Responses to referee #2

Interactive comment on "A comparison between Envisat and ICESat sea ice thickness in the Antarctic" by Jinfei Wang et al.

General Comments:

In general, the data comparisons in this paper are done adequately, but the analysis of differences is speculative and weak. I think major revisions will be needed.

Dear Reviewer:

We would like to thank you for the helpful comments to improve this manuscript. We made major revisions on this study as suggested. Specifically, we added more description about the importance of Antarctic sea ice thickness in the Introduction part. We added the discussion of possible uncertainties induced by comparing large-footprint satellite remote sensing data (Envisat and ICESat) with point measurements (ULS observations). We also corrected the mistake that Point 3 referred to by considering the sea ice thickness growth during the freezing season, rather than the melting season. In Section 4, we added some quantitative analyses to avoid the speculative and weak statements.

The specific responses and revisions are shown below. They are in blue font for clarity.

Corresponding Authors:

Qinghua Yang (yangqh25@mail.sysu.edu.cn) and Qian Shi (shiq9@mail.sysu.edu.cn)

Main Comments:

Point 1: The first paragraph of the Introduction discusses the extent of Antarctic sea ice, but it fails to mention the fact that almost all of that sea ice is seasonal – it completely melts away every year, except in a small portion of the western Weddell Sea. Therefore, it's not clear to me why "sea ice thickness is an equally critical component as sea ice extent" (line 33). I understand the importance of sea-ice extent as a barrier between the ocean and the atmosphere that affects albedo and the exchange of heat and moisture, but I think the authors need to explain better why Antarctic sea-ice thickness is so critical, given that almost all the ice melts away every year.

Response: We have added the description about the importance of sea ice thickness in the first paragraph of the Introduction: "Sea ice thickness combined with sea ice extent is necessary to quantify the sea ice volume and sea ice mass (e.g. Kurtz and Markus, 2012; Massonnet et al., 2013).

Changes in sea ice volume can influence the fresh water input into the Southern Ocean. Moreover, sea ice thickness is also necessary for assessing sea ice mass balance, the surface energy budget, and predicting changes in the polar climate system." *(please see P2 line 41-44 in the revised manuscript)*

Point 2: In the comparisons of ULS data with Envisat and ICESat (Section 3.1) there is no mention of the fact that ULS measurements are made at a single point, whereas Envisat and ICESat measurements are made over large footprints or areas. How might that affect the comparisons?

Response: We discussed the uncertainties caused by such comparison at the end of Section 3.1: "However, it is noted that the ULS measurements are recorded at fixed locations with approximately 6–8 m footprint in diameter, while Envisat has a footprint of 2–10 km and the SIT data used in the comparison represents mean values over 50 km grid cells, and ICESat has a footprint of 70 m and the SIT data represents mean values over 100 km grid cells. This large scale difference can increase the selection biases. When the ULS measures a single point like a ridge or an edge of thin ice, satellites will detect a large area including the single point and other sea ice, and their SIT are averaged through the area. In addition, although the ULS SIT and satellite SIT are all monthly mean values, one satellite SIT grid cell are actually scanned once or twice through a month. And the average of one or two values has a poor representation of the mean SIT throughout the whole month. Theoretically, more valid measurements in one grid cell, more accurate the mean SIT is. In general, uncertainties from both the spatial interpolation and temporal representation can affect the comparisons. However, considering the typical sea ice motion in the Weddell Sea, monthly average ULS sea ice thickness could be referred as a spatial average value, represent one hundred kilometers around the fixed ULS positions. In general, Envisat and ICESat can overpass ULS positions several times a month and are comparable to that of ULS SIT." *(please see P9 line 259-271 in the revised manuscript)*

Point 3: Lines 232-238. The mean sea-ice thickness in both the Envisat and ICESat data increases from spring to summer. The authors call this an "anomalous thickness growth" as if it can't possibly be true, and they attribute it to "limited comparison pairs" and "uncertainties of both data sets". However, isn't it possible that the mean ice thickness could actually be greater in summer, because the thinnest ice melts away, leaving only thicker ice? Antarctic sea-ice extent is about 18 million sq km in spring and 3 million sq km in summer. Suppose the spring ice extent consists of 15 million sq km of 1.3 m ice and 3 million sq km of 3.2 m ice, for a mean thickness of about 1.6 m (matching the actual spring ICESat mean thickness). And suppose that all the ice loses 1.3 m of thickness in the summer melt. Then only 3 million sq km are left, with a mean thickness of 3.2 - 1.3 = 1.9 m (matching the actual summer ICESat mean thickness). I'm not saying that these are the correct numbers, I'm just pointing out the plausibility of the argument that the mean thickness could be greater in summer than in spring. Of course it requires a more careful analysis.

Response: We recognized this fact and strongly agreed with you. We reproduced the probability distribution figure and changed the bin size into 0.2 m, shown in Fig.1. In addition, we chose to focus on the different growth of the two SIT products from autumn to spring following the other referee's comments. We added the analysis:

"We notice that Envisat and ICESat mean SIT have different variations from autumn to spring. ICESat SIT increases while Envisat SIT does not. For Envisat SIT, the modal (mean) values change from 1.70 m (1.95 m) to 1.30 m (1.60 m) and the distribution indicates that more thin ice is produced. But for ICESat SIT, the modal SIT stays constant of 1.1 m, while the mean values vary from 1.36 m to 1.60 m, and the distribution indicates that more thick ice is found." *(please see P12 line 339-343 in the revised manuscript)* We further examined this problem by comparison the variations with that from FDD model and the results are shown in the response for Point 4 (4).

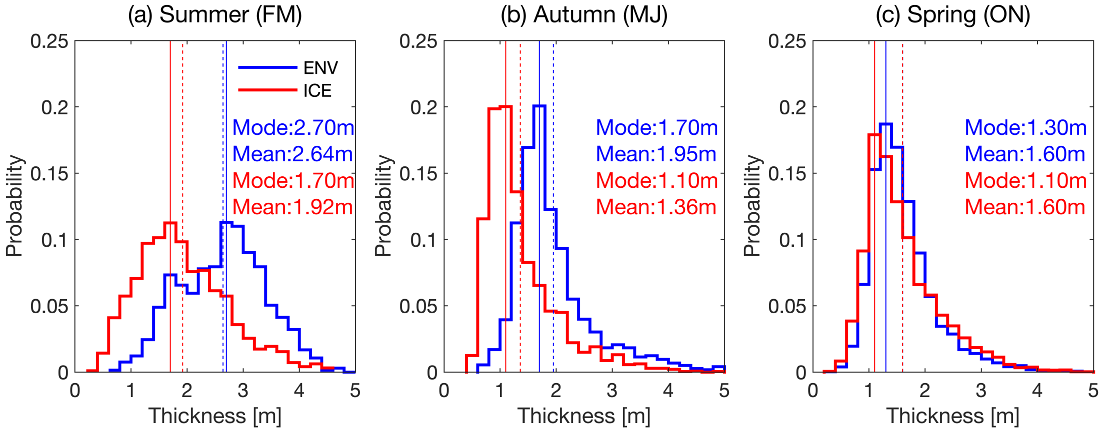

Figure 1. Probability of the Envisat SIT and the ICESat SIT for all the individual comparison pairs. The blue stairs represent Envisat ice thickness and the red stairs represent ICESat ice thickness. The solid lines indicate the modal ice thickness and the dashed lines indicate the mean ice thickness of both data sets.

