Dear Dr. Heil,

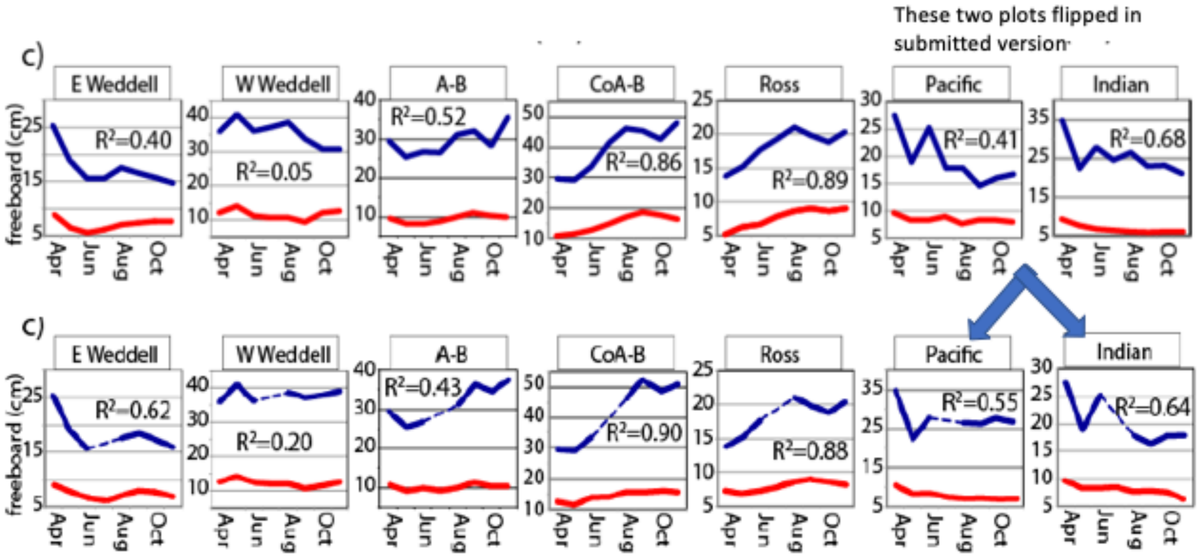
Thank you for the detail reading of our manuscript. In additions to the valuable suggestion the corrections to the small details were useful for improving the overall manuscript. In addition to our response to you (attached below) and the reviewers (submitted earlier), we would like to bring to your attention two changes that are of note in the revised manuscript:

1. In the conclusions section of the original manuscript, we stated that: "…the adjustment of the CS-2 orbits to provide improved coincidence in space-time sampling of the surface is being considered. A Joint NASA-ESA working group is exploring this opportunity, while there is an overlap in the IS-2 and CS-2 missions, to 'tune' the CS-2 orbital parameters slightly to improve the time-separation between near co-incident IS-2 and CS-2 measurements (cross-overs and along-track sampling). If this is approved. the two altimeters will provide a crucial data set for not only understanding the current retrievals but also the design of future instruments tasked to understanding the development of the Antarctic sea ice cover…"
   In fact, this has been approved and implemented. In late May (which you noted), after a year of consideration and planning, ESA announced the CRYO2ICE project to adjust the CS-2 orbits to improve coincidence for better utilization of the two altimeter missions to benefit sea ice and other science disciplines. The CS-2 orbit was adjusted in July and is now providing better coincidence in the Arctic. After the Arctic winter, CS-2 will be adjusted to optimize coverage for the lower latitude Southern Ocean ice cover. This is good news and the conclusion has been revised to deliver this message.

