RC1

1 General comments

We would like to thank the reviewers for their careful reading of the manuscript and the helpful comments. The answers to the comments are written in bold, the reviewer's comment in normal font, and the sentences we propose to add to the manuscript are in italics.

The research article "Assimilation of radar freeboard and snow altimetry observations in the Arctic and Antarctic with a coupled ocean/sea ice modelling system" introduces a multivariate assimilation system using LEGOS radar freeboard and KaKu altimetry snow depth in addition to sea ice concentration observations and compares the performance of this novel model run to a free model run and one using only sea ice concentration observations. The paper is well structured, provides a good literature overview and clear motivation for the work. Many comparisons against independent validation data are presented and the results are discussed appropriately. Furthermore, the figures are neat, and the results prove a clear overall improvement compared to the other model runs. Therefore, I recommend this article for publication after minor revisions:
General comments:

1. As most plots are only for one specific month, it would be nice to have the same plots for all months in the appendix or to publish them as supplementary dataset.

   Moreover, there are several instances, where other months are discussed with a comment "not shown", making it hard to follow.

I also wonder how you chose the months for each plot, as the choices are not consistent (Fig 2 shows July 2017 and September 2017, Fig 3 and 8 show April 2017 for the Arctic, Fig 4 shows some plots for May in addition to October 2017 for the Antarctic, but Fig 9 shows September 2017 instead of October and Figure 5 and 6 show October 2018 and Jan-Feb 2019). There might be good reasons for the choices, but to prove that the plots weren't cherry-picked to support the author's arguments most, all plots should be published somewhere alongside the manuscript.

The plots for each month and for all variables are made available in the attached document 1_Figures_review_for_RC1.

However, we think all the figures would provide redundant information in the manuscript. We propose adding a few additional figures as supplementary material attached to the article (file: 2_Supplementary_Materials) to illustrate the most important results found during two seasonal cycles and also to show that the results shown in the manuscript remain robust over the 2 seasonal cycles:

- **March and September 2018 for SIC highlighting the maximum of the extension for the SIC Arctic and Antarctic and the minimum in Arctic and close-to-minimum extension in Antarctic**
- **Snow thickness (SNT) and radar freeboard (RFB) in the Arctic: a) January 2017 to show the first month of the experiments, the biases that were already corrected and the ones remaining during this spin up b) November 2017 to show the situation after the first summer with no observations, and how and where the system has kept the memory of the RFB and SNT distributions c) March 2018 to show the variables after more than one year of assimilation and d) December 2018 to show the agreement between MULTIVAR and SNOW-KaKu measurements**
- **Snow thickness (SNT) and radar freeboard (RFB) in Antarctic: a) May 2017 to show the first month of presence of observations and their assimilation in the SH b) May 2018 to show the variables after a full seasonal cycle and the restart of data assimilation in the southern hemisphere c) October 2018 to show that**

the statements made are true and constant until the end of the periods of presence of assimilated observations.

- **Sea ice volume (SIV) in the Arctic and comparison with CS2SMOS: same months as the SNT & RFB, January 2017, November 2017 and March 2018.**
- **SIV in the Antarctic and comparison with SMOS: same months as SNT & RFB, May 2017, May 2018 and September 2018.**

For the figures not shown, we have referred to new figures in the supplementary material. We have modified the manuscript accordingly:

- **L. 260: In both hemispheres, FREE is not able to prevent excessive melting and shows a significant lack of sea ice, mainly in marginal areas, during July-October in the Arctic and in January-April in Antarctica (See Figures S1 and S2).**
- **L.309: In Antarctica, the FREE simulation presents mainly positive SIC biases in winter, particularly in the marginal ice zone (MIZ, defined by SIC values between 15% and 80%), and places the ice edge too far north compared to SSMIS observations (Figures 2 and S2).**
- **L. 324: The MULTIVAR snow distribution is very close to the Arctic SNOW-KaKu during winter (Figures S3 and S5) and matches perfectly in April**
- **L.327: The linear correlation (r-value) computed against the SNOW-KaKu observations in the Arctic results is consistently above 0.5 for MULTIVAR, peaking at 0.7 in December 2018 (Figure S6 not shown)**
- **L. 374: After re-checking, the FREE experiment does not systematically exhibit lower values, we then removed the following sentence in the manuscript: "The FREE simulation exhibits lower RFB values than the other experiments especially at the end of summer (not shown)."**