Point 4: Section 4 discusses the reasons for the differences between Envisat and ICESat sea-ice thickness: (i) if the snow is wet, the Envisat radar does not penetrate all the way to the snow/ice interface; (ii) the footprints of Envisat and ICESat are different; (iii) snow depth is treated differently in the retrieval algorithms. These are all legitimate potential reasons for the differences between Envisat and ICESat ice thickness, but as presented here, they are speculative and qualitative arguments, not quantitative. For example, consider equation (1) for the ice thickness from Envisat, in which F is the measured freeboard and S is the assumed snow depth. If the radar backscatter is from wet snow within the snow layer, rather than the snow/ice interface, then the measured freeboard F is partially ice and partially wet snow. This would lead to a modification of equation (1) and a new ice thickness I' instead of I. Does the difference I-I' account for the bias in Envisat relative to ICESat? Another example: regarding snow depth, how much of a change in snow depth in the Envisat retrieval algorithm would be needed to account for the bias in ice thickness relative to ICESat? Is this change in snow depth within the uncertainty of the snow depth measurements?

Another example: Figures 10 and 11 suggest a connection between ice thickness differences and relative humidity. What is the correlation? Have other researchers considered this connection? Another example: a very simple model of ice thickness is based on cumulative freezing-degree-days (FDD), e.g. Lebedev 1938. Using temperature fields from (say) a reanalysis product, how does a simple FDD ice thickness model compare to Envisat and ICESat ice thickness? Would this provide any insight into biases? My overall point is that the analysis in this paper (Section 4) needs to be more quantitative. The authors claim that "without enough observation data and numerical model experiments we cannot quantify the impacts of the uncertainties over the sea ice thickness." (lines 327-328). But my suggestions above for further quantitative analysis do not require any additional ice thickness data or numerical model runs that are not already publicly available. This is not a question of lack of data, it’s a question of digging into the comparisons of Section 3 more quantitatively.

Response:

(1) We did not consider this I-I’ before, because the uncertainties of Envisat caused by wet snow are not involved in SICCI data. However, we conducted some quantitative analyses here by assuming the total freeboard derived from ICESat and the snow depth product used in the retrieval of Envisat SIT are accurate. Then we can calculate the expected difference *D’* between Envisat and ICESat SIT caused solely by the radar altimeter penetration. Considering Eq. (1) in the manuscript for a transformation adapted to ICESat total freeboard *Ft*:

$$I' = \frac{(Ft\text{-}S)\cdot\rho_{water}+S\rho_{snow}}{\rho_{water}\text{-}\rho_{ice}} \quad ,$$

(6)

where *S* represents snow depth, *I’* represents the new sea ice thickness, ρ_{water}, ρ_{snow}, ρ_{ice} refer to the density of the sea water, snow cover and sea ice, respectively. Then we can derive a new difference by deducting Eq. (6) from Eq. (1):

$$D' = \frac{\rho_{water}\cdot(F+S-Ft)}{\rho_{water}-\rho_{ice}} \quad (7)$$

where *F* represents Envisat sea ice freeboard. We set ρ_{water} for 1024 kg m^{-3}, ρ_{ice} for 916.7 kg m^{-3} and *S* for the NSIDC AMSR-E snow depth (nsidc.org/data/ae_si12). For the three seasons which are spring, summer and autumn, we can calculate that the values are -0.57 m, 0.47 m and 0.32 m, respectively. Compared to the seasonal average difference shown in Table 5, which are -0.01 m, 0.51 m and 0.53 m, we can conclude that differences in summer are mainly due to radar altimeter inability. Differences in spring cannot be explained by this bias, implying that snow depth uncertainties are the major cause. However, the real difference caused by penetration is a bit more complicated than that. If the range has only partial penetration, then it is also required to adjust the snow propagation speed correction since the radar waves are not traversing the entire snow layer. *(please see P14-15 line 414-428 in the revised manuscript)*

(2) We also conducted some quantitative analyses on the uncertainties caused by the biased snow

depth. Assuming that sea ice freeboard derived from Envisat is accurate, we can calculate the required snow depth ΔS for compensating the difference between Envisat and ICESat SIT (D). According to Eq. (1), we can derive that:

$$\Delta S = \frac{\rho_{water} - \rho_{ice}}{\rho_{snow}} \cdot D ,$$

(8)

Setting ρ_{snow} for 300 kg m^{-3}, we can get ΔS for spring, summer and autumn as -0.36 cm, 18.24 cm and 18.96 cm, respectively. According to Kern et al. (2015), the average monthly retrieval uncertainties are commonly below 2 cm, albeit the standard deviations of the data are substantially larger than uncertainties. Therefore, we can infer that in spring the cause of differences is mainly the bias of snow depth product, while in summer and autumn the biases mainly come from the differences of observational technique. *(please see P16 line 466-473 in the revised manuscript)*

(3) We plotted the seasonal average maps of the four parameters as the other referee suggested, including 2 meter temperature, sea surface temperature, surface net solar radiation and surface net thermal radiation. All of them come from ERA-Interim reanalysis data. We also calculated the linear correlation coefficients between the difference of ENV-ICE SIT and each meteorological parameter in each season and the results are shown below in Table 8. We can see that the best linear correlation coefficient is the relative humidity and the others are all bad, albeit the relation with humidity is also weak. We assume that there might be relations between the difference and temperature and radiation, but they are absolutely not linear relations. In order to dig into this relation, more analyses are needed. However, this is not the kernel in this study. Therefore, we considered removing this part.

Many studies have pointed out that wet snow can affect the penetration. But they don’t combine the relative humidity with the difference before, since the relative humidity values are not that accurate due to the precipitation observations in the Antarctic are difficult and unreliable.

Table 1. The linear correlation coefficients between the difference of ENV-ICE SIT and each meteorological parameter in each season. The values in italic type have not passed the 95% significance test.