2. We reprocessed all of the IS-2 and CS-2 data with our most current analysis software, so all of the results will be slightly different (centimeter level freeboard changes). Also, we have removed July from our results because during July of 2019 there was a spacecraft anomaly and the IS-2 project recommended that we not use this release of July until the altimeter data for that period have been thoroughly checked out. This does not change any of the science and conclusions in the paper although the results are slightly different. In the attached figure (Figure 4 in the text), we show the differences between the mean CS-2 and IS-2 freeboards and their squared correlations from the original manuscript and the revised manuscript (top row: old; bottom row: new). It can see that the mean values are different but the relative month-to-month variabilities and correlations between the two freeboards for the different sectors remain substantially the same (Note also that in the original manuscript the Indian and Pacific sectors were switched – indicated by the arrows, and they have been corrected in the revision.). We feel that leaving out July is the correct approach at this time.

Cordially,

Sahra Kacimi and Ron Kwok



Top panels: submitted manuscript
Bottom panels: revised manuscript

Responses to Editor's comments (*in blue):*

General comments:
** Use of SI units:*
Similar to reviewer 2, who asked for the uniform use of units, and recommended the use of SI units, I would like to request the same. Including to remove "PSU" as salinity is now given without any units, not even "PSU". (1-16).

All the density values are now expressed in kg/m^3. The salinity units have been removed. Because of difference in the magnitude of snow depth and ice thickness (a factor of ten) we have consistently and prefer to keep snow depths in centimeters and thicknesses in meters. We believe the community (at least the remote sensing community) generally thinks in those units.

** Hyphenation: Pls review your use of hyphens, especially change "snow-radar" to "snow radar" throughout the manuscript (ms).*

Done.

** Include information on cloud etc affecting IS-2 data (i.e., missing data) and how this lack of data coverage affects the comparison. Similar, explore effects of different instrument footprints and repeat/overlapping swaths. (I found some info in section 4.12 but would prefer the basic info upfront, when the datasets are introduced.)*

All our calculations are performed with 25-km averages. Similar to our answer to the second reviewer, we will note this in the sampling description (Section 4) to alert the reader to the potential differences due to the resolution in freeboard retrievals from IS2 and CS2. The information about instrument footprints on the IS-2 data has been added in the data description section. Cloud contaminated retrievals are not used in our calculations (we have added this remark to the data description).

** In the Southern Ocean, changes in snow thickness/cover are largely driven by a combination of solid precipitation as well as by snow redistribution (incl. loss of snow into open water, such as leads) -- in addition to snow-ice formation. --> Pls include the "snow redistribution" (with appropriate reference) in your ms, i.e., 4-10 to 4-13.*

Done. - (Andreas & Claffey, 1995; Massom et al., 1997; Massom et al., 1998)

** Suggest to rename "East Weddell" and "West Weddell" to "eastern Weddell Sea" and "western Weddell Sea", respectively. Abbreviations may remain the same.*

We appreciate the suggestion, however for simplification we prefer the use of East and West Weddell sectors. Also in our definition, the eastern Weddell sector does not cover exclusively the Weddell Sea but also the Lazarev and the Riiser Larsen seas.

** Provide essential information for both primary datasets (IS-2 FB and CS-2 radar FB)*

(Sections 2.1 and 2.2). For example, information on the data granularity for CS-2 radar FB needs to be presented here - despite provision of the KC2016 reference.

We do not quite understand the granularity requested here. The IS-2 data products are detailed in the project documents available at the National Snow and Ice Data Center. We added more detailed description of both instruments and hope that they are sufficient for the purposes here.

See below for specific comments.
** Fluxgates: How are they set and what contributes to the lesser ice area in the larger fluxgate? (6-1ff)*

In the paper we mention two flux gates: One along the 1000m isobath that parallels the ice fronts of the Ronne and Filchner ice shelves; and one along the 1000m isobath that parallels the ice front of the Ross Sea Ice Shelf.

** Your discussion of the regional freeboard evolutions states that the E-Wedd sector exhibits the "lowest area-averaged freeboards" around Antarctica. Tab. 2 however shows similarly low freeboards for the Indian and not much higher for the Pacific. Would you kindly explore this?*

We have added a remark on their relative freeboards and that the same processes (large divergence) may also be at work here.

