“Frontal ablation and temporal variations in surface velocity of Livingston Island ice cap, Antarctica” by B. Osmanoglu et al. (tcd-2013-0117)

AUTHORS’ ANSWERS TO REVIEWERS

Introductory comment by authors

We first thank the reviewers for their many suggestions to improve the quality of the manuscript. Thanks to them, we have been able to generate a much improved version of the original manuscript.

In brief, the main concerns raised by the reviewers were: 1) the large uncertainty of our results, mostly attributed, by them, to the scarcity of field measurements on ice thickness and mass balance, as well as the uncertainties in the DEM used; 2) the associated need to improve or complete the error analysis, adding also a sensitivity analysis; and 3) the need to emphasise the wider significance of the study, making clear its relevance to the glaciers in the Antarctic Peninsula region.

We essentially agree in that the uncertainties involved in our estimates are large, as was clearly acknowledged in the original ms. These uncertainties, which were already analyzed and quantified in the earlier version, have now been much improved following the lines suggested by the reviewers. As we feel confident that the uncertainties are properly quantified, we firmly believe that it is important to make available to the scientific community our frontal ablation estimates, even if their error bars are rather large. The reason is that there is an urgent need to better quantify the dynamic mass losses, because they provide a mechanism for glaciers to lose mass much more rapidly than is possible through other means. We note that all global/regional-scale *projections* of glaciers outside the ice sheets, including those in IPCC2013, completely ignore mass loss by calving due to the inherent difficulty to model calving and also due to the extraordinary lack of data on the magnitude of calving of these glaciers and ice caps outside the ice sheets, particularly for those in the Antarctic periphery. Since the latter is the regional focus of our study, our paper contributes to fill a gap in the data on the partitioning of total mass loss of glaciers and ice caps into its main components (surface mass balance and frontal ablation), a knowledge which is urgently needed to derive suitable models for frontal ablation on larger scales and also to calibrate/validate these models.

We have also tried to emphasize that the field measurements on ice thickness and mass balance available for Livingston Island are not so scarce, to the point that they are, in many aspects (in particular, surface mass balance) the most complete ones available in the region.

In our effort to better quantify errors and their implications, we have improved the error analysis, completed the discussion of assumptions, and added a complete sensitivity analysis to model parameters and input data (including a new figure). There was a reviewer’s suggestion, for the sake of homogeneity and aiming to reduce the DEM errors, to substitute our combined (multi-source) DEM by a single better quality DEM covering the whole island. We followed this suggestion, but it resulted in a worsening of the misfit between model and observations, so we finally kept our combined DEM. Even so, we have included, for comparison, the results obtained when the single best quality DEM is used.

Regarding the significance of our study, we have fully rewritten the introduction, stressing why the quantification of frontal ablation from glaciers and ice caps is important and why it is especially important for this particular region. To emphasize the relevance of this study in the context of the glaciers and ice caps in the periphery of the Antarctic Peninsula, we have also made many additions to the “Study area” section.

In what follows, we give a detailed point-by-point answer to the reviewer’s comments and suggestions, using

- *blue italics, for the original comments by reviewers,*
- black normal text, for author’s answers/comments.

Anonymous Referee #1

The manuscript reports on the estimation of mass balance for an extensively ice covered island in the Antarctic Peninsula region, based mainly on information derived from observations by various Earth observation satellites, complemented by in situ measurements for limited areas. Considering the poor knowledge on mass balance of glaciers in the Antarctic periphery, it is certainly a valid goal trying to reduce this uncertainty. Unfortunately the available data base is rather inadequate for deriving accurate mass balance numbers for the ice body of Livingston Island, so that the impact of the work regarding uncertainties in mass balance of the Antarctic Peninsula region is rather limited.

Comments/answer by authors:

We first note that the areas in Livingston Island where in-situ measurements are available are not so limited. In fact, this is one of the few ice caps in the Antarctic periphery with multi-year in-situ observations. Detailed observations on mass balance, ice thickness, surface velocities and meteorological variables are available for Hurd Peninsula, and GPR ice-thickness measurements, critical to this paper, are available over many areas of the island. See more detail below, in the answer to item (i) by the reviewer.

Concerning the available data set allowing to derive mass balance numbers for the whole Livingston Island, we note that the available set of mass balance measurements on Hurd Peninsula is a very detailed (with about 50 stakes over a 10 km^2 area) and quite long-lasting (12 years) one. Moreover, Johnsons and Hurd glaciers are, at present, together with Glaciar Bahía del Diablo, on Vega Island, the only in-situ mass balance programs currently running (both of them for over 12 years) in the Antarctic Peninsula region. Additionally, the fact that Hurd Glacier terminates on land, while Johnsons is a tidewater glacier, provides an added value, since both types of glaciers have different dynamical regimes and characteristic mass balance distributions. Thereby, this mass balance data set is the best available data source in the region for mass balance studies.

There are three issues regarding the data base that significantly increase the uncertainty of the mass balance estimates:

(i) *A main deficiency is the lack of ice thickness data. Frontal ablation (primarily due to iceberg calving) is a main component of the mass balance of the island's glaciers. The authors infer the sliding parameter and flow law enhancement factor for the relation between surface velocity and ice thickness by deducing these parameters from available thickness data. The validity of this approach is questionable, as ice thickness data are available only for a very small part of Livingston Island. Accurate information on ice thickness at flux gates is essential to obtain good estimates for calving fluxes. Close to glacier fronts ice thickness fields are only available for the small Johnsons and Hurd glaciers which contribute very little to the island's frontal mass export (0.4 Mt/yr out of 509 Mt/yr for the whole island). It is questionable if the ice flow parameters determined for these glaciers are transferable to those glaciers which dominate the calving fluxes for Livingston Island and have much larger flux gates and coastlines. Even for the area where measured ice thickness data are available, the uncertainty of estimated ice thickness is high (Fig. 4), although the sliding and flow law enhancement parameters (Eq. 4) have been adjusted with this data set. For medium and fast moving glacier regions there is no obvious correlation between estimated and GPR-measured ice thickness, and for slow velocities the data points are widely scattered.*

Comments/answer by authors:

Regarding the reviewer's concern about the availability of ice-thickness data for tuning the model parameters (sliding parameter and flow law enhancement factor), we note that these data, though not abundant, are not scarce. They cover the entire Hurd Peninsula, a large portion of Bowles Plateau and the main ice divides of the island.

In particular, concerning the availability of ice-thickness data near the calving fronts, the data are not just limited to Johnsons Glacier, but the GPR profiles in the western part of the island have also several branches approaching the calving fronts. Moreover, the different flow regimes (mostly related to proximity to the calving fronts) are taken into account in our tuning of the model parameters through the separation in fast/medium/slow flow regions, which resulted in halving the RMS misfit between modelled and observed ice thickness as compared with the case where a single island-wide fit of the model parameters was done.

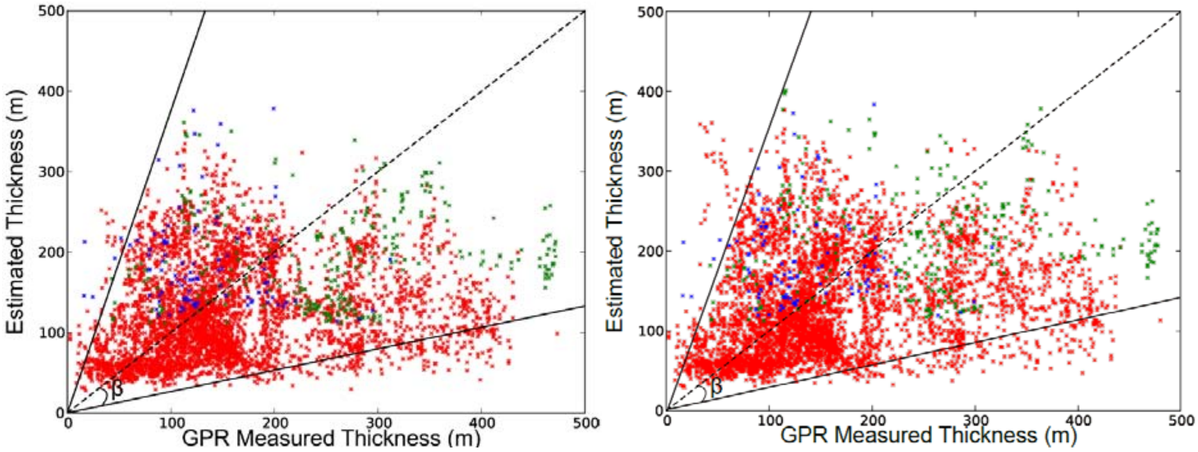
(ii) *The uncertainties of the DEMs used for the analysis of mass balance, ice flow, etc. are very high, as deduced by comparison with ICESat data (RMSEs between 125 m and 368 m, depending on the DEM). Slope errors due to inaccuracies of DEMs propagate into ice thickness estimates. Merging the different DEM data sets is not a convincing strategy, as 3 of the DEM the data sets cover only part of the island. For sake of homogeneity it would be better to use the one of the better quality DEM (e.g. sharpened RAMP) which covers the whole island. Regarding the unusually high RMSE values for the various DEMs vs. ICESat, the procedures used for error assessment should be reported.*

Comments/answer by authors:

First, please note that, as already indicated in the fist submitted version of the paper, the large RMSs for the misfits with ICESat data are not only due to the largest uncertainties of the data from certain sensors but mostly associated to the small number of overlapping points between ICESat and those sensors, so that the DEMs with the lowest number of overlaps show the largest RMSEs. We have tried to make this more explicit in the revised version of the text.