	Relative humidity	2 meter temperature	Sea surface temperature	Surface net solar radiation	Surface net thermal radiation
ON	0.28	-0.12	-0.14	-0.24	***0.01***
FM	0.38	-0.26	-0.44	-0.37	0.17
MJ	0.52	-0.25	-0.23	-0.22	0.10

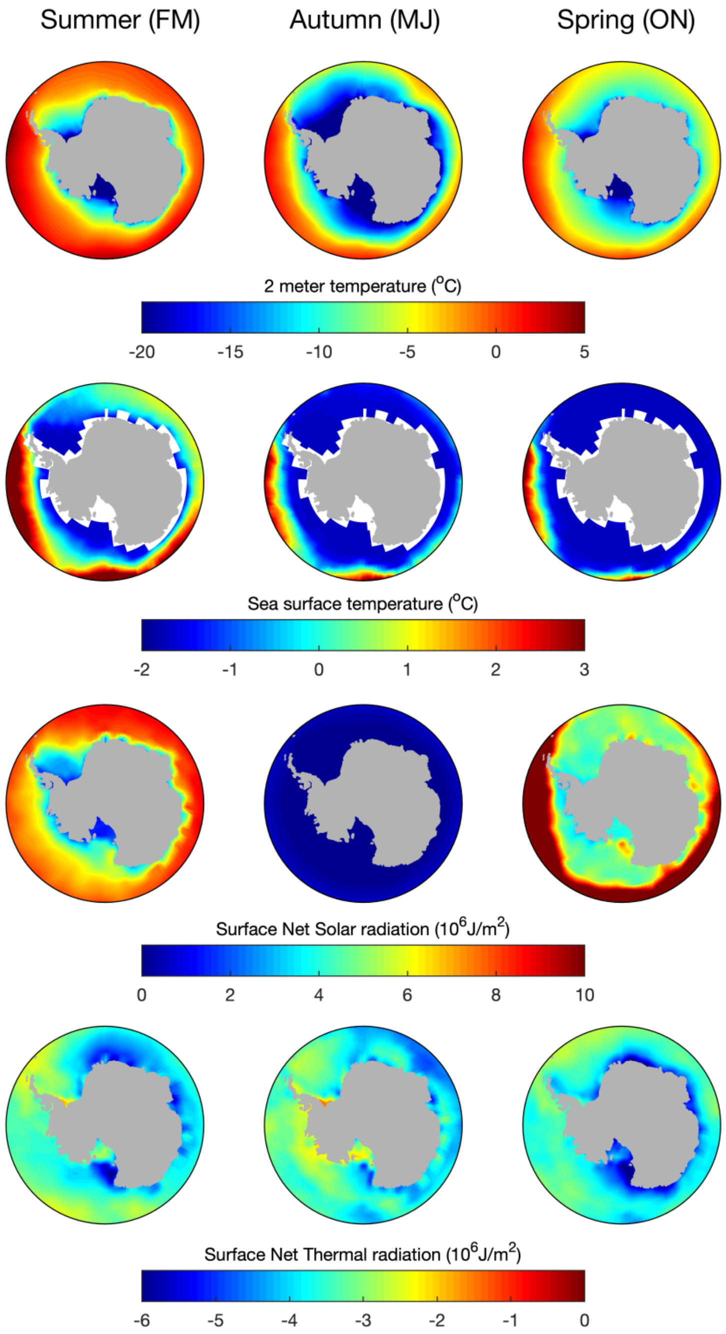

Figure 2. Seasonal average maps of 2 meter temperature, sea surface temperature, surface net solar radiation and surface net thermal radiation based on ICESat operating periods.

(4) We use 2 meter temperature data derived from ERA-5 reanalysis provide by Copernicus Climate Change Service (C3S) (2017) to generate the accumulative freezing-degree-days (FDD). According to Lebedev (1938), we construct a simple model to produce sea ice thickness and examine the growth from autumn (MJ) to spring (ON) every year. Then we compare it with the thermodynamic growth represented by Envisat and ICESat SIT. The results are added in the manuscript: "Since May-June period is the beginning of the upswing freezing season and October-November period is

near the end of it, we assume that thermodynamic growth contributes more to the SIT variations than dynamic growth. Therefore, we further compare this development with the FDD model results in 2004, 2005 and 2006, shown in Table 6. As introduced in Sect. 2.4, this model is only involved in the temperature, representing the thermodynamic growth and neglecting any dynamic contributions to sea ice thickness. Figure 8 shows the sea ice thickness growth maps from autumn to spring derived from FDD model, Envisat and ICESat in 2004, 2005 and 2006. Table 6 shows the statistical results of the growth maps. We calculate the period-average SIT from the model corresponding to ICESat operating periods. The results show that Envisat SIT has an opposite development from ICESat and model. And the development of ICESat SIT is smaller than and not constant as the model results. Although ICESat SIT has an overall increase, it also shows a decrease in Western Weddell Sea similar to Envisat SIT. In addition, both of them show an increase along the coast of Amundsen Sea in 2006. Combined with the typical sea ice motion in the Weddell Sea and Ross Sea shown in the first panel, we consider that ICESat shows more realistic sea ice change, e.g. a decrease SIT in the Ross Sea polynya and increase around it, or the increase in the East Weddell Sea." *(please see P12 line 343-355 in the revised manuscript)*

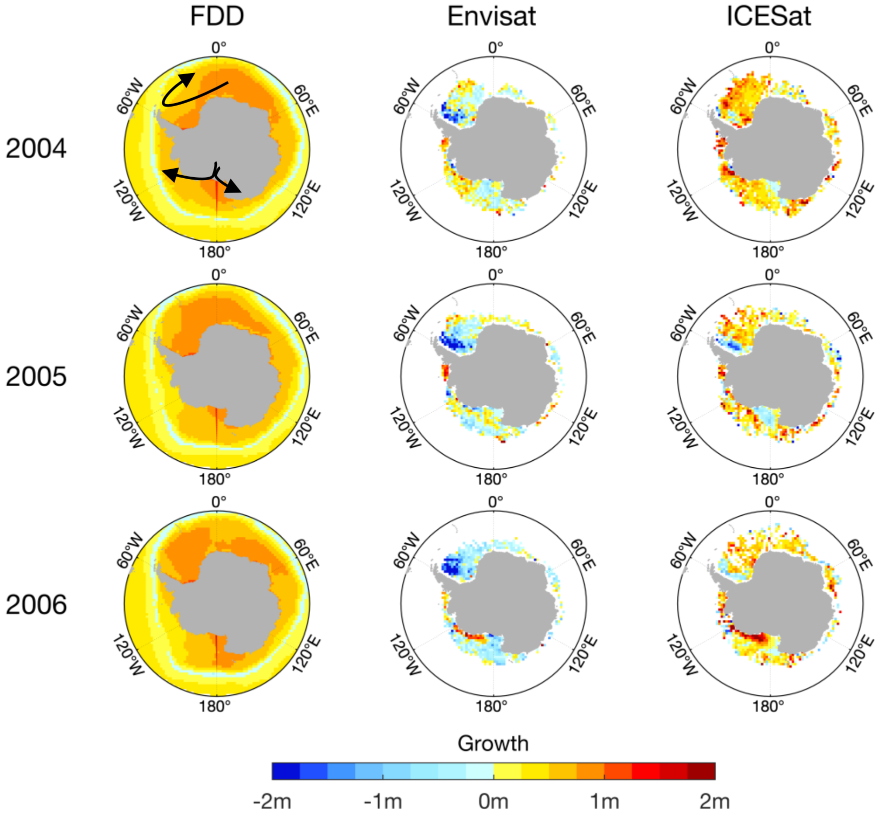

Figure 3. The sea ice thickness growth maps from autumn to spring derived from FDD model, Envisat and ICESat in 2004, 2005 and 2006. The arrows refer to the typical sea ice motions in the West Weddell Sea and Ross Sea.