** The discussion on snow-depth estimates (p9 & 10) should also consider the episodic events during which solid precipitation is delivered, versus the more frequent redistribution of snow (by wind-induced drift). -- This is an area of research by itself, but worthwhile to mention here.*

We agree and added a mention of solid precipitation and wind redistribution.

** Update the final lines (15-34ff) as this CS-2 alignment to IS-2 has taken place by now. Suggest to give a small outlook of the anticipated benefits of the Cryo2Ice objectives.*

This had been updated to read: "…An adjustment of the CS-2 orbits (by ESA) – CRYO2ICE – to provide improved coincidence in space-time sampling of the two altimeters has been successfully implemented. We anticipate that the data acquired by CRYO2ICE will provide a crucial and valuable data set for not only understanding current retrievals but also the design of future instruments tasked to understand the development of the Arctic and Antarctic sea ice covers…."

Specific comments:
1-7: Provide start date of your analysis: "April xx, 2019".
Corrected.

1-8: Correct "West Weddell sector" to "Western Weddell sector".
See our comment above.

1-8: Provide at least a qualitative statement instead of "stands out with a mean sector thickness > 2 m."
Revised to read: "The multiyear ice observed in the West Weddell sector is the thickest with a mean sector thickness > 2 m…".

1-9: Spell out "Ronne": "Ronne Ice Shelf".
Corrected.

2-2: Correct "sea ice extents" to singular "sea ice extent".
Corrected.

2-3: Suggest to change "decay rates" to singular as well, i.e., interpreting it as the interannual decay rate.
We believe decay rates are used correctly here.

2-37: "OIB" needs to be defined. So do this here: "IceBridge [OIB]),".
Corrected.

3-15ff: Need to provide some more info on the ATLAS and its build, i.e., 3 pairs of 2 beams ands ome essential info. Short will be fine. Consider a reference too... but need to include essential information here, so reader, for example, can understand meaning of "strong beam".
For clarification we added a brief description of ATLAS at the beginning of paragraph 2.1: "the Advanced Topographic Laser Altimeter System (ATLAS) onboard ICESat-2 (IS-2) uses three beam pairs to profile the surface. The pairs are separated by about 3.3-km cross track. Each pair consists of a strong and a weak beam with a inter-beam spacing of 90m. The pulse energies of the strong beams are ~4 times that of the weak. Each beam profiles the surface at a pulse repetition rate of 10 kHz."

3-20: Specify "Vertical" to read "Vertical uncertainty".
Now reads: "…Uncertainty in IS-2 freeboard retrievals…"

3-24: Provide information on which "satellite-derived ice concentration(s)" have been used.
Done.

3-25: Provide information on why "freeboard is approximately one-ninth of ice thickness", i.e., include density argument and a reference. This might make the sentence long, consider splitting into 2 sentences, as required.
Revised to read:"… Nothing that freeboard is approximately one-ninth of ice thickness (due to the density contrast between, ice and seawater)…"

3-26: Move "(Kwok & Cunningham, 2015)" forward to read "differences (Kwok & Cunningham, 2015)".
Corrected.

3-30: What changes are meant here? "expected changes in IS-2 and CS-2 freeboards": Temporal. -->Specify here.
Corrected to read "time-variable …."

3-34: Suggest to change "east sector and west sector" to "eastern sector and western sector".
See our comment above.

3-34: Change "added a coastal Amundsen-Bellingshausen region" to "divided the Amundsen-Bellingshausen Sea into a coastal region and remainder". Include info on which latitude was chosen for the separation.
The Amundsen –Bellingshausen sector includes the coastal sector. The coastal region was added to better capture the mechanical convergence event as will be described in the section.

3-35: Could be more specific than "remarkable" in "remarkable ice convergence".
Revised to read: "…remarkable ice convergence seen in 2019 (discussed below)."

3-35: Change "seen" to "observed" or "recorded".
Done.

4-*2: Suggest to change "worthwhile reviewing" to "necessary to review".*
We prefer the current phrasing.