Second, we remark that the purpose of the combination of DEMs was to improve the quality of the final combined DEM, by increasing the data coverage while not degrading the accuracy of the retrieved ice thickness (i.e. not worsening the RMS misfit between computed and observed thickness).

Nevertheless, we followed the suggestion by the reviewer and repeated all computations using only the best quality/larger coverage DEM (sharpened RAMP). This resulted in a slight worsening of the results: the RMSE for ice thickness changed from 103.44 m (our combined DEM) to 108.65 m, without any improvement in the data scatter (we include below the data scatter for both cases). Moreover, the standard deviation of errors of the combined DEM relative to ICESat measurements, of 121 m, is lower than that of the sharpened RAMP DEM (146 m).



Combined DEM   Sharpened RAMP

In general, the ice thickness for both DEMs, and the associated frontal ablations, are quite similar (see figures for ice thickness and table of results for both cases below), with the exception of basin 2 (due to ICESat contributions) and, to a lesser extent, at the north-east of the island (due to TanDEM-X contributions), where these contributions helped to improve the results. Consequently, we have decided to adhere to the original combined DEM, which is the one providing the best results, though we have included a comment on these tests in the new version of the paper. In particular, we have included the following paragraphs/sentences:

In *Data-Digital elevation model* subsection:

> "Given the large RMS misfits between some of the individual DEMs and ICESat data, and for the sake of homogeneity, we wondered whether it would be better to use one of the better quality DEMs covering the entire island, in particular, sharpened RAMP. This, however, resulted in a slight worsening (by 5%) of the RMS misfits between the computed and observed ice thickness. Moreover, the standard deviation of errors relative to ICESat measurements, of 121 m, is lower than that of the sharpened RAMP DEM (146 m). Consequently, we decided to adhere to our combined DEM. Nevertheless, we also did all computations for the Sharpened RAMP DEM, resulting small changes in the results for total frontal ablation, as will be discussed later."

In *Methods-Error analysis* subsection:

> "If the sharpened RAMP DEM is used instead of the combined DEM, this misfit increases to 109 m, without any improvement in the data scatter, confirming that our combined DEM is the best choice."

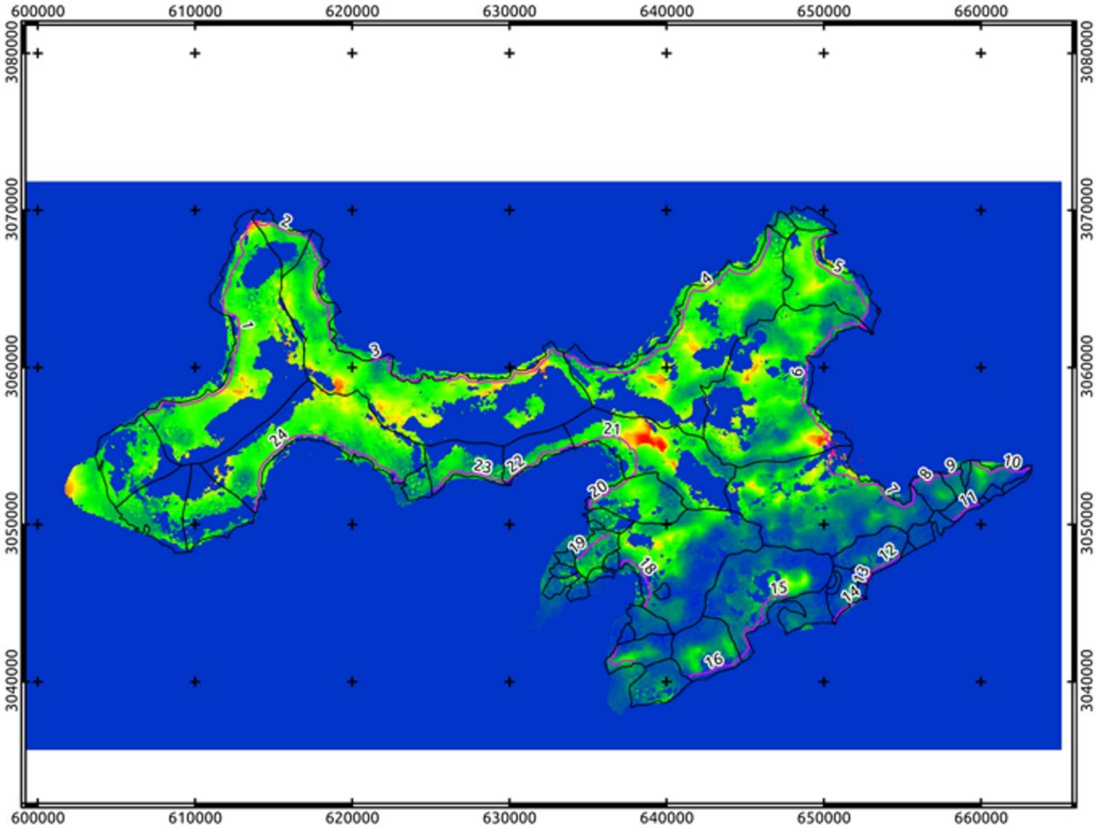
In *Results-Ice thickness* subsection:

> "The ice thickness values obtained using our combined DEM and the sharpened RAMP DEM are very similar, with the exception of basin 2 (due to ICESat contributions) and, to a lesser extent, at the North-East of the island (due to TanDEM-X contributions), where these contributions helped to improve the results obtained using the combined DEM."

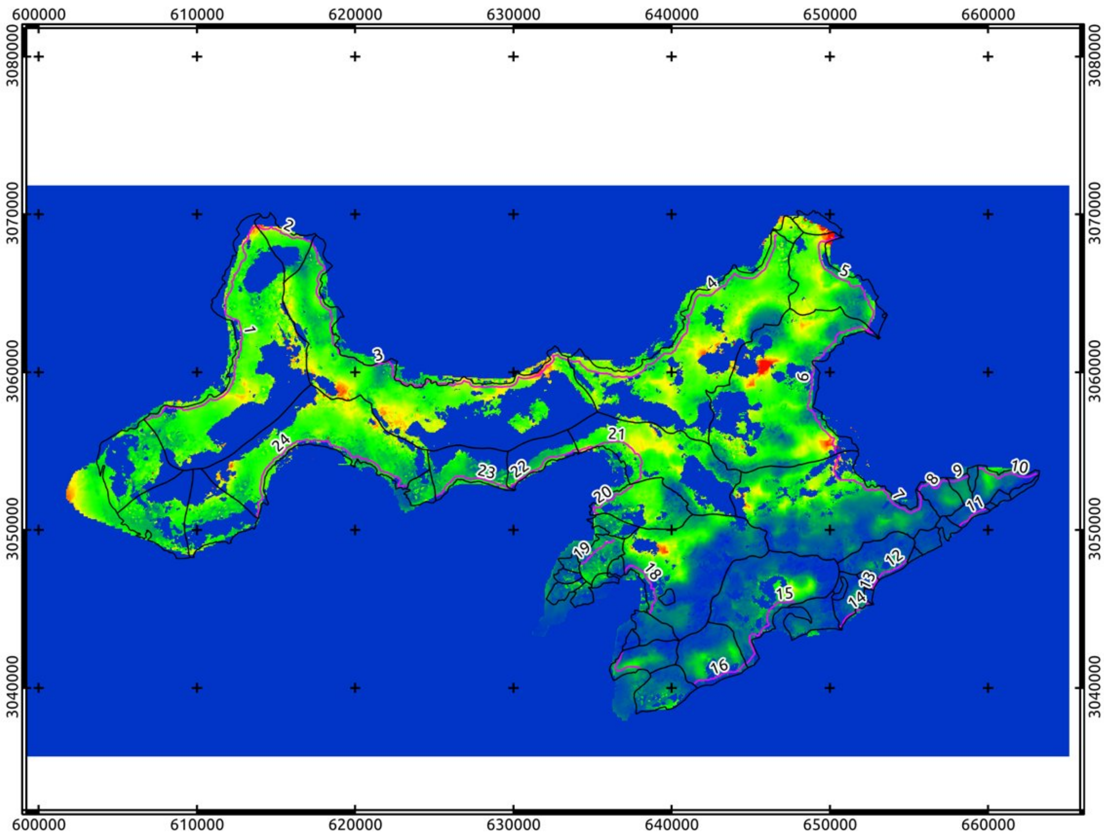
In *Results-Frontal ablation* subsection:

> "If the sharpened RAMP DEM is used instead of the combined DEM, the resulting total frontal ablation (521±374 Mt yr^{-1}) and its temporal variations (234 Mt yr^{-1}) are very similar to those obtained using the combined DEM, with local differences between the results for both DEMs at the same basins as discussed for the ice thickness."

Finally, regarding the suggestion by the reviewer that *"the procedures used for error assessment should be reported"*, this has been done at the end of subsection Data-Digital elevation model, where new explanatory text, and a new equation (current Eq. 2), have been introduced.



Ice-thickness map for the combined DEM



Ice-thickness map for the Sharpened RAMP-only DEM

Table 2. Estimated frontal ablation rates for the period between October 2007 and January 2011, basin area, and average thickness and length of the flux-gates of all investigated tidewater glaciers on Livingston Island. σ_{vel} are the standard deviations of the computed temporal variations in velocities averaged over the flux gates and ΔD_{seas} are their associated changes in frontal ablation. Frontal ablation rates are given in $\mathrm{Mt\,yr^{-1}}$ and in specific units ($\mathrm{m\,w.e.\,yr^{-1}}$).