Table 2. Statistical results of the sea ice thickness development from autumn (MJ) to spring (ON) in 2004, 2005 and 2006.

	Envisat SIT (m)	ICESat SIT (m)	FDD (m)
MJ04	1.94	1.33	0.55
ON04	1.64	1.64	1.11
ON04-MJ04	-0.30	0.31	0.56
MJ05	1.98	1.43	0.57
ON05	1.59	1.54	1.13
ON05-MJ05	-0.39	0.11	0.56
MJ06	1.92	1.32	0.58
ON06	1.44	1.63	1.14
ON06-MJ06	-0.48	0.31	0.56

Minor Comments:

Lines 19-23. It’s not clear whether the deviations are Envisat minus ICESat, or ICESat minus Envisat.

Response: We added “that Envisat SIT minus ICESat SIT” to explain this ambiguity.

Line 21. "the large correlation coefficient" – Is this a spatial correlation or a temporal correlation? Please add the word "spatial" or "temporal" as appropriate.

Response: This is the correlation between two SIT distribution maps and we added “spatial” in the revised manuscript.

Line 103. Following equation (1), say that rho is density.

Response: We add this information: “ρ_{water}, ρ_{snow}, ρ_{ice} refer to the density of the sea water, snow cover and sea ice respectively.” *(please see P5 line 136-137 in the revised manuscript)*

Line 104. Give a reference for AMSR-E snow depth climatology.

Response: The snow depth climatology is produced by and for ESA CCI by Stefan Kern. This snow-depth climatology is derived from Advanced Microwave Scanning Radiometer-EOS (AMSR-E) and AMSR-2 data for the Antarctic and is based on a revised version of the approach described by Cavalieri et al. (2014) and provided by the Integrated Climate Data Center (ICDC, http://icdc.cen.uni-hamburg.de). *(please see P5 line 138-141 in the revised manuscript)*

Line 108. A threshold of 70% is given here, but on line 131 it says 60%.

Response: The usage of different SIC thresholds is because of the different thresholds used in the retrieval of the two data sets. Envisat SIT employs a SIC threshold of 70% during the retrieval while the ICESat SIT uses 60%. Only areas with sea ice concentrations greater than the threshold are considered a valid area for detection of leads and sea ice. Therefore, we are meant to point out this information. In order to express more clearly, we changed the two sentences to:

"In addition, it is noted that values with sea ice concentration less than 70 % have been removed during Envisat SIT retrieval." *(please see P5 line 145-146 in the revised manuscript)*

"It is noted that grid cells with sea ice concentration less than 60% have been remove during ICESat SIT retrieval." *(please see P6 line 170-171 in the revised manuscript)*

We also tested the difference between using 60% and 70% SIC threshold for ICESat during the comparison with Envisat SIT. According to Table 3, this different threshold does not play an important role in the results of this paper. D(60) refers to Envisat minus ICESat (ENV-ICE) applying 60% SIC threshold for ICESat, while D(70) refers to ENV-ICE when SIC threshold for ICESat is 70%. Since the ice concentration gradients are usually quite steep, there will not be a lot of area with values 60% < SIC < 70%.

Table 3. Statistical results of the comparison between Envisat SIT and ICESat SIT using 60% and 70% SIC threshold at each operating period.

	ON04	ON05	ON06	ON07	FM04	FM05	FM06	MA07	FM08	MJ04	MJ05	MJ06
D(60)	0.00	0.05	-0.19	0.14	0.89	0.74	0.47	0.61	0.92	0.61	0.55	0.60
D(70)	0.00	0.06	-0.21	0.15	0.79	0.66	0.43	0.61	0.89	0.60	0.55	0.61

Lines 125-126. "R is the ratio of sea ice thickness over snow depth, which is a seasonally dependent factor and calculated from ASPeCt observations." I understand that R changes seasonally, but does it also change from year to year based on ASPeCt observations?

Response: No, R values are constant in each season (6.8 in summer, 6.0 in autumn, and 5.4 in spring) and do not change from year to year.

Line 139, equation (4). Please provide UNITS for the quantities in this equation.

Response: We added the units in the equation: z(m) = 0.028+1.012d(m). *(please see P7 line 183 in the revised manuscript)*

Line 146. "the deviations." – please say explicitly "the deviations between Envisat and ICESat sea-ice thickness" or whatever deviations are being referenced here.

Response: We refined it to "the differences between Envisat and ICESat sea-ice thickness".

Lines 151-153. "The seasonal classification is based on the ICESat operating periods... If ICESat data has overlapping time over ten days with respective months, we average Envisat data over the two months." OK, but wouldn't it be better to do a time-weighted average of the monthly Envisat data to match the ICESat period? For example, consider the ICESat period from Feb 17 to Mar 20.

Instead of averaging Envisat over all of February and March, consider this: the ICESat period is 32 days long – 12 days in February and 20 days in March. So calculate: (Env. avg.) = (12/32)*(Env. Feb.) + (20/32)*(Env. Mar.) Wouldn't that provide a more accurate Envisat average with which to compare ICESat?

Response: Thanks for your comments. We followed your suggestions and did a time-weighted average of the monthly Envisat data to match the ICESat period. But it is noted that the little change has little affect on the results of the comparisons but only add more accuracy.

Line 164. For the ULS data, I understand that "207" refers to location #207 in Figure 2, but I don't understand "207-6" – what is the "6"? Please explain your numbering system.

Response: The number appended behind the ULS station numbers refer to different ULS operation periods at each location. For example, "207-6" represents the sixth leg of measurements at the station #207, from 14 March 2005 to 27 March 2008. However, we combined the successive records for 229 and 231, so we changed the expression here as: "there are only three sites having enough valid data for the evaluation: 207, 229 and 231".

Line 168. "Due to the discontinuity..." – what discontinuity?

Response: The "discontinuity" here means the ICESat measurements are not continuous due to cloud coverage or lack of valid data. Each measurement campaign lasts for about 35 days and only operates three times a year. Therefore, the number of ICESat measurements for comparison with ULS is limited. To make it clearer, we change "discontinuity" to "operating period gaps".

Lines 173-174. In Figure 4, where do the error bars come from? What do they represent? One standard deviation? 95th percentile?