4-*5: Add a space " " before "and" near beginning of line.*
Corrected.

4-5: Remove a space " " before "deltah_i".
The space is a characteristic of Mathtype.

4-5: Add a space " " before "(Figure 2)".
Done.

4-7: Correct "Arctic Ocean export" to "Arctic Ocean exports".
Corrected.

4-*7ff: Pls rewrite this longwinded sentence for clarity. Also avoid a "(...)" following another set of brakets "Kwok et al., 2013)".*
Revised to read:" Since Arctic Basin exports only ~10% of its area annually (mainly through the Fram Strait - Kwok et al. (2013)) and there is relatively little melt in winter away from the ice margins. Therefore, it is simpler to observe a coherent seasonal cycle of freeboard growth over a fixed region of the Arctic Basin.(i.e.; the correlated increases in both the IS-2 and CS-2 freeboards seen in Kwok et al. (2020)).."

4-11: Include a reference for "larger ice divergence" (i.e., for Antarctic sea ice). : In "larger ice divergence", larger than ??? Pls complete sentence.
Added: "…Compared to the Arctic…"

4-12: Replace "export" with "transport" in "large-scale export".
We prefer export because the ice is exported from the interior compact regime.

4-15: Appears as if there are erroneous spaces " " before and after "h_fs" and "h_fi".
These are formatted with Mathtype.

4-17: Appears as if there is an erroneous space " " before "beta".
These are formatted with Mathtype.

4-20: Correct "fvalue" to "value".
Corrected.

4-21: "spatially" is redundant. Could be cut.
Removed.

4-21: Change "wind forcing" to "wind stress".
Changed.

4-21*: Change "is sometimes" to "may be".*
Changed.

4-27: Correct "Mechanical convergence/divergence" to "Mechanical redistribution due to convergence/divergence"
Changed.

4-31: Remove "no doubt".
Removed.

4-33: Suggest to refocus "is the large export and sea ice melt at the margins." to also consider the advective changes in the regional freeboard estimates, i.e., different 'parcels of sea ice (with snow)' are found in a certain region at a certain time due to the ice being advected.
Modified to read:"… regional variability of freeboard (below) is the advective changes and sea ice melt at the margins…"

*5-5: Clarify if the "Amundsen-Bellings*hausen (A-B)" includes the data for the "coastal Amundsen-Bellingshausen (CoA-B)".
Corrected.

5-8: Correct "Amundsen and Bellingshausen Seas" to "Amundsen and Bellingshausen seas".
Corrected.

5-10: Naming here "CoA-B sector" but in Fig.1 it is named "A-B Int". --> Unify.
Corrected.

5-20: Add "atmospheric" and remove "setup" to "The atmospheric circulation".

Changed.

5-23: "i.e., ice freeboard tends to be anti-correlated to snow accumulation": Pls clarify if this is a statement based on previous publications (then pls include reference), or based on the data analyzed here (then add an exact figure reference). -- In general, the thick or deformed ice also exhibits thick snow cover (i.e., Uto et al., 2006; Maksym and Markus, 2008; Sugimoto et al., 2016).
This is a physical statement: Snow loading tends to depress the sea ice freeboard and therefore anti-correlated.

5-31: Correct "40^oW and 62^oW" to "40^o and 62^oW".
Corrected.

5-32: Need to mention as early as here that the Weddell Sea is a (cyclonic) gyre. Otherwise any reader without prior knowledge would miss out crucial information to interprete the statement "both with boundaries that are open to the north."
Done.

5-32: Replace "areas" with "regions".
Replaced.

5-33: Add note that not all sea ice in the Weddell Sea is formed in the E-Wedd ... but some also arrives in the Weddell Sea via advection within the westward coastal current.
We think broadly speaking the largest contribution is ice production.

5-35: Change "as well," to "as well as".
We believe the phrasing is correct here.

5-36: Change "ice areas added" to "ice areas are included".
We mean area added by divergence.

5-37: Remove "are entrained in the outflow".
Removed.