Choosing which months to show is tricky because the periods observed remain discontinuous, differing from one hemisphere to another, and we cannot insert many figures. A few explanations about the inconsistency of the dates chosen:

- **Fig. 2 shows the sea ice concentration, so the months shown were chosen to present the most relevant months regarding the evolution of sea ice leads content (Fig. 1). July 2017 corresponds to the Arctic maximum sea ice leads area; whereas September 2017 in Antarctica shows the strong presence of leads (Figure 1-b) in the ice cover of MULTIVAR and UNIVAR (Figure 1 b) and the Weddell polynya appears in the observations.**
- **The other maps (Fig. 3, 4, and 8) show the variables during the last month of assimilation of the altimetric observations (snow and radar freeboard), i.e. April in the northern hemisphere and October in the southern hemisphere.**
- **The same should have been done for Fig. 9, but the SMOS measurements are not available after the 15th of October, so the month of September has been chosen instead.**
- **The PDF in Fig. 4 shows the data in October 2017 but also in May 2017 to show the evolution of the variables in Antarctica from the beginning to the end of the winter.**

2. The appendix adds a valuable comparison to completely independent in situ data and I wonder why you did not include these in the main text.

We wanted to keep the main manuscript as short as possible, given that it already is a long article. That is why the comparison with in-situ measurements was put in the appendix. We agree that this comparison is valuable and relevant; we leave it up to the reviewer and editor to decide whether to add this to the body of the text.
If so, we suggest:

- **adding this comparison with in situ as a subsection 4.2 entitled "Comparison with in-situ measurements" of the part 4 "Validation with independent datasets". We have attached a separate document containing this subsection 4.2 for the review (file: 3_section4.2 Comparison with in situ measurements). The figures within this subsection have been slightly modified to differentiate statistics by season. Further, we have added in this subsection the tables describing the root mean square error and mean differences, see comment below.**
- **adding this paragraph in the discussion part: L. 607:** "*Further comparison with in-situ independent observations in the Arctic only show general improvement with the multivariate assimilation system compared to the FREE and the UNIVAR experiments. The MULTIVAR experiment is able to maintain the remarkable agreement found with the*

FREE experiment with ULS moorings in the Beaufort Sea and favorably thickens all types of ice in the Fram Strait region. At the same time, the multivariate approach also positively increases the thickest ice even in the absence of snow data. Comparisons during the summer season show no particular deterioration or improvement with the multivariate system”

- **modifying the text in the conclusion part as follows: L. 718 “***Moreover, the diagnosed freeboard from the multivariate system compares better with Iceat-2 and in-situ independent observations in the Arctic and, to a lesser extent, in Antarctica.*”

It would also be helpful to add RMSE values to these scatter plots and discussion.

Yes, we agree. The RMSEs values between simulation and the three in-situ datasets are summarized in the tables below. The discussions and references to the Tables are added in sub-section 4.2 mentioned in the previous response.

BGEP ULS DATA	*RMSE total*	*MD total*	*RMSE winter*	*MD winter*	*RMSE summer*	*MD summer*
LEGOS			*0.194*	*0.113*		
FREE	*0.134*	*0.011*	*0.121*	*0.095*	*0.150*	*-0.087*
UNIVAR	*0.139*	*-0.038*	*0.141*	*-0.020*	*0.137*	*-0.058*
MULTIVAR	*0.191*	*0.068*	*0.182*	*0.160*	*0.202*	*-0.039*

Table 4 : Root mean square error (RMSE) and mean differences (MD) between the BGEP ULS measurements and LEGOS data (only winter months : November to April), FREE, UNIVAR and MULTIVAR experiments, by season (summer: May to October, and winter) and over the two seasons as a total.

