowledge that understanding the response of glaciers to climate change would ideally include information such as mass balance records, response times and ice dynamics, but the simple fact is that this information isn't available for most of the SPI. To expand upon our original analysis we have now incorporated factors beyond climate into the discussion section, including size, frontal characteristics and dynamics. This provides further insight into primary controls, while bringing in examples from other studies.

COMMENT: 1.4 Summary This study repeats much of what has gone before and does not utilise much of the freely existing available data from GLIMS. Before it is publishable, the authors should highlight and draw out where their work is original and new, and consider undertaking new and original data collection and analysis.

RESPONSE: It is unfortunate that the submission of our paper and publication of the Davies and Glasser (2012) paper occurred almost simultaneously, but without knowledge of each other's work. We believe that our study is valuable as it provides an independent analysis of recent glacier changes across the SPI, expands on the work of Davies and Glasser (2012) to include changes since the 1970s, and uses glacier outlines which are generally more detailed than those available in the GLIMS database.

COMMENT: The authors should also use relative area change to compare different glaciers of different sizes in different areas, and they should consider in detail the causes of asynchronicity and variance in glacier behaviour. They should investigate the influence of basic topographic factors, such as glacier size and terminal environment (calving or not) at the very least, in order to better understand glacier recession across the Southern Patagonian Icefield.

RESPONSE: As described above, we now provide both relative and absolute values for our measured glacier changes, and have expanded our analysis to include factors such as size and calving to understand the causes of the observed changes.

COMMENT: The manuscript fails to cite numerous key papers on the glaciation of the SPI and on general Patagonian climate as well as glacier inventory methods. We have included a list of numerous references below, which should be considered for citation. We are aware that our comments suggest that the authors undertake a substantial amount of work and reanalysis of the data, but we hope that ultimately this will result in a more robust, interesting and novel publication.

RESPONSE: We appreciate the extra references suggested by this and the other reviewers, and have now incorporated many of these into the text.

SPECIFIC COMMENTS: Below we have highlighted some further specific suggestions: P3 L23: What is a 'highest' advance?

RESPONSE: Text changed to: 'greatest advance'.

P4 L3-4: define abbreviations

RESPONSE: Abbreviations have been defined.

P5 L4: an inventory of the SPI has been completed (Davies and Glasser, 2012)

RESPONSE: Reference has been added.

P5 L15-20: Clarify. Were length changes measured? This section is confusing. P7:

again methods are confusing; clarify. Was length or area measured?

RESPONSE: Text updated to state that area changes were measured.

P6 L3: Give GLIMS weblink and abbreviation, and cite key GLIMS papers (see references below)

RESPONSE: Changes accepted and applied.

P6 L24: How was the ablation area defined? Explain in more detail the measurements across the ablation area and why this varies from standard GLIMS procedures. Why were existing GLIMS outlines not used?

RESPONSE: The GLIMS Analysis Tutorial (Raup and Khalsa, 2010) has been referenced in this section and a comparison has been made between the GLIMS method and the method used in this study.

P7 L25: Why not use existing glacier names in GLIMS? There is no need to introduce new and confusing glacier names/numbers.

RESPONSE: Tables have been updated to include the IDs established in the GLIMS database.

P8. How do you quantify human interpretation errors? This needs discussion at least.

RESPONSE: Section on blind mapping for quantifying human interpretation errors has been added.

P9 L1. How about also using/discussing longitudinal surface structures (Glasser and Gudmundsson, 2012)?

RESPONSE: This terminology has replaced flow lines in the paper and the Glasser and Gudmundsson (2012) paper has been referenced.

P10 L1: Be clear. Recession - change in glacier length. Shrinkage - change in glacier area.

RESPONSE: Wording has been updated to use shrinkage in relation to changes in glacier area

P10 L14. Glaciers are all of different sizes. To compare rates of shrinkage for glaciers of different sizes, use

RESPONSE: Tables 2 and 3 now include relative measures.

P10. L15: Is this change significant? Difficult to assess without knowing more about the uncertainty.

RESPONSE: The updated uncertainty/error section provides information about whether the observed changes are significant.

P11 L1. Are these differences related to size?

RESPONSE: Changes have been made throughout the document to represent glacier changes in both absolute and relative values. Relative values are now used when comparing changes between glaciers.