Basin	Frontal ablation			Area		Avg. thick.	Length	$\mathrm{Avg_{vel}} \pm \sigma_{vel}$		ΔD_{seas}	
	$\mathrm{Mt\,yr^{-1}}$	$\mathrm{m\,w.e.\,yr^{-1}}$	%	$\mathrm{km^{-2}}$	%	m	km	$\mathrm{m\,yr^{-1}}$	%	$\mathrm{Mt\,yr^{-1}}$	$\mathrm{m\,w.e.\,yr^{-1}}$
1	42.7 ± 31.3	0.61 ± 0.45	8.4	69.6	11.6	180.3	16.8	28.7 ± 10.2	35.5	25	0.4
2	5.3 ± 3.9	0.80 ± 0.59	1.0	6.7	1.1	126.6	3.7	15.5 ± 7.8	50.3	3	0.4
3	69.8 ± 51.2	0.85 ± 0.62	13.7	82.1	13.7	172.2	22.7	24.1 ± 13.5	56.0	42.9	0.5
4	58.8 ± 43.2	0.86 ± 0.63	11.6	68.3	11.4	152.5	18.1	26.2 ± 11	42.0	24.6	0.4
5	18.8 ± 13.8	0.93 ± 0.68	3.7	20.3	3.4	153.8	7.7	26.7 ± 16.5	61.8	15.9	0.8
6 (Kaliakra)	53.1 ± 39.0	0.83 ± 0.61	10.4	64.3	10.7	166.7	10.6	36.6 ± 20.8	56.8	29.7	0.5
7 (Huron)	145.4 ± 114.1	2.69 ± 2.11	28.6	54.1	9	100.4	7.2	30.1 ± 19.2	63.8	11.2	0.2
8	0.7 ± 0.5	0.15 ± 0.11	0.1	4.4	0.7	64.8	2.1	23.1 ± 15.4	66.7	1.7	0.4
9	1.3 ± 0.9	0.74 ± 0.54	0.3	1.7	0.3	64.5	1.2	22.8 ± 17.1	75.0	1.1	0.6
10	4.8 ± 3.5	0.90 ± 0.66	0.9	5.3	0.9	120.7	3.8	28.6 ± 14.9	52.1	5.5	1.0
11 (Strandzha)	1.8 ± 1.3	0.82 ± 0.60	0.3	2.2	0.4	54.1	2.1	22.9 ± 14.3	62.4	1.3	0.6
12 (Dobrudzha)	4.1 ± 3.0	0.48 ± 0.35	0.8	8.7	1.5	84.8	2.8	32.5 ± 19.6	60.4	3.8	0.4
13 (Magura)	0.4 ± 0.3	0.37 ± 0.28	0.1	1.1	0.2	52.4	1	24.1 ± 14	58.1	0.6	0.6
14 (Srebarna)	4.8 ± 3.5	1.07 ± 0.78	0.9	4.4	0.7	74.2	2.3	45.4 ± 22.7	50.0	3.1	0.7
15 (Macy)	2.4 ± 1.8	0.08 ± 0.06	0.5	30.1	5	70.6	3.4	25.5 ± 17.2	67.5	3.4	0.1
16 (Prespa)	8.7 ± 6.4	0.68 ± 0.50	1.7	12.7	2.1	81.9	3.5	32.1 ± 23.3	72.6	5.4	0.4
17 (Charity)	1.0 ± 0.7	0.15 ± 0.11	0.2	6.6	1.1	95.2	3.1	23.5 ± 14.5	61.7	3.4	0.5
18 (Huntress)	15.2 ± 11.2	0.37 ± 0.27	3.0	40.8	6.8	108.1	4.3	24.3 ± 15	61.7	5.7	0.1
19 (Johnsons)	0.4 ± 0.3	0.07 ± 0.05	0.1	5.3	0.9	120.5	2.1	11.2 ± 8.7	77.7	1.8	0.3
20	2.6 ± 1.9	0.20 ± 0.15	0.5	13.2	2.2	141.4	3	25.3 ± 10.9	43.1	3.8	0.3
21 (Perunika)	23.8 ± 17.5	0.71 ± 0.52	4.7	33.7	5.6	168.9	6.2	36.3 ± 18	49.6	15.3	0.5
22	10.0 ± 7.3	1.21 ± 0.89	2.0	8.3	1.4	131.9	5	18.8 ± 9.3	49.5	4.9	0.6
23	6.9 ± 5.1	0.58 ± 0.43	1.4	11.8	2	120.1	4.8	22.3 ± 10.5	47.1	4.9	0.4
24	26.1 ± 19.2	0.60 ± 0.44	5.1	43.7	7.3	152.2	13.8	22.4 ± 11	49.1	18.8	0.4
Total	508.9 ± 380.9	0.85 ± 0.64	100	599.4	100					236.8	0.4
Entire ice cap		0.73 ± 0.55		697.3							0.3

Table 3. Estimated frontal ablation rates for the period between October 2007 and January 2011, basin area, and average thickness and length of the flux-gates of all investigated tidewater glaciers on Livingston Island, using only the sharpened RAMP DEM. σ_{vel} are the standard deviations of the computed temporal variations in velocities averaged over the flux gates and ΔD_{seas} are their associated changes in frontal ablation. Frontal ablation rates are given in $\mathrm{Mt\,yr^{-1}}$ and in specific units ($\mathrm{m\,w.e.\,yr^{-1}}$).

Basin	Frontal ablation			Area		Avg. thick.	Length	$\mathrm{Avg_{vel}} \pm \sigma_{vel}$		ΔD_{seas}	
	$\mathrm{Mt\,yr^{-1}}$	$\mathrm{m\,w.e.\,yr^{-1}}$	%	$\mathrm{km^{-2}}$	%	m	km	$\mathrm{m\,yr^{-1}}$	%	$\mathrm{Mt\,yr^{-1}}$	$\mathrm{m\,w.e.\,yr^{-1}}$
1	42.7 ± 30.7	0.61 ± 0.44	8.0	69.6	11.6	183.9	16.8	28.7 ± 10.2	35.5	25.5	0.4
2	6.5 ± 4.7	0.97 ± 0.70	1.2	6.7	1.1	201.5	3.7	15.5 ± 7.8	50.3	4.7	0.7
3	73.9 ± 53.1	0.90 ± 0.65	13.8	82.1	13.7	179.8	22.7	24.1 ± 13.5	56.0	44.8	0.5
4	65.7 ± 47.2	0.96 ± 0.69	12.3	68.3	11.4	169.0	18.1	26.2 ± 11	42.0	27.3	0.4
5	19.7 ± 14.2	0.97 ± 0.70	3.7	20.3	3.4	156.0	7.7	26.7 ± 16.5	61.8	16.2	0.8
6 (Kaliakra)	48.1 ± 34.6	0.75 ± 0.54	9.0	64.3	10.7	151.7	10.6	36.6 ± 20.8	56.8	27	0.4
7 (Huron)	164.5 ± 118.2	3.04 ± 2.18	30.7	54.1	9	98.2	7.2	30.1 ± 19.2	63.8	10.9	0.2
8	0.5 ± 0.4	0.12 ± 0.08	0.1	4.4	0.7	66.6	2.1	23.1 ± 15.4	66.7	1.7	0.4
9	1.3 ± 1.0	0.77 ± 0.55	0.2	1.7	0.3	68.9	1.2	22.8 ± 17.1	75.0	1.2	0.7
10	4.4 ± 3.2	0.83 ± 0.60	0.8	5.3	0.9	109.7	3.8	28.6 ± 14.9	52.1	5	0.9
11 (Strandzha)	1.9 ± 1.4	0.85 ± 0.61	0.4	2.2	0.4	56.4	2.1	22.9 ± 14.3	62.4	1.4	0.6
12 (Dobrudzha)	4.2 ± 3.0	0.49 ± 0.35	0.8	8.7	1.5	79.4	2.8	32.5 ± 19.6	60.4	3.6	0.4
13 (Magura)	0.2 ± 0.1	0.18 ± 0.13	0.1	1.1	0.2	53.3	1	24.1 ± 14	58.1	0.6	0.6
14 (Srebarna)	4.4 ± 3.1	0.98 ± 0.70	0.8	4.4	0.7	71.4	2.3	45.4 ± 22.7	50.0	3	0.7
15 (Macy)	2.6 ± 1.8	0.09 ± 0.06	0.5	30.1	5	73.5	3.4	25.5 ± 17.2	67.5	3.5	0.1
16 (Prespa)	9.5 ± 6.8	0.75 ± 0.54	1.8	12.7	2.1	82.5	3.5	32.1 ± 23.3	72.6	5.5	0.4
17 (Charity)	1.0 ± 0.7	0.15 ± 0.11	0.2	6.6	1.1	96.4	3.1	23.5 ± 14.5	61.7	3.5	0.5
18 (Huntress)	13.5 ± 9.7	0.33 ± 0.24	2.5	40.8	6.8	98.3	4.3	24.3 ± 15	61.7	5.1	0.1
19 (Johnsons)	0.3 ± 0.3	0.06 ± 0.05	0.1	5.3	0.9	117.3	2.1	11.2 ± 8.7	77.7	1.7	0.3
20	3.5 ± 2.5	0.27 ± 0.19	0.6	13.2	2.2	141.0	3	25.3 ± 10.9	43.1	3.8	0.3
21 (Perunika)	24.7 ± 17.7	0.73 ± 0.53	4.6	33.7	5.6	173.3	6.2	36.3 ± 18	49.6	15.7	0.5
22	9.2 ± 6.6	1.11 ± 0.80	1.7	8.3	1.4	137.0	5	18.8 ± 9.3	49.5	5.1	0.6
23	6.1 ± 4.4	0.51 ± 0.37	1.1	11.8	2	121.0	4.8	22.3 ± 10.5	47.1	4.9	0.4
24	27.2 ± 19.6	0.62 ± 0.45	5.0	43.7	7.3	156.1	13.8	22.4 ± 11	49.1	19.2	0.4
Total	520.7 ± 374.3	0.87 ± 0.62	100	599.4	100					234.3	0.4
Entire ice cap		0.75 ± 0.54		697.3							0.3