NPI ULS DATA	*RMSE total*	*MD total*	*RMSE winter*	*MD winter*	*RMSE summer*	*MD summer*
LEGOS			*0.427*	*0.366*		
FREE	*1.040*	*-1.040*	*0.696*	*-0.696*	*1.402*	*-1.402*
UNIVAR	*1.238*	*-1.238*	*1.02*	*-1.029*	*1.458*	*-1.458*
MULTIVAR	*0.645*	*-0.571*	*0.316*	*-0.189*	*0.991*	*-0.972*

Table 5: Same as Table 4 with the NPI ULS measurements.

OiB AIRBORNE DATA	*RMSE totale*	*MD totale*	*RMSE lat<81.5°N*	*MD lat<81.5°N*	*RMSE lat>81.5°N*	*MD lat>81.5°N*
LEGOS			*0.449*	*0.068*		
FREE	*0.639*	*-0.503*	*0.459*	*-0.200*	*0.744*	*-0.681*
UNIVAR	*0.869*	*-0.794*	*0.574*	*-0.416*	*1.042*	*-1.016*
MULTIVAR	*0.652*	*0.182*	*0.486*	*0.135*	*0.750*	*0.209*

Table 6: Same as Table 4 with the OiB Airborne data and, according to the areas where SNOW-KaKu data is present (<81,5°N) or not (> 81,5°N) and for all OiB Airborne data.

3. Throughout the paper, English grammar is not always used correctly, but the text is generally understandable. I, therefore, trust that copy editing will deal with this.

Thank you. We apologize for the English mistakes, we do our best to correct the text.

2 Specific comments

L.110: SSMIS is not explained. Here, I would maybe just talk about SIC.

We have modified the text accordingly, L110: “*What are the impacts of using altimetric radar freeboard and altimetric snow observations in addition to the SIC data?*”

L.200 onwards: In the methods section, SSMIS should be explained and mentioned in the text, also to make the difference to the OSISAF AMSR2 product, which is used later on, clearer.
The sentence has been modified to : "*The observation data used for sea ice concentration (SIC) assimilation is the global daily reprocessed passive microwave dataset, measured with Special Sensor Microwave Imager / Sounder (SSMIS) satellites instruments, from the European Organization for the Exploitation of Meteorological Satellites (EUMETSAT) Ocean and Sea Ice Satellite Application Facility (OSISAF) OSI-450 (OSI SAF, 2022).*"

L.207: How was the 40% value for Antarctica chosen?
We increased the observation error in Antarctica to avoid moving too far away from the free model solution. Increasing the observation error reduces the impact of the assimilation on the sensitive coupling between ocean and ice in the Southern Ocean . The value of 40% has been however chosen arbitrarily.

L.213: 'measure' rather than 'detect'
Thank you.

L.225 and 230: Which months are counted as winter? Please specify.
A table (see below) has been added to specify the gaps in the assimilated observations and commented in subsections 2.2.1, 2.2.2 and 2.2.3. See answers to the reviewer's comments 2.
L. 199:

Observations	*SIC SSMIS*	*RFB-LEGOS*	*SNOW-KaKu*
Producer	*EUMETSAT OSI-SAF*	*LEGOS*	*LEGOS*
Temporal resolution	*Daily*	*20 Hz*	*Monthly → weekly (linear interpolation)*
Temporal coverage	*All-time*	*Winter: November to April in the Arctic; May to October in the Antarctic.*	
Spatial resolution	*40 km (effective resolution); 25 km (grid resolution).*	*Along-tracks*	*12.5 km (grid resolution).*
Spatial gaps	*None (reprocessed).*	*Central Arctic (latitude > 88°N); in-between satellite tracks.*	*Central Arctic (latitude > 81.5°N) ; coastal areas.*
nsel	*400*	*4000*	*400*

Table 2: Assimilated observation products and their specificities.