P12 L3. How is this difference defined? Why is it based on square blocks rather than on the ice divide? There are large differences in size, precipitation, aspect, steepness, etc, on either side of the ice divide, which is not discussed.

RESPONSE: The blocks are defined to match the cell extents used for the climate reanalysis, and are closely aligned to the east/west drainage divide along the centre of the icefield (Fig.1). Our discussion is also now expanded to include consideration of factors such as glacier size in accounting for measured area change rates.

P13. Discussion is very descriptive and needs more analysis and depth. Results from this work need to be better integrated with previous analyses. The structure is confused and unclear. There is no detailed analysis on the impact of climate / temperature on glaciers; that which exists is very vague.

RESPONSE: To improve clarity, the discussion has been reworded and restructured, and new subheadings have been added to help organize the text.

P14 L11: citation needed for surging looped moraines.

RESPONSE: Citation added: Meier and Post, 1969.

P14 L25. It is very difficult to attribute glacier change to warming directly without detailed mass balance studies, analysis of precipitation or response times, particularly when one is discussing calving glaciers.

RESPONSE: See responses above – we have now expanded our discussion of the causes of glacier changes to include factors such as calving and glacier size

P15 L2: Declining snow precipitation is not rigorously documented in this study; this is better omitted.

RESPONSE: The statement made regarding the snow precipitation has been omitted.

P16 L2: Compare with Davies and Glasser's (2012) and Glasser et al.'s (2011) study of the NPI and SPI

RESPONSE: These papers have now been referenced and discussed in the text

P16 L9: "97 RESPONSE: This value has been changed to reflect the new results.

P17 L1. "reduction in the proportion of total precipitation falling as snow". There is no evidence for this in this study. Remove or substantiate.

RESPONSE: This has been omitted.

P18 L21: What is the status of this paper now?

RESPONSE: The status of this paper has not yet changed.

Table 1: How do you account for the different length of time between analyses when calculating annual recession rates? RESPONSE: To calculate recession rates we use the exact acquisition dates of the image pairs being analyzed for a given glacier (this

information is now provided in the 'Analysis ID' column in Tables 2 and 3), and then normalize the time between them to an annual value.

There are not GCPs associated with every image. How does this affect overall error assessment? It is more where there are no GCPs? On steeper ground?

RESPONSE: As described in Section 2.2, we did not use GCPs to correct images if they were already well aligned (within one pixel) with the master mosaic from 14 January 1985. Our error assessment is based on an alignment within one pixel, so the lack of GCPs for some images is already taken into account. As discussed in the text it is quite possible that errors were higher on steeper terrain, but this would have little impact on our results as we only analyzed the generally flatter ablation areas of glaciers.

Table 2: N/D not applicable.

RESPONSE: Change accepted and applied.

Table 3: Consider showing area change as a Far-reaching conclusions are drawn from 1976-1984 with few data points.

RESPONSE: We provide all available area change measurements from 1976-1984 in Tables 2 and 3 (in both absolute and relative terms), but as discussed in the text the dataset is not complete due to the lack of imagery from the 1970s. However, data is still available from the majority of SPI basins over this period (>75% of total), so we believe that it's reasonable to make conclusions based on this sample.

Figure 1: Too small, cannot read. Simplify.

RESPONSE: We have found this figure to be the best way to show the location of each individual glacier, and have worked to make it as clear as possible. In addition the coordinates for every glacier are provided in Tables 2 & 3.

Figure 2: Is East or West changing more? Why?

RESPONSE: The results section has been updated to explain the difference between changes in the east and west. Explanations for these differences are included in the discussion with regards to climate.

Figure 4: A prime example of how glacier dynamics can influence recession rates. Perito Moreno Glacier is strongly influenced by grounding against land on the far side of the lake (Stuefer et al., 2007)

RESPONSE: We have now expanded our text and list of references to improve discussion of calving dynamics as a control on glacier recession patterns.

Figure 6: Is this a graph of aspect / orientation or location? Unclear. Putting the years on the individual graphs would make it a lot easier to read.

RESPONSE: This is a graph showing shrinkage rates by location on the icefield (north, south, east and west). Clarification regarding graph contents has been added to the figure caption, and the years for each graph are now shown directly on the figure.

Figure 7: It is clear from this figure that larger glaciers have lost more absolute area, but this is not surprising.

RESPONSE: This figure has now been updated to include parts (a) and (b) to show both absolute and relative area changes.

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