Authors point-to-point response on Referee Comment #2 to tc-2021-325

General comments

#1 Difficult to follow
My main concern with the manuscript is that I found it very difficult to follow and I feel that the manuscript could benefit from a slight restructuring and having a greater focus on hammering home the key points.
Small things such as re-structuring the manuscript so it goes through all the uncertainties associated with ice discharge first (e.g. scaling, velocity, ice thickness and grounding line) and then the SMB stuff could make the manuscript easier to follow. At the moment the manuscript is ordered: ice discharge scaling -> SMB -> and then back to other ice discharge stuff, sometimes individual paragraphs contain information on both ice discharge and SMB methods, that makes it difficult to follow.
For example, in the methods section you could have new subsections 2.3 Ice Discharge – where you would go through systemically, paragraph by paragraph, what the manuscript focusses regarding ice discharge (e.g. scaling, velocity, ice thickness and grounding line). You could also do the same for a new subsection (2.4) on SMB. You could then structure the results section in a similar manor.
The results section should stick to results and not wonder off into speculative discussions
Response 1: We have carefully considered all the comments, and made major revisions. Particularly, we have restructured the manuscript. The revised manuscript has been ordered as: ice discharge -> SMB. The methodological uncertainty of the D has been assessed and discussed in the revised subsections of the ice discharge.

I think the discussion needs to be more streamlined and more to the point. At the moment it is lengthy and contains a lot of numbers and other bits of text that really don't add anything. I do not think it hammers home the key points. Which brings me to the question what are the key points? Is scaling suitable? What is the dominant source of uncertainty, SMB? Is it imperative that even small grounding line changes are accounted for? Please let the reader know in a concise manor.
Response 1: We agree and have deleted the repeating points and make it more streamlined in the revised manuscript.

#2 Unclear on Discharge scaling factor
You compare discharge using the full pixel values and using a scaling method. I think this is potentially a valuable contribution and I agree there is an unknown impact of using this scaling, particularly going back in time where velocity data is more sparse. But I am not entirely sure how you have done this:
Presumably in the innterannual mosaics used for this experiment there are plenty of data gaps, with some regions presumably having no data at some time periods. How do you account for this?

How do you get a seemingly ice sheet wide estimate of ice discharge using the pixel value when some of the mosaics will have very large data gaps? More precisely what is a pixel scale estimate, is this simply taking the velocity value directly at the grounding line. A better explanation is needed here.

Response 2: Thank you for your suggestion. There are gaps of annual data. We have used years of data interpolation to fill the gap. Because the ice velocity and ice thickness vary considerably at the pixel scale, we estimated D at a fine scale by discretizing the grounding line into grids of the same cell size (1 km) as the ice thickness and ice velocity data, which divided the MEaSUREs InSAR-based grounding line into 58,597 flux gates at pixel scale. "A pixel scale estimate" is that we calculated D at each flux gate. We have clarified it in the revised manuscript.

Why did you choose only 100 m, what is the reason for this? For me 100 m yr is still relatively slow flowing ice.

Response 2: We chose 100 m yr^{-1} because more than three quarters of 58,597 flux gates have velocities less than 100 m yr^{-1}. The slow flowing ice (less than 100 m yr^{-1}) only accounts for 13.3% of the total discharge of Antarctica, which is the possible reason why that the uncertainty due to scaling is small.

How do you treat the Antarctic Peninsula which has some difficult topography (e.g. narrow fjords) and how does this compare to other studies e.g. (Gardner et al., 2018).?

Response 2: The difficult topography like narrow fjords requires higher spatial resolution, and the 1-km raster we used may omit or simplify these topographies. But we haven't treat the Antarctic Peninsula in the special way. And compared to the ice discharge of AP during 2008–2015 in Gardner et al. (2018) (234±27 Gt yr^{-1}), our ice discharge result is much smaller (161.5 Gt yr^{-1}). Therefore, our results of the Antarctic Peninsula probably contain errors that were not clarified in the original manuscript. We have added the D's difference between Gardner et al. (2018) s' result and the reference D in the Table 3 and discussed this point in the discussion of the revised manuscript.