L.226: Do you average all altimetry observations within a model grid cell or within a radius from the grid cell? Any weighting? Please specify.
We use a gaussian weight for the observations. This is done for all the observations in the localization algorithm of the assimilation system (see sentence L. 150: "*The increments at each model grid point are calculated independently in a local scheme, where a localization algorithm controls the spatial influence of observations. This approach helps to limit the impact of sampling noise on the increments.***"). The radius of the localization scheme is the minimum between a fixed distance of 176 km and a radius defined by the inclusion of a number 'nsel' of observations. This number 'nsel' is set to 400 for gridded products such as the SIC and snow depth data and to 4000 for the high resolution radar freeboard data. The following sentence has been added L. 151** "*The radius of the localization scheme is set as the minimum between an arbitrary fixed distance of 176 km and a radius defined by the inclusion of a number of observation nsel (see the chosen nsel values in Table 2).*"

L.232: Why do you scale the uncertainties and how do you decide on this range?
The observation errors for the snow and the radar freeboard are not modified from the ones given by producers. We set a maximum/minimum to these observation errors to make sure no observation error would be erroneous.

Especially, the numerical computation could become impossible if a 0 value exists, then we set the minimum error to 0.01 m. The maximum value of 5m is chosen arbitrarily and to be large enough to exclude outliers.

L.245: How were these dates chosen?

The assimilation cycle lasts 7 days and begins on a Wednesday to match the design of the weekly analysis cycles of Mercator's operational systems (real-time or reanalysis systems). The first day of the analysis was chosen arbitrarily. The period 2017-2018 was selected to capture interesting features of the sea ice such as the Weddell Polynya in September 2017 and the Greenland polynya in February 2018. We ran the experiment for 2 years to have 2 complete seasonal cycles and also to have the ICESat data available at the beginning of 2019.

L.252: referred to 'as' leads

Thank you.

L.254: I would call it 'lead fraction' rather than 'lead content'

Thank you.

L.257: explain CDR

Thank you. L.256: "*... and the Climate Data Record (CDR) dataset …***"**

Figure 1 caption: Do you mean 'range' rather than 'surface' covered by them?

Thank you. Figure 1 caption: "*Daily time evolution of Arctic (a) and Antarctic (b) surface covered by sea ice leads in millions of km² for SSMIS (black), AMSR2 (dashed black), NSIDC (dotted black) satellite data with the range covered by them (shaded grey) and for FREE (blue), UNIVAR (green) and MULTIVAR (pink) experiments.***"**

L.259-262 and L.285-314 + Fig 2: I suggest a separate section for SIC e.g. before the lead section. Especially the first paragraph on sea ice concentration (L259-262) currently sits between two paragraphs on lead fraction and interrupts the flow.

This actually makes sense, we've moved the 2 paragraphs concerned and we modified the text accordingly. We separated the two ways of evaluating the modelled sea ice concentration: a first paragraph evaluating the spatial distribution of SIC in both hemispheres, and a second one evaluating the area of leads in sea ice. We've modified the title of the subsection 3.1 L. 250: "*Sea ice concentration and sea ice leads***". We have inverted the figure numbers, with figure 2 becoming the figure 1 and vice versa. We have attached a separate document containing this subsection 3.1 for the review (file: 4_section3.1 Sea ice concentration and sea ice leads).**

Figure 2: I would stick to SIC rather than SICONC in the titles and colourmap legend;

Thank you. The figure has been modified accordingly.

In the caption 'experiences' should be 'experiments'?!

Thank you.

L.318: ..but there are more unobserved polynyas for MULTIVAR according to Fig.2 ?!

We mentioned this result in the conclusion and we can indeed mention it in this section and refer to a figure in the supplementary materials. L.318: **"***In the Antarctic, the two assimilated experiments generate variability and occurrence of unobserved polynyas, but MULTIVAR creates them more frequently all around Antarctica (Figure S2).***"**

Figure 3 and 4: Shouldn't the RMS have the same unit as SNV and RFBV?