Response: The Envisat error bars come from the SIT uncertainty σ_{sit} contained in the Envisat SIT product and is computed as the error propagation of all input uncertainties with the assumption that the sea water density is negligible (Paul et al. 2017):

$$\sigma_{sit} = \sqrt{(\frac{\rho_w}{\rho_w-\rho_i}\sigma_{frb})^2 + (\frac{frb\cdot\rho_w+sd\cdot\rho_i}{\rho_w-\rho_i}\sigma_\rho^i)^2 + (\frac{\rho_s}{\rho_w-\rho_i}\sigma_{sd})^2 + (\frac{sd}{\rho_w-\rho_i}\sigma_\rho^s)^2}$$

where *frb* represents Envisat sea ice freeboard, *sd* represents snow depth, ρ_w, ρ_s, ρ_i refer to the density of the sea water, snow cover and sea ice, σ_{frb}, σ_ρ^i, σ_{sd}, σ_ρ^s represent the uncertainties of sea ice freeboard, ice density, snow depth and snow density, respectively.

ICESat SIT uncertainties σ_I are calculated based on the uncertainties of sea ice and snow, also neglecting the uncertainty of water density (Li et al., 2018):

$$\sigma_I = \sqrt{(\frac{R * F * \rho_w}{(R+1) * (\rho_w - \rho_i^*)})^2\sigma_{\rho_i}^2 + (\frac{F * \rho_w}{(R+1) * (\rho_w - \rho_i^*)})^2\sigma_{\rho_s}^2}$$

where *F* represents ICESat total freeboard, *R* represents the sea ice thickness to snow depth ratio, ρ_w, ρ_s, ρ_i^* refer to the density of the sea water, snow cover and the modified density of sea ice,

σ_{ρ_i}, σ_{ρ_s} represent the uncertainties of sea ice density and snow density, respectively.

Therefore, we added the information as: "We draw the error bars from uncertainty information provided by both SIT products. The Envisat SIT uncertainty is computed as the error propagation of all input uncertainties with the assumption that the sea water density is negligible (see Section 2.9.8 in Paul et al. 2017). ICESat SIT uncertainties are calculated based on the uncertainties of sea ice and snow, also neglecting the uncertainty of water density (see Eq. (6) in Li et al., 2018)." *(please see P8 line 237-240 in the revised manuscript)*

Line 190. It would be helpful to indicate on one of the maps the location of the Ross Ice Shelf polynya and the Ronne Ice Shelf polynya.

Response: The locations of the two polynyas have been indicated on the figure.

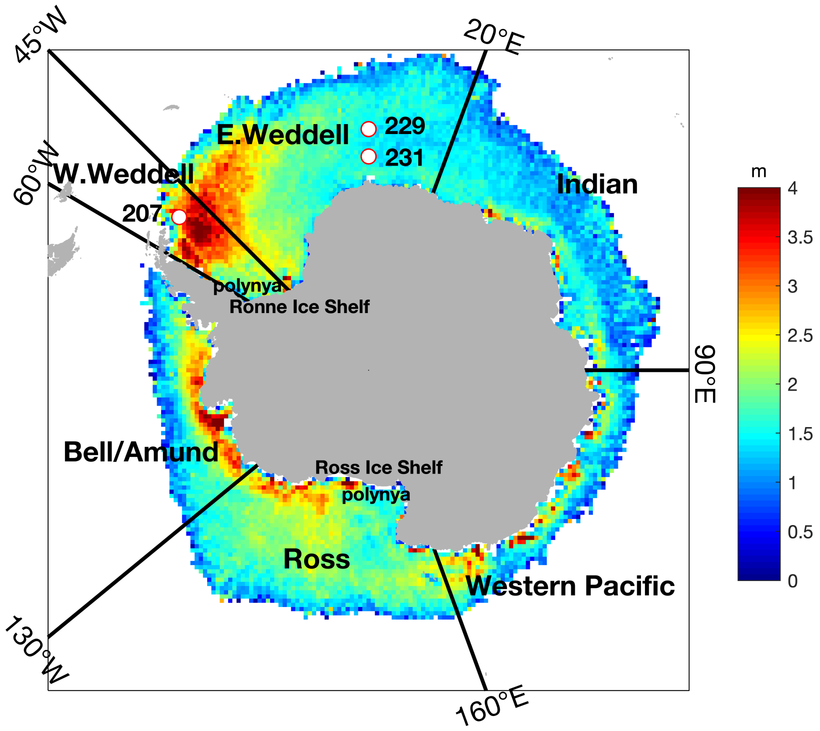

Figure 4. Map of the different sectors referred to in the study. The background is the average of the September sea ice thickness from Envisat during 2003-2011 with 50 km grid size. Each sector and the two ice shelf polynyas are indicated in the figure. The circles and the corresponding numbers refer to the sites of the ULS. The white grid cells stand for open water or sea ice with concentration less than 70% or missing data.

Line 192. I think "clockwise" should be "counter-clockwise". Please check.

Response: Thanks for your remind but here we removed this statement as the other referee's comments because this is not critical in the paper.

Lines 216-217. "Comparing the values in the eastern Antarctic, ICESat shows some deformed ice up to 3 m while Envisat shows smaller thickness by about 1.5 m." I don't see this in Figure 7. Please give approximate longitudes or otherwise indicate in Fig 7.

Response: Along the coast of the Eastern Antarctic (90–160), there are some points of larger SIT from ICESat, which can be proved by the negative deviations in the difference maps.