5-36: Rewrite "and formed in the Ronne and Brunt ice shelves" to correct. Sea ice does not form in ice shelves per se.
Revised to read:"… formed seaward of the Ronne and Brunt ice shelves…"

6-2: Pls provide some information on the "flux gate" extent (in km).
See our comment above.

6-2: Do you mean "~1100km." or "~1100m.", i.e., refernce to another isobar??
Here, we are referring the length of the fluxgate.

6-9: Change "On an area-averaged sense," to "Genearlly,".
Changed.

6-16: Clarify the location by replacing "in the sector" with "in the E-Wedd". Suggest to remove "As for the E-Wedd,"
Changed.

6-23: Correct "Sound Polynyas." to "Sound polynyas."
Corrected.

7-4: Change "160^oW and 90^oE" to "90^oE and 160^oW".
Changed.

7-4: Correct "90^oE and 15^oE" to "15^o and 90^oE".
Changed.

7-5: Clarify text by chagning "the broader extent of the ice cover in Indian Ocean Sector (around 15^oE and 40^oE)" to "wider latitudinal pack ice extent in the Indian Ocean Sector (from 15^o and 40^oE)".
Revised to read: "…larger extent…"

7-6: Change "the ice cover occupies a very narrow band, and" to "the ice covers a narrow band, that"
Changed.

7-7: Regarding the 2019 ice drift (being westward): Why is this remarkable? Mention the separation of the westward coastal current with eastward drift in the southern bands of the ACC.
There is nothing remarkable – we reported that this was consistent with the mean multiyear drift fields in Fig. 5.

7-10: Rewrite to improve readability "the Indian Ocean sector is seasonal ice from coastal polynyas and from the Pacific Sector." and include that sea ice forms locally in the Indian Ocean sector OUTSIDE "coastal polynyas". Text currently reads as if all sea ice formed in the Ind Oc has done so in a coastral polynya.
Rewritten as suggested.

7-19: This sentence is incomplete: "We have filtered most of these anomalous freeboards in the IS-2 and CS-2 processing some are still present."
Revised.
At least start with "Although we have".
--> Provide some detail and a refernce on the filtering of wave-effected data.
This was done visually and is now stated in the text.

8-8: Remove comma ",' before " (Ulaby".
Removed.

8-10: Include "snow" to read "bulk snow density".

Done.

8-10: Pls use SI units. I.e., avoid "0.32 g/cm 3". - Throughout ms, pls.
Done.

8-20: Include brief motivation for chooseing 30cm freeboard differences, for completeness.
Typical winter value used as an example.

9-7: Change "(compared to the Arctic)" to "than the Arctic". Or better simplify the complete sentence. I.e.: Antarctic sea ice is found at lower latitudes, hence a lesser coverage by polar-orbiting satellites proves difficult when deriving snow depth from IS-2 or CS-2 freeboards.
Revised as suggested.

9-8: "Gridded IS-2 freeboards are averages of the three strong IS-2 beams ..." -- Provide footprint comparison of IS-2 freeboards with CS-2 freeboards.
Because the freeboards are all matched at a 25km resolution we feel there is no need to discuss their respective footprints.

9-10ff: Are both, IS-2 and CS-2 derived/treated the same way here? I.e., what about adjusting IS-2 for ice concentration? I am also concerned about the temporal coverage (per location pixel) for each derived data set. --> Would you pls include some background on this here? (I know IS-2 data are only there for ice concentration above 50%.
The ICESat-2 data is not weighted for ice concentration, as the open water is already included in the freeboard calculations.

9-15: Correct "75-km" to "75 km".
We think 75-km is the correct usage here. It refers to a 75-km box, not 75 km in distance.

9-19: This "advantage", however, reduces the true sample variability and due to IS-2 data gaps this is likely to bias the derived results.
True, although the simulations suggest the effect to be minor.