No, because the values for the SNV and RFBV are the variables integrated over the whole iced area, to be able to discuss a 3D volume. The RMS is computed on each grid cell, with the variables expressed as SNV and RFBV averaged over the cell's iced area, meaning values in [m^3]/[m^2], following the model's definition of these variables.

I really like the distribution plots in a). Maybe these could also be added to the plots for SIC (Fig.2), total fb (Fig. 5, 6) and SIV (Fig. 8,9)?

Thank you for this comment. Indeed, the PDF nicely provides a synthetic evaluation. We don't think they are as relevant for SIC and this study does not aim at presenting a detailed validation of SIC. We did not conduct a detailed analysis of the total FB and SIV distributions for comparisons with IceSat-2 and SMOS because the article is already too long and focuses on showcasing the potential of the multivariate/multi-data approach.

Figure 4: It would be nice to see the full first peak around 0. Maybe add an inset with a higher y axis.

The 0 peak goes up to 25% and above. We chose to limit the view in the y-axis to be able to see the second mode of this PDF.

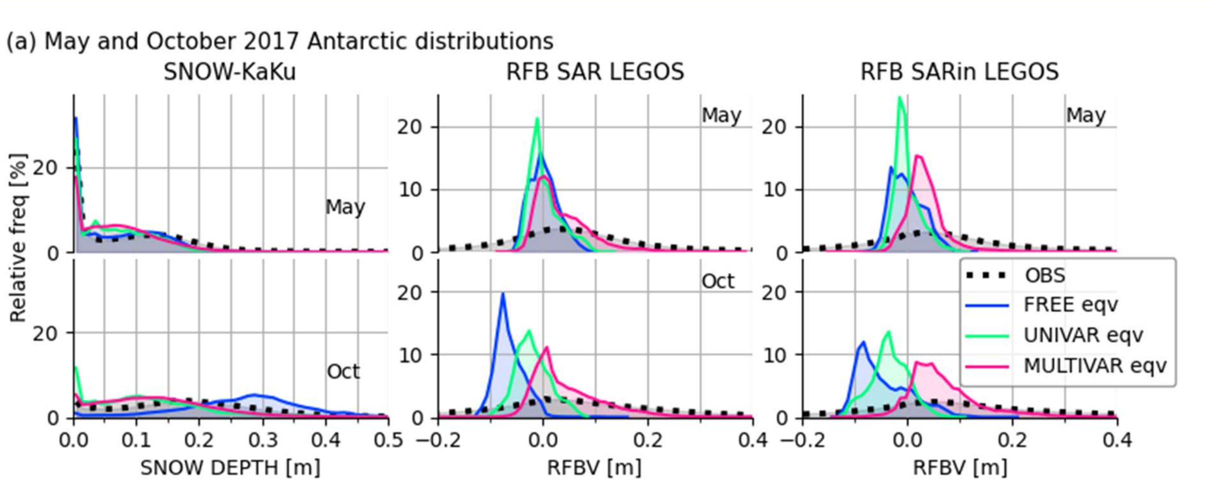


Figure RC1fig1: Panels (a): Probability density functions (%) of the snow thickness, the radar freeboard SAR and radar freeboard SARin observations (dotted black) and their model equivalent for the FREE (blue), UNIVAR (green) and MULTIVAR (pink) experiments in the Antarctic for May and October 2017. The full extent of the 0-mode is shown for the snow thickness PDFs.

L.354: FREE diverges the most, but also matches best with the observations in May

That is true. The sentence has been modified to "*Among the simulations, the FREE experiment matches better the observations in May 2017 but then diverges the most from the observations, showing an increasing accumulation of snow as winter progresses, with a main mode 11.2 cm higher than the observed mode in October 2017***".**

L.460: 'excludes' rather than 'includes'?

Thank you.

L.472: Stick to SIV instead of SIVOLU (I think this is what you mean?!)

Thank you.