Revised Table 3:

Table 3. Data and method uncertainties of the D and SMB (Gt yr^{-1})

Components	EAIS	WAIS	APIS	Islands	AIS
D$_{reference}$	895.8	750.2	157.7	132.4	1936.0
U_D					
Standard uncertainty					
U_D(V$_{InSAR-based}$)	33.0	13.3	3.2	10.9	60.4
U_D(V$_{Phase-based}$)	8.9	5.5	1.9	3.3	19.5
U_D(T$_{BEDMAP2}$)	265.3	145.0	86.4	50.3	547.0
U_D(T$_{Bedmachine}$)	93.1	50.6	30.9	33.5	208.2
U_D(V$_{Phase-based}$ +T$_{Bedmachine}$)	95.6	52.4	31.3	34.5	213.8
Monte Carlo uncertainty					
U_D(V$_{InSAR-based\_re}$)	5.3	2.2	0.3	1.8	9.6
U_D(V$_{Phase-based\_re}$)	0.9	0.6	0.2	0.3	2.0
U_D(V$_{re}$ 20 m yr^{-1})	17.4	10.1	4.0	9.7	41.1
U_D(T$_{BEDMAP2\_re}$)	27.9	14.5	11.6	7.3	61.4
U_D(T$_{Bedmachine\_re}$)	17.1	5.9	5.7	6.8	35.5

U_D(T_{re} 100 m)	3.2	1.7	3.0	4.8	10.5
Uncertainty due to system error					
U_D(V_{se} 20 m yr^{-1})	138.1	80.1	29.0	53.4	302.6
U_D(T_{se} 100 m)	151.2	105.1	70.4	43.1	369.8
Uncertainty presented by difference					
U_D($V_{InSAR-based}$-$V_{Phase-based}$)	7.7	2.6	5.1	1.5	17.1
U_D($T_{BEDMAP2}$-$T_{BedMachine}$)	18.4	32.9	25.7	24.6	101.7
U_D($GL_{Advance}$-GL_0)	-97.2	-107.1	-44.4	24.7	-278.1
U_D($GL_{Retreat}$-GL_0)	-8.8	-7.5	-0.8	-62.5	-79.6
U (D_{ref}−D_{Rignot})	-214.6	-24.9	-172.0	55.3	-356.2
U (D_{ref}−D_{Garder})	-56.2	11.2	-62.3		
U (D_{ref}−D_{Shen})					-171.3
U_MAX(ABS(D_{pixel}−D_{scale}))	3.2	6.5	1.8	7.4	10.4
Maximum uncertainty					
Max(ABS(U_D$_V$))	*138.1*	*80.1*	*29.0*	*53.4*	*302.6*
Relative(% of D$_{ref}$)	*15.4%*	*10.7%*	*18.4%*	*40.3%*	*15.6%*
Max(ABS(U_D$_T$))	*265.3*	*145.0*	*86.4*	*50.3*	*547.0*
Relative(% of D$_{ref}$)	*29.6%*	*19.3%*	*54.8%*	*38.0%*	*28.3%*
Max(ABS(U_D$_{GL}$))	*97.2*	*107.1*	*44.4*	*62.5*	*278.1*
Relative(% of D$_{ref}$)	*10.9%*	*14.3%*	*28.2%*	*47.2%*	*14.4%*
SMB$_{reference}$	1153.5	649.5	253.6	61.4	2118.0
U$_{SMB}$					
Standard uncertainty					
U_SMB$_{p2-27}$ (4%)	46.1	26.0	10.1	2.5	84.7
Uncertainty presented by difference					
U (SMB$_{p1-35}$-SMB$_{p1-27}$)	-26.1	-51.6	-119.4	-19.6	-216.7
U (SMB$_{p2-27}$-SMB$_{p2-5.5}$)			-51.7		
U (SMB$_{p1-27}$-SMB$_{p2-27}$)	-78.5	3.1	39.4	15.6	-20.4
U (SMB$_{ref}$-SMB$_{Rignot}$)	78.5	-3.1	-39.4	-15.6	20.0
U (SMB$_{ref}$-SMB$_{Gardner}$)	95.5	108.5	19.0		
U (SMB$_{ref}$-SMB$_{Shen}$)					217.0
Maximum uncertainty					
Max(ABS(U_SMB))	*95.5*	*108.5*	*119.4*	*19.6*	*217.0*
Relative(% of SMB)	*8.3%*	*16.7%*	*47.1%*	*31.9%*	*10.2%*