9-30: Would you agree that the spatio-temporal averaging plus the footprint limitations contribute to make this variance in snow depth appear so low? -- Some discussion on this would be useful here. There is also the loss of snow when entering into the open ocean during a deformation event, i.e., it is not accounted for as snow-ice.
We expect the variance to be representative of the length scale chosen (i.e., 25 km). So yes, this would be lower than what one would expect at the 10s of meters. We have added that the loss of snow during deformation may have a confounding effect.

9-31: Avoid use of "results" twice in same sentence: "These results suggest that the effect of sea-ice deformation in biasing the derived snow depth may be small."
Revised to read: ”These results suggest that the effects of sea-ice deformation in biasing the snow depth estimates may be small”

9-31: Ensure to replace "dynamics" with "deformation".
Corrected.

10-9: Correct "southern Ross and Weddell Seas" to "southern Ross and Weddell seas".
Corrected.

10:31: The zero freeboard/zero snow thickness argument leaves room for further discussion. Is this based on Ozsoy-Cicek et al (2013)? Suggest to include a qualifier here.
No, this is a physical statement based on definition. Revised to read:"… as one should expect – by definition – zero snow depth at near zero IS-2 freeboard…"

11-1ff: Provide reference(s) for the retracker and related information such as temperature dependence.
Revised to read:"… One likely source of these biases is the displacement of retracking point (RP) of the radar altimeter (CS-2) away from the snow-ice interface resulting in higher CS-freeboards (Kwok, 2014). At K_u-band frequencies (CS-2), the RP's are displaced from the true ice surface when elevated snow salinities (due to brine-wicking, flooding) are found near the snow-ice interface, or the changes in scattering the presence of moisture in the snow layer when air temperature warms (Winebrenner et al., 1994)…"

12-3: Consistency is important: Here densities are in kg/m^3. Pls use this SI unit throughout the ms.
All densities are now in kg/m3.

12-16: Correct "(mean 2.40±1.00 m) in May)" to "(mean 2.40±1.00 m in May)".
Corrected.

12-16: Correct "CoA-B sectors" to "CoA-B sector".
Corrected.

12-19: Correct "Ross Sea polynyas" to "Ross Sea Polynya".
The lower case is correct in this case because we are referring to multiple polynyas in the Ross Sea.

12-26: Change "between April and November" to "from April to November".
Changed.

12-27: Change "field records" to "field observations".
Corrected.

12-29: There are updates to the ASPeCt database from those included in Worby et al. (2008). No updated climatology. The cleaned and calibrated data can be accessed at:
https://data.aad.gov.au/aspect/
Select "Download cruises". (Access via AADC, so "free login" required.)

Thank you. We added the data citation to the acknowledgment.

12-35: Correct "Bellingshausen and Amundsen Seas" to "Bellingshausen and Amundsen seas".
Corrected.

12-35: This is correct for "operational underway data". If a vessel however travels along a science transect, then it follows the waypoint line without deviations motivated by the "hunt for thinner ice". -- ASPeCt should flag these.
Noted.

13-3: As a field going scientist, I refute this. Sea-ice transects should be laid out to be representative of the ice conditions of the entire ice floe and the general region, so would include ridged areas and thick ice, and a range of snow covers.
Noted. I assume that during drilling that thinner ice is avoided for safety considerations.

13-8 and 13-10: Be consistent: Reporting ice thicknesses from the same source should provide them in a uniform presentation: I.e., number of decimals: "2.4 to 2.6 m" versus "0.48 and 0.99 m".
Revised.

13-16: Fullstop over "unlikely" missing.
Corrected.

14-33: Change "In this paper," to "In this study".
Corrected.

15-6: Correct "Ross Sea polynyas" to "Ross Sea Polynya". Alternatively rewrite to "Ross Sea and Ronne polynyas".
Corrected.

15-20: Remove erroneous "the" from "from basal-layer salinity the is sound."
Removed.

15-26: Add a sentence here to recommend urgent need for sustained and extensive field measurements.
Added,

15-30: Add fullstop at end of sentence.
Corrected.

15-32: Correct "altimeter" to "altimeters".
Corrected.