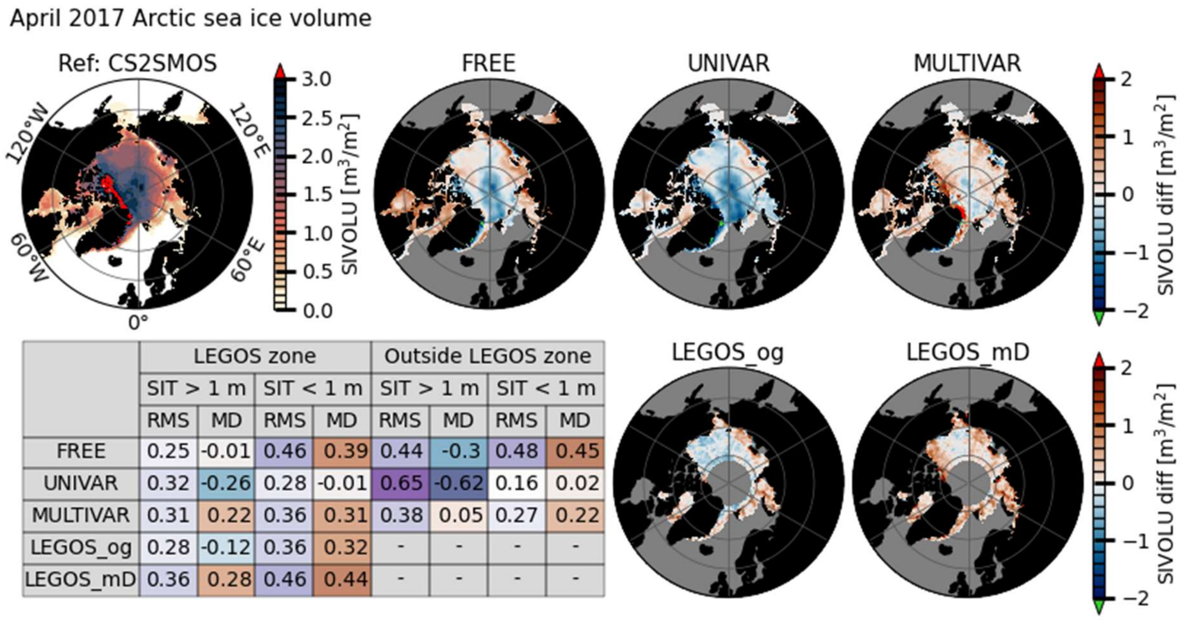
L.486: I am missing a paragraph on the Antarctica plot in Figure 7b and specifically also a comment/explanation why the timings of sea ice volume decrease are offset between observations and model. In 2018, the observations clearly drop between September and October, whereas the models are still increasing.

The paragraph describing the sea ice volume in Antarctica has been added. Thank you for noticing. The added paragraph starts now L.487: "*As in the Arctic, MULTIVAR has the highest freezing rate and the highest total sea ice volume in Antarctica among the experiments for the most part of the simulation periods (Figure 7(b)), with, on average, 25% and 141% higher ice volume than FREE and UNIVAR estimates respectively. UNIVAR consistently presents the lowest ice*

volume. The assimilated experiments have irregular time series during the second half of the growing season, the MULTIVAR simulation especially collapses many times before reaching its peak. These collapses coincide between the two assimilated experiments and are also present in the observation space (solid lines, Figure 7(b)). These sudden ice volume losses are due to the occurrence of large open waters or polynias within the sea ice cover which first and foremost causes an increase of sea ice leads from July to September 2017 and in August and September 2018 (Figure 1(b)). Some of them also appear in the observation products such as the well-known Maud-rise polynya in the Weddell Sea in 2017.
*The use of the model constant densities (LEGOS_mD) results in higher SIV estimates than the LEGOS_og product using seasonally varying ice and snow densities to convert RFB into ice thickness (Figure 7 (b)). The deviation between these two datasets is maximum in October because of the significant drop in ice density from 900 kg.m-3 to 875 kg.m-3 between September and October. With one exception (October 2018), both LEGOS_og and LEGOS_mD observations present systemically higher SIV values than MULTIVAR simulation. And even if the MULTIVAR experiment remains the closest experiment to the LEGOS observations, it is still up to 10 million km3 below the LEGOS_mD estimates. Over both 2017 and 2018 winters, the datasets present mean SIV of respectively 4.6, 8.0, 10.8, 15.2 and 18.5 million km3 for the UNIVAR, FREE and MULTIVAR simulations, and the LEGOS_og and LEGOS_mD products. The LEGOS_og product displays a sea ice maximum in September, a month earlier than the FREE simulation. LEGOS_mD also has a SIV maximum in September for 2018 winter only, but the differences in densities make it unclear to identify the exact peak period in 2017. Similarly, the occurrence of polynias in assimilated experiments makes it impossible to accurately determine the maximum period.***"**