#3 Lack of the highly relevant reference
What about other SMB models apart from RACMO? I think some analysis of this has already been done, so it is not necessary to repeat. But I am certainly surprised not to see any mention of the below paper at all in the manuscript, it seems highly relevant.

Mottram, R., Hansen, N., Kittel, C., van Wessem, J. M., Agosta, C., Amory, C., Boberg, F., van de Berg, W. J., Fettweis, X., Gossart, A., van Lipzig, N. P. M., van Meijgaard, E., Orr, A., Phillips, T., Webster, S., Simonsen, S. B., and Souverijns, N.: What is the surface mass balance of Antarctica? An intercomparison of regional climate model estimates, The Cryosphere, 15, 3751‒3784,

https://doi.org/10.5194/tc-15-3751-2021, 2021.

Response 3: Thanks for your suggestion. The RACMO SMB is the most commonly used in the mass balance estimation of Antarctic ice sheet using the IOM. The comparison between RACMO and other SMB have been done in many work just as the reference you suggest. We have added the reference in the revised description of the SMB product and calculated the standard uncertainty of RACMO2.3p2 SMB (revised Table 3) as suggested by Agosta et al. (2019).

Agosta, C., Amory, C., Kittel, C., Orsi, A., Favier, V., Gallee, H., van den Broeke, M. R., Lenaerts, J. T. M., van Wessem, J. M., van de Berg, W. J., and Fettweis, X.: Estimation of the Antarctic surface mass balance using the regional climate model MAR (1979-2015) and identification of dominant processes, The Cryosphere, 13, 281-296, https://doi.org/10.5194/tc−13-281-2019, 2019.

#4 Ice thickness

I agree with reviewer 1 that it is odd not include some analysis on the uncertainty product associated with BedMachine.

Response 4: Thanks for the reviewer's comment. In the revised version, we have added the D's uncertainty estimations from the uncertainty field of provided by datasets of BEDMAP2, BedMachine, InSAR-based and Phase-based velocities both using the mathematical treatment and Monte Carlo method.

Specific comments

Line 63-69: It is not clear to me what the 'maximum difference' is here? The difference to what exactly?

Response: The "maximum difference" means that the max diff value among these studies mentioned above in the same available year. We have clarified this point in the revised manuscript.

Line 67-69: Over what time periods are these comparisons made? Are you directly comparing the average mass balance from the entire rignot record (1979-2017) to the much shorter record of Shen or Gardner (2008-2015), I can not tell? For example, for Pine Island because it is changing so rapidly different estimates of mass balance would be expected over different timescales. So this is not really a fair comparison.

Response: These comparisons are made in the same available year for the studies mentioned above. Rignot et al. (2019) provided the annual results from 1979 to 2017 in supplement materials. Shen et al. (2018) evaluated the AIS mass balance for 2008, 2014 and 2015, and Gardner et al. (2018) calculated mass balance for 2008-2015. We selected the intersections of their time period, including 2008, 2014 and 2015.

Line 83: I am not sure what you mean by an uncertainty analysis framework

Response: The "uncertainty analysis framework" is a scheme on how to make the uncertainty evaluation of IOM open and transparent. There are more than five research groups to estimate mass balance of Antarctic ice sheet using the IOM. They have done a lot work to reduce the uncertainties.