16-4: Include acknowledgement/source of CS-2 data.

Similar for the PM ice-concentration data used, and any other data (i.e., atmospheric reanalysis if the Davis Strait Low pressure pattern was updated here).
Corrected.

20-7f: Check doi in Giles et al. (2008) for correctness. - Remove linebreak.
20-15: Remove "Doi " (including space).
20-39: Remove "Doi".
20-43f: Correct doi for Maksym and Markus (2008).
20-46: Remove "Doi " (including space).
20-48: Remove "Doi " (including space).
21-29: Remove "Doi " (including space).
21-36f: Correct doi for Maksym and Markus (2008).
21-43f: Correct doi for Yi et al. (2008).

All doi's used here are from the endnote and formatting is based on APA recommendations. We assume that the typesetting process will correct these anomalies.

Fig1: Change caption to "Naming convention for the sea-ice sectors around Antarctica." or similar.
Done.

What is "A-B Int"?
Corrected to CoA-B.

Fig3: Include info on pixel size for IS-2 and CS-2 data shown in figure (and hence also for derived snow depth).
Done.

Fig4a: Colourbar missing.
There is no colourbar, they are normalized distributions.

Fig5: Colourbar and scale for ice drift are missing.
The colorbar and scaling is displayed in the middle of the figure.

Fig6a&b: Colourbar missing.
There is no colourbar, they are normalized distributions.

Fig9a&b: Colourbar missing.
There is no colourbar, they are normalized distributions.

Kwok, R., S. Kacimi, M. A. Webster, N. T. Kurtz, & A. A. Petty. (2020). Arctic Snow Depth and Sea Ice Thickness From ICESat‐2 and CryoSat‐2 Freeboards: A First Examination. *Journal of Geophysical Research: Oceans, 125*(3). doi:10.1029/2019jc016008

Massom, R. A., M. R. Drinkwater, & C. Haas. (1997). Winter snow cover on sea ice in the Weddell Sea. *Journal of Geophysical Research-Oceans, 102*(C1), 1101-1117. doi:Doi 10.1029/96jc02992

Massom, R. A., V. I. Lytle, A. P. Worby, & I. Allison. (1998). Winter snow cover variability on East Antarctic sea ice. *Journal of Geophysical Research-Oceans, 103*(C11), 24837-24855. doi:Doi 10.1029/98jc01617

Winebrenner, D. P., E. D. Nelson, R. Colony, & R. D. West. (1994). Observation of Melt Onset on Multiyear Arctic Sea-Ice Using the Ers-1 Synthetic-Aperture-Radar. *Journal of Geophysical Research-Oceans, 99*(C11), 22425-22441. doi:Doi 10.1029/94jc01268

Responses to Reviewer 1's comments (*in blue):*

This paper presents the first Antarctic-wide combination of ICESat-2 and CryoSat-2 data over sea ice to provide snow depth, freeboard, thickness and volume. Honestly, I was concerned that the first paper of this type to cover Antarctica would feel rushed and leave me with a lot of unanswered questions. But this manuscript was clearly structured and very thorough. I appreciate that the authors were transparent about the limitations of the method, but have still published what is an interesting, unique study. I'm happy to say that I learned a lot. I commend the authors' efforts and strongly recommend this paper for publication. However, I do have some comments that should be addressed first. The number of comments is due to the length of the paper, not a reflection on the quality.

We thank the reviewer for her time in reviewing the manuscript and providing helpful feedback. The suggestions have helped improve the revised manuscript.

——————————- General comments ——————————

The authors need to be very clear and consistent with which "freeboard" they are referring to, i.e. radar(CS2)/lidar(IS2)/ice/snow. "Total" freeboard should really be "IS2 freeboard" for consistency with the fact that they are using "CS2 freeboard" as separate to "ice freeboard". We're still not fully aware of the uncertainties associated with IS2 penetration and retrievals, so to frame it as undisputed total freeboard is misleading.