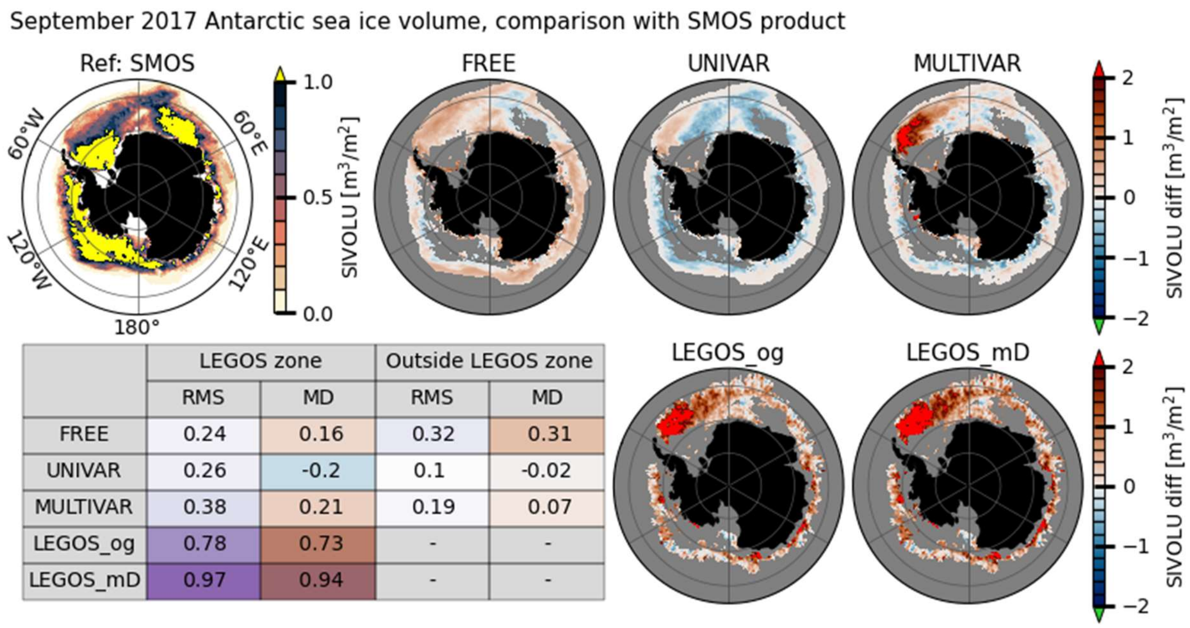
Figure 8: I find greener colours in the table to mark worse results counterintuitive and would suggest using another colour like yellow.

We agree. Instead of yellow, for which a color gradient is not so visual, we changed the green colormap to a purple one. (See Figures 8 and 9 below)



	LEGOS zone				Outside LEGOS zone			
	SIT > 1 m		SIT < 1 m		SIT > 1 m		SIT < 1 m	
	RMS	MD	RMS	MD	RMS	MD	RMS	MD
FREE	0.25	-0.01	0.46	0.39	0.44	-0.3	0.48	0.45
UNIVAR	0.32	-0.26	0.28	-0.01	0.65	-0.62	0.16	0.02
MULTIVAR	0.31	0.22	0.36	0.31	0.38	0.05	0.27	0.22
LEGOS_og	0.28	-0.12	0.36	0.32	-	-	-	-
LEGOS_mD	0.36	0.28	0.46	0.44	-	-	-	-