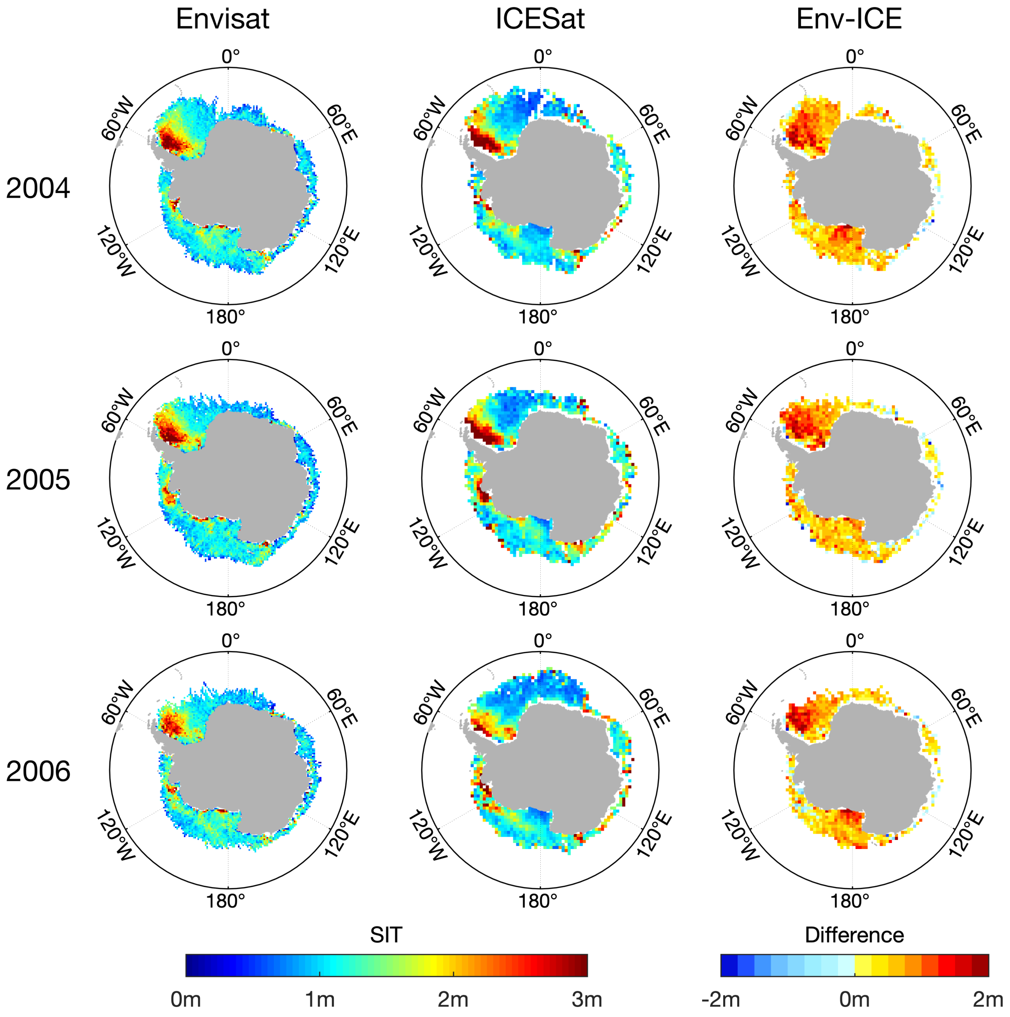

Figure 5. Comparisons of Envisat versus ICESat sea ice thickness for each ICESat operating period in autumn (May & June). The first and second columns show the sea ice thickness distribution of Envisat and ICESat respectively, and the last column shows the difference map (Envisat minus ICESat) of sea ice thickness. Each row represents a year from 2004 to 2007. The sea ice thickness maps are at their native grid resolution while the difference map is interpolated onto the polar-stereographic grid of the ICESat product. The white cells denote sea ice concentration less than threshold or missing data.

Lines 241-242. In reference to Figure 9, "In the western Weddell Sea, the regression lines have large positive intercepts in all three seasons." Yes, this is true for all five regions, not just the western Weddell Sea.

Response: Agreed, we changed the sentence to “For all the five panels, the regression lines have large positive intercepts in all three seasons.” *(please see P13 line 377-378 in the revised manuscript)*

Lines 261-262. "ICESat uses the modified snow-ice density to get rid of the biased snow depth." I don't see how equation (2) would get rid of a biased snow depth. The snow depth S is part of the factor R = I/S.

Response: Here we were meant to clarify that this product can get rid of the biased snow depth from remote sensing. Based on the previous study (Kern and Ozsoy-Cicek 2016; Kern and Ozsoy 2019; Price et al. 2019), Antarctic snow depth products from remote sensing have a lot of uncertainties. Although the one-layer-method employs the ASPeCt SIT and snow observations, which are also likely biased, the ratio between them is more reliable.

Lines 295-298. "wet snow caused by melt or flooding could lead to underestimations while refreezing of molten snow could lead to overestimations [of snow depth]. All of the above biases can also cause the differences between Envisat and ICESat." I don't see how underestimates AND overestimates of snow depth can BOTH lead to a positive bias in Envisat ice thickness relative to ICESat. Please clarify.

Response: Here "cause the differences" does not refer to the actual difference between Envisat and ICESat SIT. It only means that the biases in snow depth might affect the difference between Envisat and ICESat SIT. For the calculated differences in each season, we will discuss the main reasons respectively.

Lines 300-301. "in underestimations of snow depth... the sea ice thickness deviation presents negative." It's not clear to me whether "deviation" refers to the error in the Envisat ice thickness, or the difference Envisat-ICESat ice thickness. Consider equation (1). If the snow depth S is an underestimate, then the true snow depth S' > S. If the measured freeboard F remains constant, then the true ice thickness I' > I. The error I-I' < 0 (i.e. negative error in the original estimate I). On the other hand, I'-ICEsat > I-ICESat (i.e. increased bias of Envisat). Please clarify the use of "deviation" and the effect of snow depth on the calculated ice thickness.

Response: The "deviation" refers to the difference of Envisat-ICESat ice thickness. We clarified this part as: "Considering Eq. (1), if sea ice freeboard F remains constant, and the snow depth is underestimated, then the Envisat sea ice thickness is biased low, and the difference that Envisat minus ICESat SIT is negative. Therefore, we attribute the negative differences shown in Fig. 4 to snow depth uncertainty." *(please see P16 line 477-480 in the revised manuscript)*

Figure 2. It would be helpful to outline the zero contour (the coastline) to make it easier to distinguish land from ocean. Also, the caption should say that the background is bathymetry, and give the source of the bathymetry data.

Response: Although we reproduced the figure in the following, we chose to remove this figure and marked the three sites used in the comparison in Fig. 2 in the revised manuscript. The figure has been modified as follows:

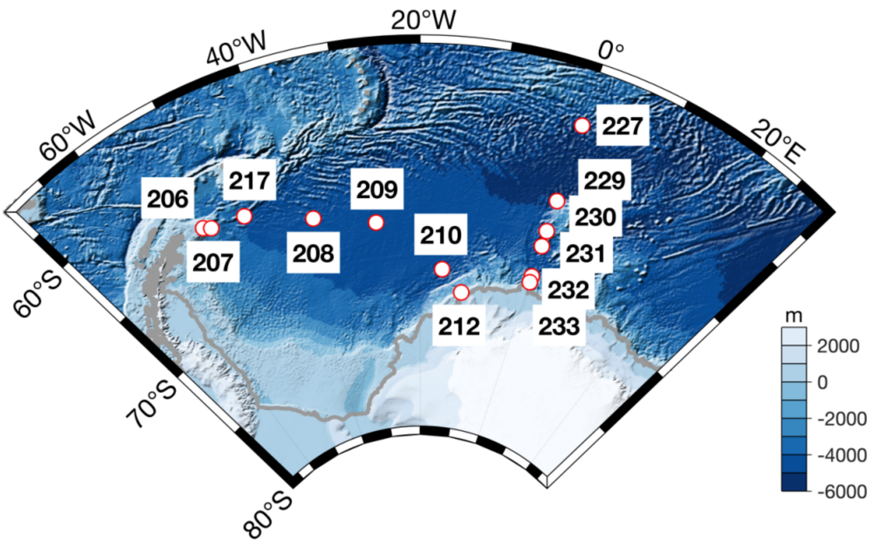

Figure 6. Map of the AWI ULS mooring locations. The background is the land topography and ocean bathymetry from ETOPO1 Global Relief Model data (doi:10.7289/V5C8276M). The circles and the corresponding numbers in the white boxes refer to the sites of the ULS. The gray line refers to the coastline of the Antarctica.