(iii) *The uncertainties of the retrieved velocities need to be properly assessed and specified for the different data sets. Significant variations in relative accuracy are to be expected, depending on sensor resolution, time span of an image pair, stability of features, and magnitude of ice velocity. The velocity data in Figure 6 show an overall trend for higher velocities in summer (to be expected for this glacier type), but the data seem to be quite noisy so that only for few of the glaciers the seasonal trends are statistically significant. In order to learn about the reliability of the velocities, error bars should be provided for the individual velocity data in Fig. 6. In addition, it would be of interest to relate the temporal variations to the mean velocities for each of the glaciers.*

Comments/answer by authors:

The uncertainties of the PALSAR-retrieved velocities are discussed in the subsection Methods-Surface velocities. The temporal baseline for each velocity measurement is indicated by the corresponding horizontal error bar in Figure 7 (formerly Figure 6). Vertical error bars quantifying the errors in velocity for the individual measurements have been added to Figure 7. The temporal variations of velocity have been related to the mean velocity of each basin by introducing a new column in Table 1 (now Table 2); in addition to adding the standard deviations of the computed temporal variations, we have indicated the percentage of the latter over the average velocity for each basin. Additionally, we have included in Table 2 the percentage of each basin's frontal ablation over the total ablation of the ice cap.

The new version of Figure 7 follows

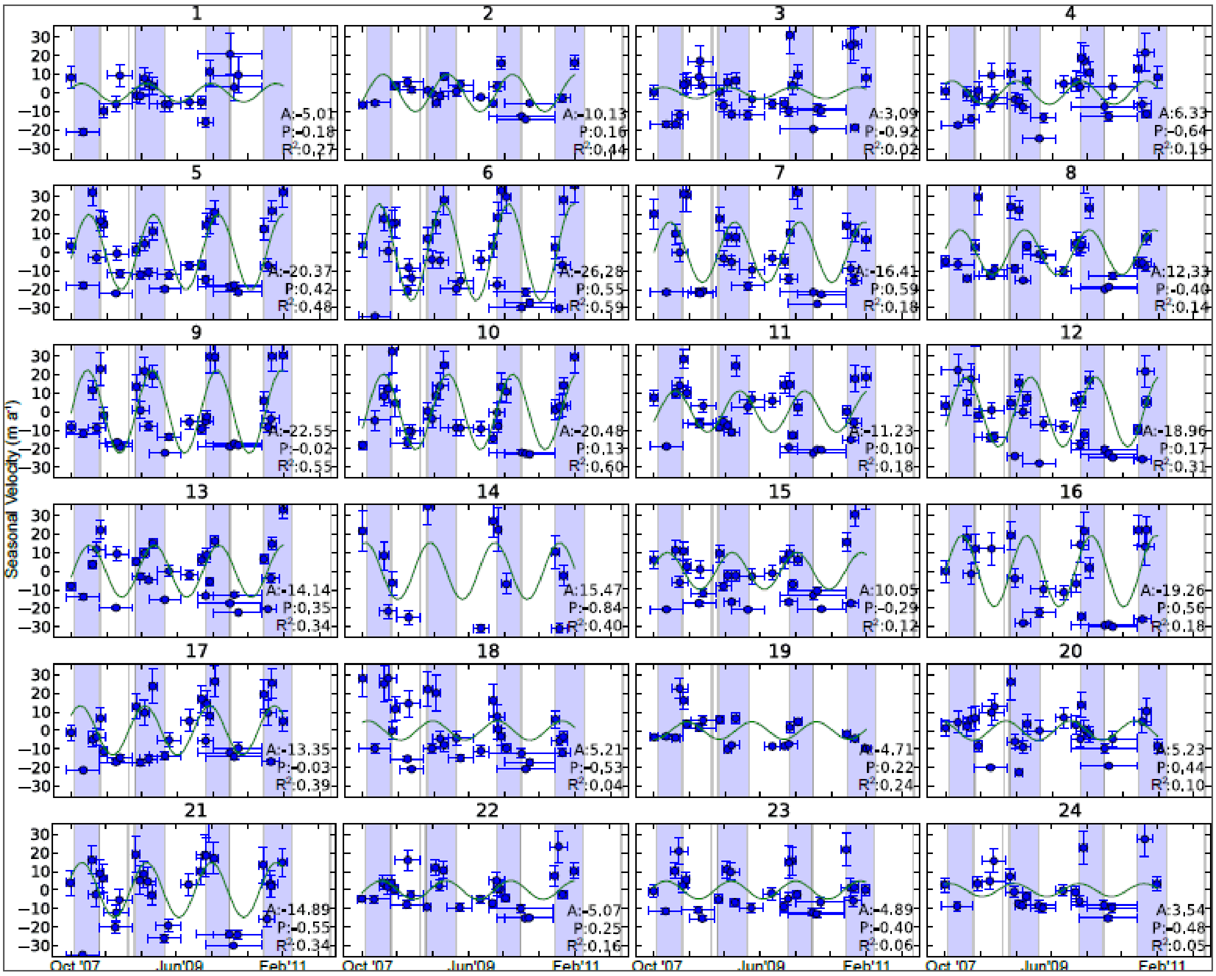


Figure 5, maps of surface velocity and ice thickness. The selected colour scale provides very little discrimination for the majority of the glacier area, being dominated by low values. (may possibly use a logarithmic scale).

Comments/answer by authors:

We tried different colour scales and scalings (including logarithmic, as suggested) to better discriminate velocity and thickness values, in particular for areas of fast flow. However, this did not lead to real improvements and hence we preferred to maintain a linear scaling, as this seems most adequate to us.

Anonymous Referee #2

General points:

In this paper, the authors estimate ice frontal ablation of the ~700km2 glaciated portion of Livingstone Island, situated off the north west tip of the Antarctic Peninsula, a study area. The authors use a flux-gate approach to estimating total ablation, which estimates ice mass flux from depth-averaged ice flow near the margin from observations of ice velocity. Due to a dearth of ice thickness measurements, flux gate geometry is estimated from the observed velocity field by making various assumptions about the ice flow dynamics. Large uncertainties in the resulting ablation estimates arise from inaccurate flux-gate geometries, which in turn result from assumptions made when estimating depth-averaged velocity from observed velocity and the fact that longitudinal coupling is neglected. Furthermore, the authors point out that there is significant temporal variability in observed ice velocity, which introduces additional uncertainty into both the estimates of ice flow through the flux gate, and the geometry of the flux gate itself. While these various uncertainties are acknowledged, they are not fully explored, which calls into question the robustness of the frontal ablation estimates.

Comments/answer by authors:

See our 'general' comment at the very beginning above

The authors have clearly performed a large amount of analysis, which could be split into 2 or more separate studies. The inclusion of the various strands of analysis in a single study means that the manuscript feels a little disjointed and may benefit from being re-structured.

Comments/answer by authors:

We think that the different strands of analyses directly complement each other and are necessary to reach the best possible understanding of the ice cap's mass changes based on the existing data. Partitioning the total ablation into frontal ablation and surface ablation can only be addressed if, as done in the paper, an estimate of the surface mass balance of the entire ice cap is included in the analysis. In addition, quantifying the temporal variations in velocities, and their associated variations in frontal ablation, is crucial to be aware of the errors that could be incurred if computations of frontal ablation based on measurements for a particular season were extrapolated to a longer period.
We have followed a classical and clear structure with sections of data-methods-results-discussion, each being subdivided into subsections for each of the data sets/variables being analysed. Hence, we have retained the overall structure, but we have tried through some rewording to make the individual parts appear more connected.

The subject area sits firmly within the scope of the TC and will be of interest to the wider scientific community. New data is presented for an under-studied glaciated region, though the wider significance of the study should be emphasised. Uncertainties arising from lack of primary observations prevent substantial conclusions from being made, though these limitations are well discussed. The methods and assumptions are outlined clearly and concisely, though could be elaborated on in some areas. Overall, the paper is well written and figures are clear on the whole, though I recommend a few changes be made.

Comments/answer by authors:

The Introduction section has been fully rewritten to emphasize the wider significance of the study. Several additions to the "Study area" section have also been added with the same purpose. The methods and assumptions have been clarified through many additions detailed later in response to particular suggestions by the reviewer.