Figure 8: April 2017 sea ice volume in the Arctic for CS2SMOS dataset (reference) and its difference with the FREE, UNIVAR, and MULTIVAR experiments (first line) and the observations LEGOS_og (original) and LEGOS_mD (with model constant densities). Table: root mean square error (RMS) and mean difference (MD) between FREE, UNIVAR, MULTIVAR, LEGOS_og, LEGOS_mD and CS2SMOS data, calculated on the LEGOS zone and outside the LEGOS zone and for CS2SMOS sea ice thickness of less than or greater than 1m. The table colours highlight the values close to 0 (white) and the extremes (green for the RMS, and blue/red for the negative/positive MD). The LEGOS zone corresponds to areas where the KaKu snow depth is available.



	LEGOS zone		Outside LEGOS zone	
	RMS	MD	RMS	MD
FREE	0.24	0.16	0.32	0.31
UNIVAR	0.26	-0.2	0.1	-0.02
MULTIVAR	0.38	0.21	0.19	0.07
LEGOS_og	0.78	0.73	-	-
LEGOS_mD	0.97	0.94	-	-

Figure 9: September 2017 sea ice volume in the Antarctic for the SMOS data (reference) and its difference to the FREE, UNIVAR, and MULTIVAR experiments (first line) and to the observations LEGOS_og (original) and LEGOS_mD (with model constant densities). The colorbar shows only which only measures the ice that is thinner than 1 m (thicker ice is represented in yellow). Table: root mean square error (RMS) and mean difference (MD) between FREE, UNIVAR, MULTIVAR, LEGOS_og, LEGOS_mD and SMOS data, calculated on the LEGOS zone and outside the LEGOS zone. The table colours highlight the values close to 0 (white) and the extremes (green for the RMS, and blue/red for the negative/positive MD). The LEGOS zone corresponds to areas where the KaKu snow depth is available.

Figure 9: Explain the white areas in the figure caption

We changed the figure to have the ice area for thicknesses above 1 m in yellow (see Figure 9 above). Now, the white areas are only related to the free ocean surfaces. We added the precision "*The colorbar shows only the ice that is thinner than 1 m (thicker ice is represented in yellow),*" **in the caption.**

L. 601: You say most of the analysis in Antarctica was done in summer when no data is assimilated, however, most plots for the Antarctic are shifted by 6 months compared to the Arctic and if not, why don't you show those plots to make it a fairer comparison? Ideally, as mentioned above, all plots should be available to the reader anyway.

The issue we encounter with the comparison with ICESat-2 data is that they are available from the 15th October 2018. Then, only 15 days of altimetric observations assimilation are available in Antarctica for that season. We stopped the simulations in March 2019, so there is no other period where both ICESat-2 measurements and the altimetric observations are available. We don't provide maps of differences with ICESAT-2 in the manuscrit, we don't understand which plots you are referring to? On Figure 6, the period January-February 2018 is shown in Antarctica and presents results in summer, with a comparison between our simulations' results and IceSat-2 measurements.

L.678: Explain VP and EVP

Thank you. VP stands for Viscous-Plastic, EVP for Elastic-Viscous-Plastic. The modification has been done in the manuscript: L.578 "*Sea-ice models using Viscous-Plastic or Elastic-Viscous-Plastic rheologies***".**

L.742: CRISTAL will also have a higher inclination orbit and hence provide these measurements with a much smaller hole (data gap) around the poles.
Thank you. A sentence has been added to the manuscript to convey this information L.741: "*Moreover, a higher inclination orbit will enable measurements with a smaller hole around the North pole with the CRISTAL satellite.***"**

L.744: CIMR will also provide thin ice estimates like SMOS from L-band radiometry.
Thank you. A sentence has been added in the conclusion to convey this information: "*CIMR will also provide thin ice estimates from L-band radiometry, similar to SMOS.***".**