Modified from Fig.2 in Behrendt et al. (2013).

Figure 3. Please add at the end of the caption: "with 50 km grid size."

Response: Accepted.

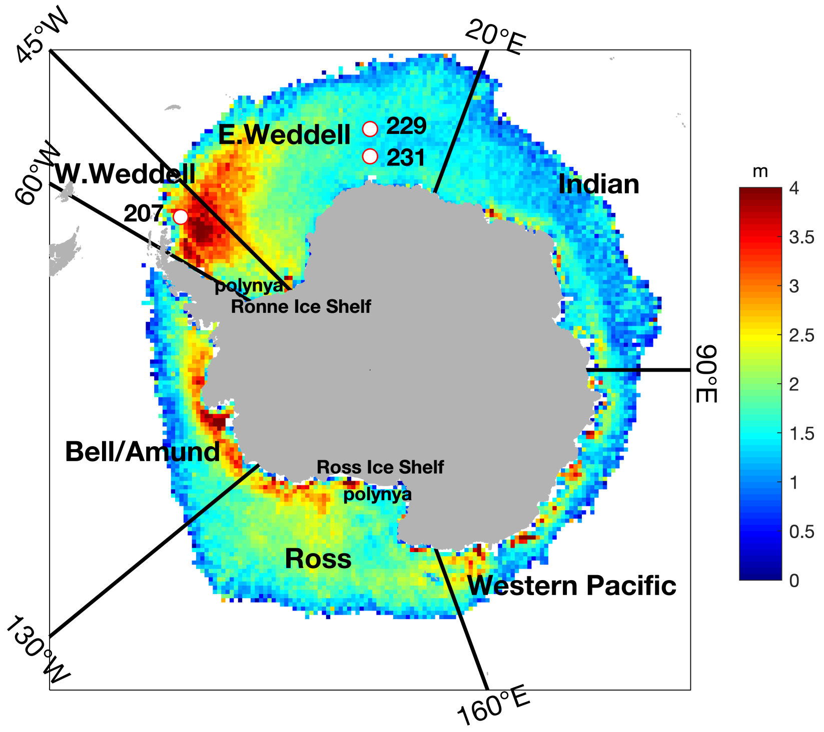

Figure 7. Map of the different sectors referred to in the study. The background is the average of the September sea ice thickness from Envisat during 2003-2011 with 50 km grid size. Each sector and

the two ice shelf polynyas are indicated in the figure. The circles and the corresponding numbers refer to the sites of the ULS. The white grid cells stand for open water or sea ice with concentration less than 70% or missing data.

Figure 4. See comment above for line 164: I understand that 207 refers to a location in Figure 2, but what does "207-6" mean? Also, see comment above for lines 173-174: in the caption, say what the error bars represent. Also, the dates along the horizontal axes should be in a more readable format such as 2008/03 instead of 200803. Perhaps the journal has a standard format for such dates.

Response: The number appended behind the ULS station numbers refer to different ULS operation periods at each location. For example, “207-6” represents measurements from 14 March 2005 to 27 March 2008 at location #207. But here we reproduced the figures combining different periods at one site together.

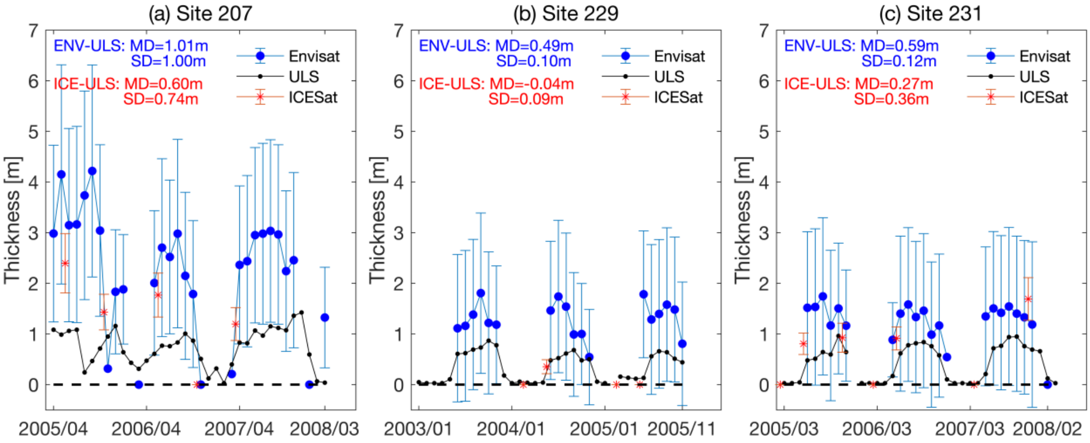

Figure 8. Time series of sea ice thickness and their errors for the Weddell Sea ULS, Envisat and ICESat. The numbers on the top of each panel represent the location of each site for the comparisons. The site locations can be searched in Fig.2. ICESat SIT values are placed between the two months that each period covers. The mean differences and their standard deviations are shown in the figures.

Figure 6. Consider rotating the whole figure into landscape mode, which would allow the panels to be larger.

Response: The figure has been modified as follows:

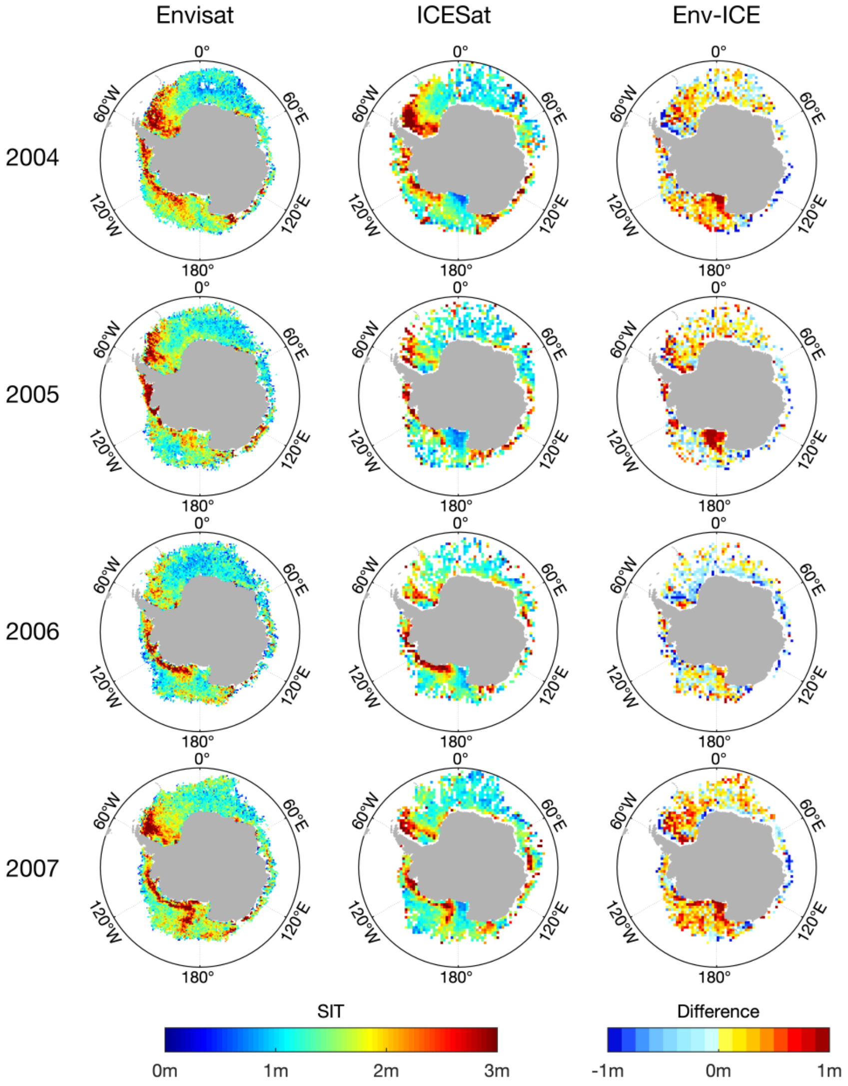

Figure 9. Comparisons of Envisat versus ICESat sea ice thickness for each ICESat operating period in summer (February & March). The first and second columns show the sea ice thickness distribution of Envisat and ICESat respectively, and the last column shows the difference map (Envisat minus ICESat) of sea ice thickness. Each row represents a year from 2004 to 2007. The sea ice thickness maps are at their native grid resolution while the difference map is interpolated onto the polar-stereographic grid of the ICESat product. The white cells denote sea ice concentration less than threshold or missing data.

New table. This is just a suggestion, but I found it helpful to create a table for myself of the different data sources, their spatial and temporal resolutions, and their treatment of snow. For example:

Source | Spatial res | Temporal res | Snow ——————————————————————- Envisat | 50 km grid | monthly avg | AMSR-E climatology ICESat | 100 km grid | see Table 1 | ASPeCt observations ULS | single point | monthly avg | built into eq (4)

Response: Thanks for your suggestion. We added the new table in the revised manuscript.

Table 4. A summary of the sea ice thickness data used during the comparison, including

different data sources, spatial resolution, temporal resolution and snow product.

Source	Instrument	Operation time	Footprint	Grid resolution	Temporal resolution	Snow product
Envisat satellite	Radar altimeter	2002-2011	2–10 km	50 km grid	Monthly average	AMSR-E climatology
ICESat satellite	Laser altimeter	2003-2009	70 m	100 km grid	See Table 1	ASPeCt observations
Weddell Sea ULS	Upward Looking Sonars	1990-2010	6–8 m	Single point	Monthly average	built into Eq. (4)

Typographical Corrections

Response: All the suggested typographical problems have been corrected.

Line 280. What is "shorter" ice? Does this mean "less extensive" in area? Line 281. Does "wider" mean "more extensive"?

Response: Yes, “shorter” means “less extensive” and “wider” means “more extensive”. In the revised manuscript we have modified the paragraph and deleted those words.

Line 296. What is "molten snow"? Is it "wet snow"?

Response: Yes, “molten snow” is the “wet snow” and we amended this.

References:

Behrendt, A., Dierking, W., Fahrbach, E., and Witte, H.: Sea ice draft in the Weddell Sea, measured by upward looking sonars, Earth Syst. Sci. Data, 5, 209–226, https://doi.org/10.5194/essd-5-209-2013, 2013b.

Cavalieri, D. J., Markus T., and Comiso J. C.: AMSR-E/Aqua Daily L3 12.5 km Brightness Temperature, Sea Ice Concentration, & Snow Depth Polar Grids, Version 3, Boulder, Colorado USA. NASA National Snow and Ice Data Center Distributed Active Archive Center. http://dx.doi.org/10.5067/AMSR-E/AE_SI12.003, 2014.

Copernicus Climate Change Service (C3S) (2017): ERA5: Fifth generation of ECMWF atmospheric reanalyses of the global climate. Copernicus Climate Change Service Climate Data Store (CDS), date of access. https://cds.climate.copernicus.eu/cdsapp#!/home

Kern, S., and Ozsoy-Cicek, B.: Satellite Remote Sensing of Snow Depth on Antarctic Sea Ice: An Inter-Comparison of Two Empirical Approaches. Remote Sens., 8, 450, https://doi.org/10.3390/rs8060450, 2016.

Kern, S., and Ozsoy, B.: An attempt to improve snow depth retrieval using satellite microwave radiometry for rough antarctic sea ice. Remote Sens., 11, 2323, https://doi.org/10.3390/rs11192323, 2019.

Kern, S., Frost, T., and Heygster, G.: D1.3 Product User Guide (PUG) for Antarctic AMSR-E snow depth product SD v1.1, available at : https://icdc.cen.uni-hamburg.de/fileadmin/user_upload/ESA_Sea-Ice-ECV/SICCI_ANT_SIT_Option_PUG_D1.3_Issue_2.1_final.pdf, 2015.

Kurtz, N. T., and Markus, T.: Satellite observations of Antarctic sea ice thickness and volume, J. Geophys. Res., 117, https://doi.org/10.1029/2012JC008141, 2012.

Lebedev, V. V.: The dependence between growth of ice in Arctic rivers and seas and negative air temperature (in Russian). Probl. Arkt. 5-6, 9-25, 1938.

Li, H., Xie, H., Kern, S., Wan, W., Ozsoy, B., Ackley, S., and Hong, Y.: Spatio-temporal variability of Antarctic sea-ice thickness and volume obtained from ICESat data using an innovative algorithm, Remote Sens. Environ., 219, 44-61, https://doi.org/https://doi.org/10.1016/j.rse.2018.09.031, 2018.

Massonnet, F., Mathiot, P., Fichefet, T., Goosse, H., König Beatty, C., Vancoppenolle, M., and Lavergne, T.: A model reconstruction of the Antarctic sea ice thickness and volume changes over 1980–2008 using data assimilation, Ocean Model., 64, 67-75, https://doi.org/https://doi.org/10.1016/j.ocemod.2013.01.003, 2013.

Paul, S., Hendricks, S., and Rinne, E.: Sea Ice Thickness Algorithm Theoretical Basis Document (ATBD), v1.0, ESA Climate Change Initiative on Sea Ice (SICCI), https://icdc.cen.uni-hamburg.de/fileadmin/user_upload/ESA_Sea-Ice-ECV_Phase2/SICCI_P2_ATBD_D2.1__SIT__Issue_1.0.pdf, 2017.

Price, D., Soltanzadeh, I., Rack, W., and Dale, E.: Snow-driven uncertainty in CryoSat-2-derived Antarctic sea ice thickness – insights from McMurdo Sound, The Cryosphere, 13, 1409–1422, https://doi.org/10.5194/tc-13-1409-2019, 2019.