The new version of the Introduction follows:

> "According to the recent Fifth Assessment of the Intergovernmental Panel on Climate Change (IPCC, 2013), the mass losses from mountain glaciers and ice caps (henceforth referred to as glaciers) continue to be one of the largest contributors to sea-level rise, with a share of 27% of the sum of the estimated contributions over the period 1993-2010, larger than the combined contribution by the Antarctic and Greenland ice sheets, of 21%. Frontal ablation is an important component of the total ablation of marine-terminating glaciers. By frontal ablation we mean the loss of mass from the near-vertical calving fronts of the marine-terminating glaciers, including losses by calving, subaqueous melting, and subaerial melting and sublimation (Cogley et al., 2011). The recent availability of a nearly-complete world-wide inventory of the world's glaciers (Pfeffer et al., 2014) has revealed that 38% (by area) of them are marine-terminating, and this number increases to 98-99% for those in the Antarctic periphery (Gardner et al., 2013; Bliss et al.,

2013). However, little is known about the magnitude and relative importance of mass loss through frontal ablation at these termini.

Global-scale assessments of mass change of the glaciers outside the ice sheets did not include frontal ablation up to IPCC (2007), which was based on three extrapolations of in-situ surface mass balance measurements combined into a consensus estimate by Kaser et al. (2006). Subsequent estimates, such as those by Cogley (2009, 2012), included geodetic mass-balance measurements (i.e. based on digital elevation model (DEM) differencing), and thus at least partially included frontal ablation. The global-scale estimate by Jacob et al. (2012), based on data from the Gravity Recovery and Climate Experiment (GRACE), included all forms of mass change, and thus frontal ablation. Gardner et al. (2013), which provided the basis for IPCC (2013) estimates, relied to a large degree on GRACE gravity data and ICESat altimetry data, and thus also included frontal ablation for most regions. While the most recent global-scale assessments of mass wastage from glaciers include mass loss by frontal ablation, we emphasize that all global scale mass change projections that exclude the ice sheets, including those considered in IPCC (2013), are based exclusively on surface mass balance, thus disregarding frontal ablation and leading to a systematic underestimation of mass loss (Raper and Braithwaite, 2006; Radić and Hock, 2011; Marzeion et al., 2012; Slangen et al., 2012; Giesen and Oerlemans, 2013; Radić et al., 2013). This is due to the inherent difficulty of assessing and modelling of calving (Benn et al., 2007b,a; Amundson and Truffer, 2010; Otero et al., 2010; Bassis, 2011; Vieli and Nick, 2011) and submarine melt (Motyka et al., 2003; Enderlin and Howat, 2013; Bartholomaus et al., 2013). While mass loss through surface melting is reasonably well understood (Hock, 2005), the processes involved in frontal ablation are largely non-linear and operate on time scales that are not necessarily linked to regional climate variations (Truffer and Fahnestock, 2007). There is a need to better quantify the dynamic mass losses because they provide a mechanism for glaciers to lose mass much more rapidly than is possible through other means.

Data regarding the partitioning of total glacier mass loss into its main components (surface mass balance and frontal ablation) are very scarce, but are needed to derive suitable models for frontal ablation on larger scales and also to calibrate/validate these models. A few studies on marine-terminating ice caps in the Arctic show that frontal ablation might account for roughly 30-40% of the total ablation (Dowdeswell et al., 2002, 2008). Other studies in the Arctic region have also calculated the frontal ablation, but have presented their results as a percentage of the net losses. For instance, Burgess et al. (2005) compared the total volume of ice lost due to calving with the total (net) mass loss from Devon Ice Cap between 1960 and 1999 estimated by Burgess and Sharp (2004), concluding that iceberg calving may account for up to 30% of the total volume loss over that period. Similarly, Burgess et al. (2013) estimated regional calving losses of 17.1 Gt yr $^{-1}$, over the period 2007-2011, for Central Alaska glaciers, which is equivalent to 36% of the total annual mass change throughout Central Alaska. We emphasize that computing the share of frontal ablation to total ablation (which always is a mass loss) is very different from computing the share with respect to the net mass budget (that can be either gains or losses). The former approach requires that the partitioning of the budget between mass gains and losses is known, as happens with any method of the input-output type. In contrast, geodetic or gravimetric methods do not allow discriminating the components of the mass budget.

The regional focus of the present study is the Antarctic Peninsula region. Shepherd et al. (2012) gave an estimate of the mass budget (1992-2011) for the entire Antarctic Peninsula of -20 ± 14 Gt yr $^{-1}$ excluding glaciers peripheral to the Antarctic Peninsula. They pointed out that “the spatial sampling of mass fluctuations at the Antarctic Peninsula Ice Sheet is as present inadequate, particularly considering that it provides a significant component of the overall Antarctic Ice Sheet imbalance”, thus stressing the importance of the studies of mass losses in this region. Gardner et al. (2013) have given an estimate of -6 ± 10 Gt yr $^{-1}$ for the mass budget of the glaciers of the Antarctic periphery during 2003–2009, which corresponds to 2% of global glacier wastage. In contrast, Hock et al. (2009) concluded that these glaciers made up 28% of the global estimate for the period 1961-2004, stressing the importance of further mass balance studies in this region. In addition, the contribution of the Antarctic periphery has been projected to strongly increase during the 21st century. Using a multi-model approach that encompasses 14 global climate models, Radić et al. (2013) have estimated total contributions to sea-level rise from glaciers in the Antarctic periphery, over the period 2006-2100, of 21 and 28 mm SLE for emission scenarios RCP4.5 and RCP8.5, respectively, which represent 14% and 13% of the projected total glacier contribution. For the glaciers covering the islands off the western coast of the Antarctic Peninsula, some estimates of frontal ablation have recently been reported (Osmanoglu et al., 2013a; Navarro et al., 2013).

> Such estimates are crucial to understand the evolution of the mass balance in a region that has shown considerable regional warming (Steig and Orsi, 2013; Turner et al., 2013).
>
> Here we estimate the average frontal ablation rate of the ice cap on Livingston Island, the second largest island in the South Shetland Islands archipelago, located northwest of the tip of the Antarctic Peninsula (Fig. 1), for the period October 2007-March 2011. We adopt a fluxgate method approximating frontal ablation by the ice discharge through defined flux-gates close to the marine termini. Hence, the approach does not distinguish between the individual components of frontal ablation. This is not a demerit to the method, since our study allows partitioning the total mass loss between surface and frontal ablation. We assume that calving and submarine melting of the grounded glacier termini are the dominant processes of frontal ablation.
>
> The flux-gate approach requires the knowledge of both ice velocities and ice thickness at given flux gates. Radar remote sensing data are used to derive ice velocities, which in turn are used to approximate ice thickness based on principles of glacier dynamics and calibrated against the available GPR-retrieved ice thickness. We also investigate the temporal variations of ice velocity, and their seasonality, at the defined flux gates. For our analyses we compile a new 50mx50m resolution DEM by merging existing data sets with satellite-derived elevations."

Specific points:

The introduction attempts to emphasise the importance of frontal ablation of this region but I found some of the points unclear. For instance, it is not clear if the authors' definition of frontal ablation includes subaerial melting – on line 30 they define it as "the sum of iceberg calving and submarine melting", while on line 66 it is defined as "the loss of mass from the near-vertical calving fronts of the marine terminating glaciers, including loss by calving, subaqueous melting and sublimation". As stated, the mass flux method used cannot discriminate between the different mechanisms of ablation, so the latter definition appears correct. If so, the relevance of the statement on lines 51-54 is not clear – if the method used cannot discriminate between the different ablation mechanisms, how can this study "better quantify the dynamics mass losses". Also, does the cited Shepherd et al., (2012) estimate of mass loss include Livingstone Island? If so, this should be stated, and if not, the relevance of the present study to the glaciers of the Antarctic Peninsula should be clarified.

Comments/answer by authors:

The reviewer is right in that there was a certain inconsistency between the two locations in the text where frontal ablation was introduced/defined. With our comprehensive re-writing of the introduction, this inconsistency has been eliminated, as the frontal ablation is rigorously defined on its first appearance in the text.

It is true that the method cannot discriminate between ablation mechanisms, but it is also true that our study allows partitioning the total mass loss between surface and frontal ablation. We have added the following clarifying statement:

> "This is not a demerit to the method, since our study allows partitioning the total mass loss between surface and frontal ablation. We assume that calving and submarine melting of the grounded glacier termini are the dominant processes of frontal ablation."

Concerning Shepherd et al. (2012) paper, its results do not cover Livingston Island. They present results for the Antarctic Peninsula Ice Sheet (APIS), *excluding* the glaciers in the periphery of the Antarctic Peninsula (and, in particular, the South Shetland Islands, and hence Livingston island). But this paper is relevant, as pointed out in the author's answer to the previous comment by the reviewer, and we have emphasized its relevance, as well as that of our study, as explained there.

A concise summary of relevant previous studies in the study area is given, but it would be informative to include here e.g. mean annual temperature, typical annual accumulation rates and variability, any accumulation gradients, etc. Also, I feel more could be said about the ice cap in relation to other ice-covered areas on the periphery of the Antarctic Peninsula - how applicable are the results of this study to other ice masses in the region? What is the estimated total ice mass (or ice area if insufficient ice thickness estimates) of the South Shetland islands for instance?

Comments/answer by authors:

The following paragraphs have been added to the text of Section 2 (Study area), considerably extending the context information:

> “Using data from the Randolph Glacier Inventory V3.2 (Pfeffer et al., 2014), Livingston Island area represents 23% of the area of the entire South Shetland Islands archipelago, while its ice volume, estimated using volume-area scaling as described in Bliss et al. (2013), is 25% of the volume of the whole archipelago. None of the marine termini of the ice cap are floating. The highest elevation on Livingston Island reaches above 1700 m, in the Mount Friesland Massif, in the south-eastern part of the island, while the island has an average height of about 300 m.”