But it is hard to use their method or repeat the work without the details. We presented the details in our uncertainty estimation. For example, to demonstrate the D's details, we showed 58,597 flux gates around the grounding line. We recognized that the "framework" expression is inappropriate and have modified it in the revised manuscript.

Line 125: More detail on the scaling factor is needed (See main comments)
Response: Yes. We have added it in the revised manuscript.

Line 133: New paragraph as you move onto SMB
Response: Done.

Line 167: What is the source for the original flux gate
Response: The original flux gate is generated based on the InSAR based grounding line of the MEaSUREs Antarctic boundaries (Rignot et al., 2013).

Line 176-177: Probably a point for the discussion. Also, this is a large number, why is this? I presume it is something to do with the ice thickness used to calculate D – Rignot uses SMB as a base ice flux from the 1970s where there is no suitable ice thickness data?
Response: Thank you for your suggestion. The large number is something to do with the ice thickness. We have discussed in the original version: "Our reference D of 1936 Gt yr^{-1} obtained using the BedMachine thickness is much smaller than the average D of 2217 Gt yr^{-1} for the period 1979-2017 estimated by Rignot et al. (2019), which is mainly caused by the difference between the BedMachine thickness and the balance thickness in the EAIS and APIS."

Line 188 – discharge, not 'mass balance'
Response: Corrected.

Line 195: This sentence seems out of place
Response: We have modified it in the revised manuscript.

Figure 3: Specify in caption on figure that the multi-year average is 12 years
Response: Done.

Line 255: 'cannot be ignored' – or confirms internal variation in ice discharge driven by climatological factors
Response: Yes. We have revised.

Line 279 – 285: This is speculative discussion and should not be in the results. Also I would certainly disagree that ice shelves such as the Ross Ronne and Amery are 'significantly thickening', likewise for 'significantly thinning' ice shelves in Wilkes Land – much depends on what timescales you are referring too. I do not think this is a valid conclusion.
Response: Thank you for your comment. We have removed this part in the revised version.

Line 303: I was not aware that the Measures grounding line covers the whole ice sheet? Are there not gaps? What did you use for the gaps?

Response: We used the MEaSUREs Antarctic boundary dataset (Rignot et al., 2013) for the estimates in different regions and basins because this AIS boundary is consistent with the MEaSUREs InSAR based grounding line.
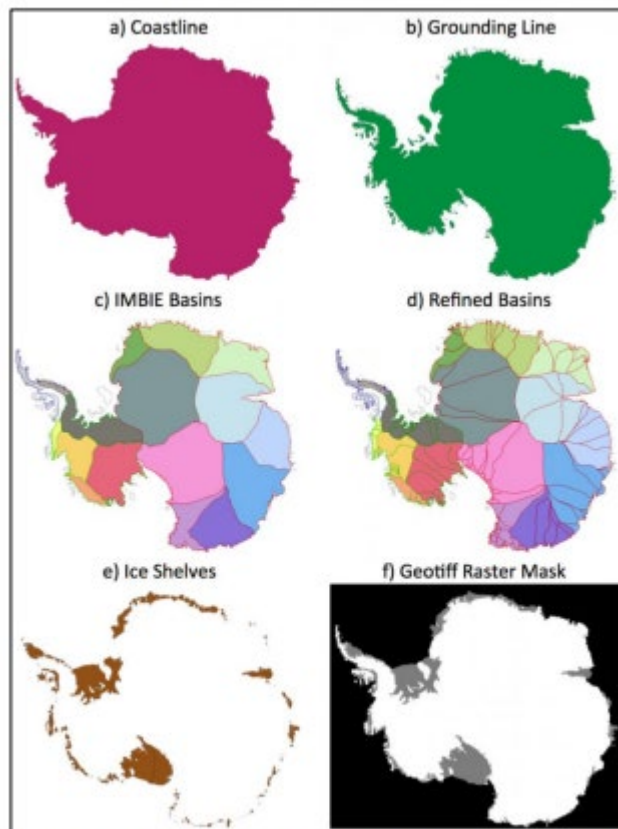