> “The annual average temperature at Juan Carlos I Station (12 m a.s.l., on Hurd Peninsula, Fig. 1) since 1988 is –1.0ºC, with average summer (DJF) and winter (JJA) temperatures of 2.4ºC and –4.4ºC, respectively. The cloudiness is high, with an average of 6/8 and, consequently, insolation is small, with 2 h day^{-1} of average insolation during summer and spring, though the cloud-free days during such seasons show a high irradiance. The average relative humidity is above 80% (unpublished data from Agencia Estatal de Meteorología, AEMET).”

> “Mass balance estimates at a glacier basin level are only available for Hurd Peninsula glaciers (Fig. 2). Molina et al. (2007) estimated a geodetic mass balance of –0.23±0.10 m w.e. yr^{-1} averaged over the period 1956-2000 for the ensemble Hurd-Johnsons (main glacier basins of Hurd Peninsula). The mass balance estimates for the last decade show that the mass losses of Hurd (land-terminating) and Johnsons (tidewater) glaciers have decelerated, as compared to the average values for 1956-2000. The equivalent average geodetic mass balances during 2001-2011 were –0.15±0.10 and –0.09±0.11 m w.e. yr^{-1} for Hurd and Johnsons, respectively, including –0.14±0.04 m w.e. yr^{-1} of equivalent specific balance for the calving losses of Johnsons, estimated by Navarro et al. (2013) for the period 2005-2008. The summer, winter and annual surface mass balances and the equilibrium line altitude for the decade 2001-2011 were B_w = 0.62±0.16, B_s = –0.77±0.33, B_a = –0.15±0.44 m w.e. yr^{-1}, ELA = 222±67 m for Hurd Glacier, and B_w = 0.76±0.18, B_s = –0.71±0.24, B_a = 0.05±0.30 m w.e. yr^{-1}, ELA = 187±37 m for Johnsons Glacier (Navarro et al., 2013). The errors given are the standard deviations of the 10-yr measurements. The errors of the individual measurements are much smaller, of the order of ±0.10 m w.e. yr^{-1}, for the surface mass balance measurements, and ±10 m, for the equilibrium line altitude estimates. The standard deviations given show that the largest interannual variability of the surface mass balance corresponds to the summer balance, which is mostly a consequence of the large interannual variability of the summer temperature record (Navarro et al., 2013). The land-terminating Hurd Glacier shows, for all variables, a larger interannual variability than the marine-terminating Johnsons Glacier. The latter shows a more positive balance and a lower equilibrium line altitude.”

In sections 3.1 and 3.2 the authors describe ice thickness and ice velocity measurements acquired at the Hurd peninsula. The peninsula appears to be covered by thin, slow-flowing, land-terminating ice, so it is not clear what these measurements can tell us about frontal ablation at the ice cap. The relevance of these measurements should be clarified.

Comments/answer by authors:

The ice thickness data set described in subsection 3.1 is not restricted at all to Hurd Peninsula, but also covers the Bowles Plateau (accumulation area of Perunika Glacier) and all of the main ice divides of the western part of the island, with several branches approaching certain calving fronts. This data set is crucial for calibrating the calculated ice thickness, by tuning the model parameters so that the misfit between calculated and observed ice-thickness is minimized.

Regarding the measured ice velocities at Hurd Peninsula, those at Johnsons Glacier are the basis for the calving estimates by Navarro et al. (2013), which are compared with our results. We have noted this in the revised version of the text, adding the following sentence to Section 3.2 (In-situ velocities):

> “Johnsons’ measured velocities close to its calving front, together with dynamical modelling results, have been used to derive the only local calving estimate so far available for Livingston Island (Navarro et al., 2013).”

The various SAR data used in the study are described in section 3.3 – citations should be provided that describe the satellite sensors in detail.

Comments/answer by authors:

Citations have been included, as suggested. The new references are Mittermayer et al. (2008), Krieger et al. (2007) and Rosenqvist et al. (2007).

Mittermayer, J., Schattler, B., and Younis, M.: Terrasar-X Commissioning Phase Execution And Results}, in: Geoscience and Remote Sensing Symposium, 2008. IGARSS 2008. IEEE International, vol. 2, pp. 197-200, IEEE, doi:10.1109/IGARSS.2008.4778961, 2008.

Krieger, G., Moreira, A., Fiedler, H., Hajnsek, I., Werner, M., Younis, M., and Zink, M.: TanDEM-X: A Satellite Formation for High-Resolution SAR Interferometry, IEEE Trans. Geosci. Remote Sens., 45, 3317-3341, 2007.

Rosenqvist, A., Shimada, M., Ito, N., and Watanabe, M.: ALOS PALSAR: A Pathfinder Mission for Global-Scale Monitoring of the Environment, IEEE Trans. Geosci. Remote Sens., 45, 3307-3316, 2007.

Figure 1: Caption states "Green colour denotes ice free areas". In my copy, the area appears to be brown rather than green. I think it is important to indicate the ice-free areas in subsequent maps of the ice cap (figs 2, 3 and 5).

Comments/answer by authors:

"Green colour" changed to "brown colour". Added the extent of the ice-free areas in the mentioned maps.

Line 167: The authors state that "Details on the exact penetration depth of the SAR signal are unknown" but I feel this warrants more discussion. In particular, it would be useful if this led into a discussion of typical firn depths at the ice cap as this will have implications for the depth-averaged density used in the flux gate calculations.

Comments/answer by authors:

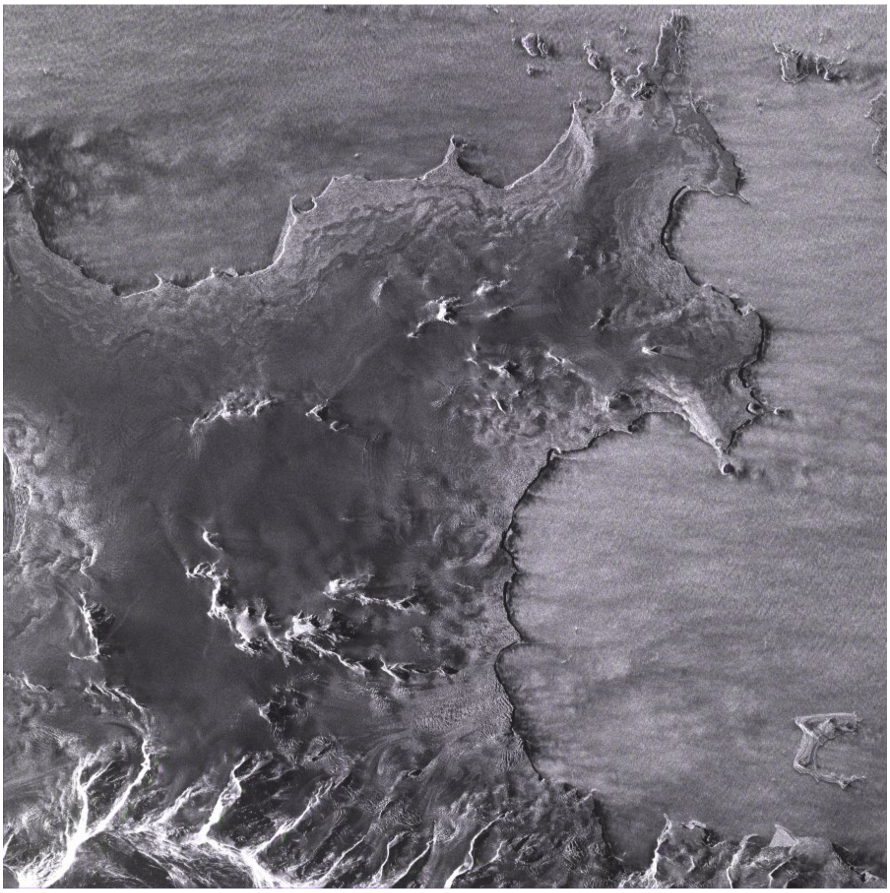
We agree with the reviewer that the penetration depth of SAR signal is an uncertainty of the DEM computations from TanDEM-X. However, to our knowledge there are to date no published analysis on TanDEM-X penetration into snow and firn under different surface conditions. As the reviewer is certainly aware of, penetration depth in X-band is dependent on various factors like moisture content, density, layering etc. and hence can vary locally depending on the meteorological conditions. In our case we do not have concurrent reference measurements on surface elevation to compare the TanDEM-X elevation to. We have expanded our earlier statement in the paper to:

> "Details on the exact penetration depth of the X-band SAR signal are unknown. The X-band penetration into snow, firn and ice is influenced by various factors like liquid water content, density, crystal size and layering of the snow/firn column. It is generally considered to have maximum penetration depths of about 10 m in dry snow and of a few centimetres under wet snow conditions. The TanDEM-X acquisition occurred on 18 March 2012, at the transition from late summer to cooler winter conditions. However, the TanDEM-X amplitude image indicates still wet snow conditions (low backscatter) and some bare ice areas close to the glacier front. Hence we consider the penetration depth for this case minimal although we have no concurrent in-situ measurements for exact validation."

A quicklook of the TDX amplitude image is included below (next page) to support our argument above on the snow wet conditions, but we think that including this figure in the paper is not warranted.