Figure 2. Shapefile Spatial Coverage Maps (a-e) and GeoTIFF raster map (f). Each file is available separately, the full information content is provided in the file IceBoundaries_Antarctica_v02.shp

Line 308-310: Again this is discussion. Furthermore, I don't think I understand what you are trying to say in this point

Response: Our point is that the D of a 1-km retreat in the islands is closer to the balanced ice flux (equal to the multi-year average SMB) of 77.0 Gt yr^{-1} (Rignot et al., 2019) compared to the original D. As the islands are typically surrounded by fast ice flows, the D of a 1-km advance of the grounding line in the islands may be significantly greater than the original D in the islands. Therefore, we believe that the true grounding line in the islands is closer to the 1-km retreat MEaSUREs grounding line. The grounding line for multiple islands from Lei et al. (2017) based on DInSAR is similarly backward compared to the MEaSUREs product, which supports this view. We have clarified it more clearly in the revised manuscript.

Line 318-329; Example of text that is arguably not needed, most of it is repeated elsewhere in the manuscript

Response: Done.

Line 336-337: I am not sure of the relevance of this sentence. Slow flowing ice only accounts for a small portion of the total discharge of Antarctica, So in absolute terms faster flowing ice is always going to have larger interannual variability.

Response: Thank you for your comment. The slow flowing ice (less than 100 m yr^{-1}) only accounts for 13.3% of the total discharge of Antarctica, which is the possible reason why that the uncertainty due to scaling is small. If we choose 200 m yr^{-1} or larger for slow flowing ice, the uncertainty may be larger. We have clarified it in the revised paper.

Line 343: '*The annual SMB data are probably closer to the real values*' – *I do not understand what you mean here*

Response: The annual SMB data can reflect the climate-related anomalies compared to the multi-year average SMB. For example, in the EAIS, the SMB exhibited two significant positive anomalies in 2009 (178.0 Gt yr^{-1}) and 2011 (110.8 Gt yr^{-1}) compared with the 12-year mean, which were both caused by extreme snowfall episodes.

Line 318-435: In general this discussion needs to be more streamlined and have less of a focus on repeating points made earlier in the manuscript.

Response: Thank you for your suggestion. We have deleted the repeating points and make it more streamlined in the revised manuscript.

References

Agosta, C., Amory, C., Kittel, C., Orsi, A., Favier, V., Gallee, H., van den Broeke, M. R., Lenaerts, J. T. M., van Wessem, J. M., van de Berg, W. J., and Fettweis, X.: Estimation of the Antarctic surface mass balance using the regional climate model MAR (1979-2015) and identification of dominant processes, The Cryosphere, 13, 281-296, https://doi.org/10.5194/tc−13-281-2019, 2019.

Gardner, A. S., Moholdt, G., Scambos, T., Fahnstock, M., Ligtenberg, S., van den Broeke, M., and Nilsson, J.: Increased West Antarctic and unchanged East Antarctic ice discharge over the last 7 years, The Cryosphere, 12, 521-547, https://doi.org/10.5194/tc−12-521-2018, 2018.

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Mottram, R., Hansen, N., Kittel, C., van Wessem, J. M., Agosta, C., Amory, C., Boberg, F., van de Berg, W. J., Fettweis, X., Gossart, A., van Lipzig, N. P. M., van Meijgaard, E., Orr, A., Phillips, T., Webster, S., Simonsen, S. B., and Souverijns, N.: What is the surface mass balance of Antarctica? An intercomparison of regional climate model estimates, The Cryosphere, 15, 3751–3784, https://doi.org/10.5194/tc-15-3751-2021, 2021.

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