Second, the reviewer suggests initiating a discussion on typical firn depths at the ice cap, as "this will have implications for the depth-averaged density used in the flux gate calculations". We believe that linking the typical firn depth to the depth-averaged density used in the flux gate calculations would be quite misleading for the reader, as we compute ice discharge at the flux gates, where, in summer, there is bare ice and, in winter (when calving is minimum), there is a rather thick column of ice topped by a thin (< 2 m) layer of snow. A discussion on the density at the flux gates has anyway been included in Section 4.2 (Methods-Frontal ablation), in response to another suggestion by the reviewer. Neither it is relevant to speak here of typical firn depths on the island, since, as pointed out, wet snow conditions occurred and thus the X-band penetration is of only a few centimetres. Nevertheless, for completeness, we have added the following comment on typical firn thickness where it seems more appropriate to us, namely in Section 3.1 (Data-Ice thickness):

> "Higher frequency 200 MHz GPR measurements have allowed to estimate the typical firn thickness on the ice cap. For the accumulation areas at lower elevations (< 300-400 m), where summer melting is frequent and the firn compaction is more intense, the firn thickness rarely exceeds 15 m, while for the accumulation areas at higher elevations the firn thickness reaches up to 30-35 m (Navarro et al., 2009; Macheret et al., 2009)."



Line 209: The justification and reasoning for scaling the values between 0.75 and 1.25 should be clarified.

Comments/answer by authors:

The reasoning has been considerably extended in the modified version of this paragraph, which now reads:

> "The RAMP DEM covers the entire island with 200m x 200m grid cell resolution, which we resample to 50m x 50m (Fig. 3a). First, the RAMP DEM was sharpened using a SAR intensity image. The intensities of a SAR interferogram generated from PALSAR-1 images were used to estimate local slopes (Eineder, 2003). The slope measurements obtained using SAR are one-dimensional and can not be used to infer topography. One-dimensional slope information can be used to sharpen an existing DEM, by means of scaling the elevation values using relative slope information. One-dimensional slope information were then scaled to the range between 0.75 and 1.25, and multiplied by the RAMP DEM to superimpose the obtained structure from the intensity image to the RAMP DEM, without altering the histogram of original elevation values (Fig. 3b). Even though the sharpened RAMP DEM has smaller scale variability, statistically its misfit to ICESat elevations did not change after this operation. Mean and standard deviation values for RAMP and sharpened RAMP DEMs show little difference (RAMP: 148±74m; sharpened RAMP: 139±67m). For comparison, the ICESat laser footprint is ~60m, separated by ~170m along the ground track (Fig. 3c)."

Line 221: Suggest change "done" to "performed" and "put on" to "resampled to".

Comments/answer by authors:

Changed as suggested.

Line 225: Suggest change "We further..." to "Further, we...".

Comments/answer by authors:

Changed as suggested.

Equation 2: The chosen value of gamma should be explained and justified. This value is likely to vary across the ice cap and will affect the calculated ice flux value. Although the authors acknowledge this in section 6.2, I feel that more could be said on this point, especially in relation to section 3.2 and figure 5.

Comments/answer by authors:

The following explanation/justification for the choice of gamma has been added to the text:

> "For glacier deformation in simple shear (as assumed here), γ is bounded between 0.8, if the motion is entirely by internal deformation, and 1, if the motion is entirely by slip (Cuffey and Paterson, 2010). In the absence of additional information on the vertically-averaged velocity, it is therefore reasonable to assume γ=0.9. Note, additionally, that we will later tune a parameter weighting the contributions of internal deformation and basal sliding to the glacier surface velocity."

Equation 3: Value of rho(ice) should be justified – given the low ice thickness of some of the flux gates (9 are less than 100 m thick) and relatively high accumulation rates at the ice cap (should be stated), I suspect the depth averaged density is lower than 900 kg m-3. Clearly, this will reduce the calculated discharge values.

Comments/answer by authors:

The difference of the average densities at the flux gates from the standard density of ice (900 kg/m^3) is insignificant, as reasoned in the paragraph below, which has been added to the revised version of the paper to justify the choice of the density value:

> "Note that we are here considering the vertically-averaged density at the flux gates, which are located at the lowest elevations of the ablation area, Consequently, during summer time, when calving is largest, the column is made of ice, while in winter, when calving is lowest, the ice column is topped by a snow layer of, at most, 2 m of snow (an upper bound for the winter accumulation). The average thickness at the flux gates (weighted by the flux gate length) is 142 m. Assuming 2 m of snow in winter time, and 900 and 500 kg/m^3 as densities for ice and snow, respectively, the average density of the ice-snow winter column would be 894 kg/m^3, while in summer it would be 900 kg/m^3. The difference from the standard value for ice (900 kg/m^3), nil in summer time and lower than 0.7% in winter time, is therefore insignificant, while using 900 kg/m^3 additionally allows for direct comparison with the ice discharge values found in the literature."

Line 395: *What is the scientific basis for separately fitting equation 4 to the different areas based on flow speed? This should be explained.*

Comments/answer by authors:

The following text has been added to justify the partitioning:

> "Allowing for the possibility of having different material responses (through the enhancement factor *E*) and a different fractioning of the motion into internal deformation and basal slip (through the sliding parameter *f*) for the various zones, according to their distinct dynamical regime, substantially improved the results, as will be discussed in Section 6.2."

Line 407: the authors state that 3 of the 4 error sources can be quantified by comparing the estimated ice thickness with available data, yet have already acknowledged the lack of ice thickness measurements. This seems unsatisfactory, especially as the only ice thickness measurements are in areas of slow-flowing and predominately thin ice.

Comments/answer by authors:

(See figures 2 and 5a for reference) Though most of Hurd Peninsula ice is slow flowing, and of course the ice divides are slow flowing, there are ice thickness measurements on Bowles Plateau, which feeds basin 21, which is fast flowing (and the GPR measurements on the lower reaches of Bowles Plateau cover part of the area of fast flow). There are also some GPR profiles in part of Basin 6 (Kaliakra), which is among the fastest-flowing, and also on the fast flowing part of Basin 3. Concerning thickness, though most of Hurd Peninsula is not too thick, thickness up to 200 m are reached, but some of the thickest ice zones of the island, such as Bowles Plateau and the upper reaches of Basin 6 (Kaliakra) have also been radio-echo sounded.

Figure 4: *More discussion of the spread of the slow, medium and fast glacier data is warranted. What is the significance of the beta value?*

Comments/answer by authors:

First, a reference has been added in Section 5.2 to the extended discussion on ice-thickness errors in Section 6.2-Uncertainties):

> "Further information about the ice thickness and related errors are provided in Section 6.2."

The following paragraph has been added to section 6.2:

> "In Figure 4, most of the comparable ice thickness data correspond to the slow moving glacier regions. For the slow moving ice the data is scattered around the 1-to-1 line. The medium flowing glaciers are the thickest, with measurements reaching over 450 m, and most of the points are scattered below the 1-to-1 line, indicating that the ice thicknesses are generally underestimated for these glaciers. Points from the fast flowing glaciers are scattered over the 1-to-1 line, indicating overestimated ice thickness for these glaciers."

Also the individual misfits for the regions of slow, medium and fast flow have been added to section 6.2:

> "Individual rms misfit values for slow, medium and fast flow glaciers are 104, 117 and 70 m, respectively."

In Figure 4 caption, we have added:

> "Beta angle is used for error projections."

Line 433: suggest change "the fits are" to "the fit is".

Comments/answer by authors:

Changed as suggested.

Line 445: suggest change "the fit" to "the poor fit".

Comments/answer by authors:

Changed as suggested.

Section 6.2 does a good job of highlighting the various sources of uncertainty. It would be interesting to include a sensitivity analysis for each source.

Comments/answer by authors:

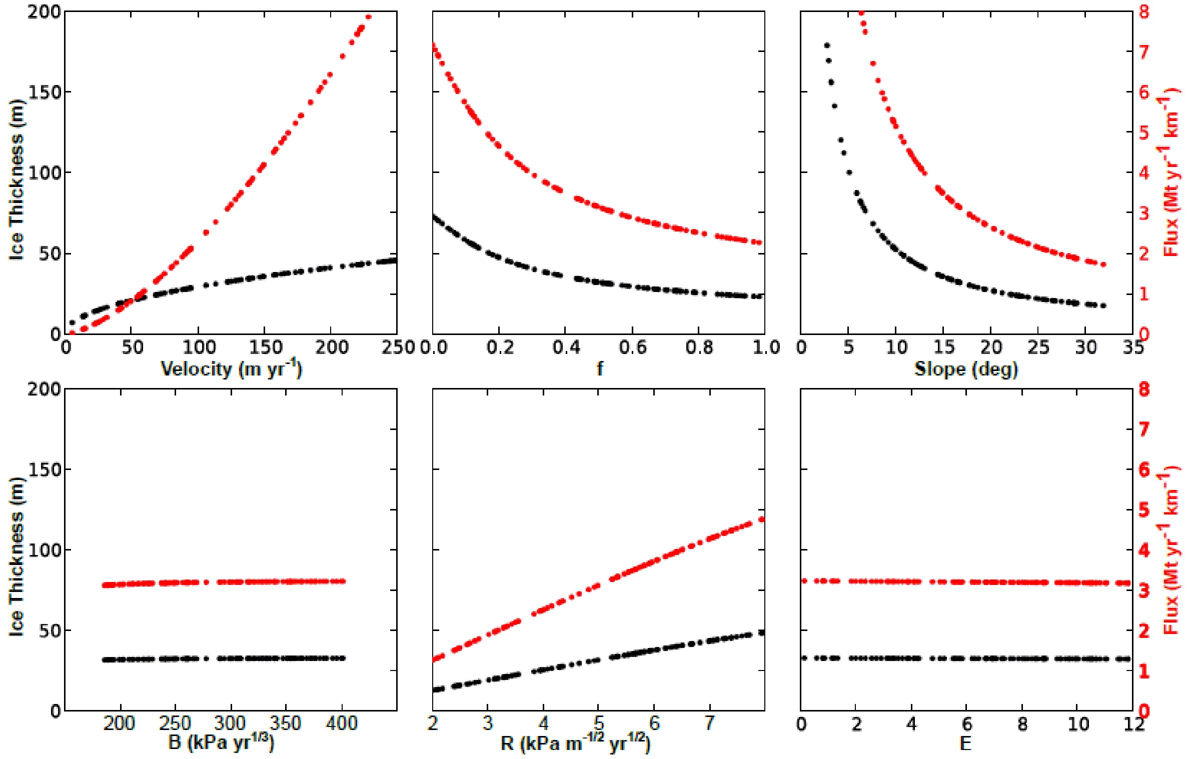
A comprehensive sensitivity analysis has been added at the end of Section 6.3, together with a new figure (Figure 6 in revised version) showing its results. It analyses the sensitivity of both the derived ice thickness and the ice discharge per unit length of flux gate to variations in the model parameters *B* (ice stiffness), *R* (bed roughness), *E* (enhancement factor for deformation), *f* (partitioning of motion between deformation and slip), and also to variations in the input data (velocities and surface slope).

The new added text is:

> "We performed a comprehensive sensitivity analysis to explore how variations in the model parameters, as well as variations in the input data (velocity and surface slope), affect the estimated ice thickness and ice flux per unit length of flux gate. The model parameters analysed were the sliding factor *f*, the stiffness parameter *B*, the bed roughness *R* and the enhancement factor *E* (Eq. (5)). Each parameter was varied within its range of expected values. In the case of input data, they were varied within the range of observed values (velocity) and, in the case of surface slope, from 1° to its average value plus three standard deviations (see Fig. 6). We proceeded as follows: for analysing a particular parameter or input data variable, we set all others to the central value of their range of variation, and then used Eq. (5) to estimate the corresponding ice thickness. The latter was then used to calculate the flux through a flux gate of unit length (1 km).
>
> The results of the tests are shown in Fig. 6. Because the ice flux is proportional to both velocity and ice thickness, it follows a power-law relationship for velocity. For all other parameters (and surface input data), the effect on ice thickness dictates the effect on ice flux. Among the model parameters, the results for both ice thickness and flux are most sensitive to *f* and *R*, while rather

insensitive to *B* and *E*. In our tuning of model parameters described in Section 4.4 we fixed the values of *B* and *R*, because they are best constrained by observations, while we tuned the values of *f* and *E* (for the regions of slow, medium, and fast flow separately) to minimize the misfit between computed and observed ice thickness. Consequently, the bed roughness *R* remains as the model parameter to which our results are most sensitive. Concerning the sensitivity to variations in the input data, both velocity and surface slope have an important effect. Regarding velocities, the computed ice thickness is only moderately sensitive to velocity, though clearly more sensitive in the range of low velocities, while the flux is quite sensitive to velocities over their entire range. However, since the errors in average velocity at the flux gates are relatively small, as shown in Fig. 7, our results are not expected to be much influenced by variations in input velocities. The surface slope, to which both ice thickness and flux are shown to be very sensitive, especially for low slope values, is therefore the largest source of uncertainty of our results."

And the new figure is:



Section 6.3 introduces observations of temporal variations in ice flow and discusses ideas relating to temporal changes in the ice flow regime resulting from e.g. the effect of rainfall on the basal hydrological system. This introduces additional uncertainties into the preceding analysis (e.g. parameter values in equations 2 and 4) which do not appear to be fully explored. It would be instructive to know the acquisition dates of the SAR data used to derive the ice flow fields and ice thickness estimates, in relation to temperature and precipitation data from the nearby met station, as well as in relation to the periodic signals shown in figure 6. The variability in ice flow, which occurs throughout the year, calls into question the validity of using SAR image pairs with temporal baselines of 46 days and longer to estimate a representative ice flow field. More discussion of these issues is warranted.

Comments/answer by authors:

A new table (now Table 1; see to the right) has been added, which includes the dates of all satellite imagery used. We note that the former Figure 6 (now Figure 7) includes (in the form of horizontal bars for each measurement point) the temporal

Satellite	Track	Row	Date
ALOS	125	5890	MAR-15-2011
ALOS	125	5890	JAN-28-2011
ALOS	125	5890	OCT-28-2010
ALOS	125	5890	JAN-25-2010
ALOS	125	5890	DEC-10-2010
ALOS	125	5890	OCT-25-2009
ALOS	125	5890	JUL-25-2009
ALOS	125	5890	MAR-09-2009
ALOS	125	5890	JAN-22-2009
ALOS	125	5890	DEC-07-2008
ALOS	125	5890	OCT-22-2008
ALOS	125	5890	JUN-06-2008
ALOS	125	5890	APR-21-2008
ALOS	125	5890	DEC-05-2007
ALOS	125	5890	OCT-20-2007
ALOS	124	5890	JAN-11-2011
ALOS	124	5890	NOV-26-2010
ALOS	124	5890	OCT-11-2010
ALOS	124	5890	FEB-23-2010
ALOS	124	5890	JAN-08-2010
ALOS	124	5890	NOV-23-2009
ALOS	124	5890	OCT-05-2008
ALOS	124	5890	MAY-20-2008
ALOS	124	5890	APR-04-2008
ALOS	124	5890	FEB-18-2008
TanDEM-X	159	13	MAR-18-2012

baseline of each velocity measurement, and that the overlap of these bars with the blue-shaded areas of the figure (which indicate the periods with above-zero daily temperatures at the meteorological station) are useful to establish such correlation with temperature. Unfortunately, the meteorological records for liquid precipitation are poor and useless for undertaking a reliable comparison. An extended discussion on this Figure has been included in the revised version of the text, as commented in the author's response to another suggestion by the reviewer.

Table 1: It would be interesting to see the mean values of ice flow at the fluxgates and the values of sigma_vel expressed as a percentage of the mean flux gate velocities.

Comments/answer by authors:

This has been included in the new version of the table (now Table 2).

Figure 6: only a few of the flux gates show significant r2 values. Discussion of this variability of the r2 and phase values is warranted.

Comments/answer by authors:

The text referring to former Figure 6 (now Figure 7) has been considerably extended, including a deeper analysis of the temporal variations of velocity:

> "Noticeable temporal variations in surface velocities at the given flux gates are apparent from both Fig. 7 and the $\pm\sigma_{Vseas}$ values in Table 2. Surface velocities tend to be higher during summer (30 ± 17 m yr $^{-1}$) than winter (20 ± 12 m yr $^{-1}$). Summer is defined by a year's longest continuous period with air temperatures exceeding 0ºC at Juan Carlos I meteorological station. This suggests that enhanced summer velocities may be caused by surface melting and associated changes in the water supply to the glacier bed and resulting basal water pressure changes (e.g. Sugiyama et al., 2011). Clear seasonal variations are observed for several basins on Livingston Island. In particular, basins 6 (Kaliakra), 9 and 10, all located on the east side of the island, show large amplitudes and the seasonal variations can be approximated reasonably well by the sinusodial fit as indicated by R2 values between 0.55 and 0.6. Since these measurements are averaged along ten parallel flux gates for each basin and for each image-pair used in this analysis, it is very unlikely that these variations could arise from an error in our analysis.
>
> However, for other basins seasonal variations are less obvious with occasional increased velocities during the winter season. Occasional periods of surface melting and liquid precipitation events during the winter are not unusual in this region, which could imply basal water pressure changes and associated speed-up events.
>
> In other cases a seasonality in velocity is evident (e.g. basins 11 and 14) but the correlation coefficient for the sinusoidal fit is poor. This indicates that the seasonality is not captured well by the highly simplistic sinusoidal fit. In these cases the amplitude and phase of the velocity seasonality seem to vary from year to year (e.g. basins 14 and 21).
>
> Independently of their fit to the sinusoidal variation, the largest temporal variations in velocity correspond to the fastest flowing basins: basins 6 and 7 to the east and basins 12, 14 and 16 to the south; the latter are small basins with large velocities due to large surface slopes. Basin 21also shows both large average velocity and temporal variations. There is no clear relationship with other variables such as basin area or average ice thickness at the flux gate.
>
> Regardless of the underlying mechanism for the temporal variations in surface velocity, these variations exert a direct influence on the frontal ablation rates, as shown in Table 2. The group of basins to the northern and north-eastern parts of the island (1-6), most of them having large frontal ablation rates, shows consistently large seasonal changes in frontal ablation (see ΔD_{seas} in Table 2). The sum of the seasonal changes of analysed basins corresponds to 46% of the total frontal ablation for the entire Livingston Island ice cap. Overall, the seasonality in ice velocities and frontal ablation rates stresses the importance to account for these variations when computing frontal ablation."

Line 659: suggest change "estimation" to "estimates".

Comments/answer by authors:

Changed as suggested.

Line 666: Suggest change “account the temporal” to “account temporal”.

Comments/answer by authors:

Changed as suggested.

Figure 7: I am not convinced of the merit of including this figure.

Comments/answer by authors:

We believe that this figure (now Figure 8) is relevant to the discussion and should be left. It shows the different hypsometry of the marine-terminating and land-terminating basins, which is very relevant for the surface mass balance estimates. This figure also illustrates the summer, winter and net balances of Johnsons (marine-terminating) and Hurd (land-terminating), and their interannual variability, giving support to the extrapolation done to estimate the surface mass balance for the whole ice cap.