Agreed. All occurrences of 'total freeboard' in the text have been replaced by 'IS2 freeboard'.

I'd like to know why they did not use a whole year of data.

The period of study covers April to November of 2019. The summer and transition months were not included because of the known impact of warmer temperatures on snow wetness and thus radar (CS2) penetration into the snow layer.

The long sentences are confusing at times (e.g. P1L12-15). I appreciate this is a style preference but it was an issue for me. I suggest the authors re-read the paper and check for clarity throughout.

The sentences from P1L12-15 were rephrased to read: "The remarkable mechanical convergence in coastal Amundsen Sea, associated with onshore winds, was captured by ICESat-2 and CryoSat-2. We observe a corresponding correlated increase in both freeboards, snow depth and ice thickness. While the spatial patterns in the freeboard, snow depth, and thickness composites are as expected, the observed seasonality in these variables is rather weak. This most likely results from competing processes (snowfall, snow redistribution, snow-ice formation, ice deformation, basal growth/melt) that contribute to uncorrelated changes in the total and radar freeboards."

——————————————- *Specific comments* ——————————————

*P1P7: "…freeboards, snow depth, **ice thickness** and ice volume*.
Corrected.

*P1P7: "…April **1st**…"*
Corrected.

P1L8: The phrase "stands out" isn't very explanatory, How about "is the thickest" or similar
Revised to read: "The multiyear ice observed in the West Weddell sector is the thickest with a mean sector thickness > 2 m…"

P1L15: Don't need the word "broadly" (or "surprisingly" above). These types of phrases distract from the narrative.
We deleted the word "Broadly".

P1L15: This relates to my general comment above, about clarity regarding real and observed freeboard. The authors mention "biases in CryoSat-2 freeboards" but a more accurate statement would be ""biases in CryoSat-2 measurements of the ice freeboard".
We replaced "biases in CryoSat-2 freeboards" by "biases in CryoSat-2 estimates of ice freeboard".

P2L2: "several decades" -> "four decades"
Done.

P2L21: The statement that Kurtz and Markus (2012) "assumed that the snow depth is equal to the ice freeboard" is misleading. The Kurtz and Markus paper assumed that snow depth is equal to snow/lidar/total freeboard ("ice freeboard" should unambiguously be used to refer to the snow-ice interface). Better phrasing might be "assumed that the ice freeboard is zero, and so snow depth is equal to the total freeboard". They should really spell it out here because it's a key concept of the manuscript.
We replaced "assumed that the snow depth is equal to the ice freeboard" by "assumed that the snow depth is equal to the total freeboard "

*P2L23: "ice **and snow** cover"*
Corrected.

P2L23-25: How are the author's familiar with the pros and cons of each method – have they been validated? If so, please provide references.
The approaches and shortcomings are discussed in the cited references - P2L20-22.

P22L26-27: Does "these approaches" refer to all approaches, or just empirical?
By "these approaches" we are referring to all of the approaches. To improve clarity, we changed to: "all these approaches".

P3L11-12: Why do the authors use the 10 km product and not the 150-photon aggregate product? It would be useful here to explain that higher spatial resolution IS2 products are available, and why they chose this one.
The freeboards that we use (from ATL10) have identical resolutions as those of the derived heights. Individual freeboards (i.e., 150-photon aggregate freeboards) are derived only if there was a local sea surface reference available within a 10-km along-track segment. The 10-km does not refer to the freeboard resolution, only the constraint placed on proximity to the sea surface reference.

*P3L23: "…freeboard estimates **in the Arctic**."*
We added "in the Arctic" at the end of the sentence P3L23.

Section 2.2: Are they using individual waveform thicknesses, and how is the concentration weighting done?
The weighting was done by multiplying the gridded CS2-freeboard (25-km averages) by the corresponding ice concentration at a given grid cell.

*P3L26: "…thickness measurements **in the Arctic**…"*
Added.

P4L10-13: This is a really nice summary!
Thank you.

P5L28-29: From this I understand that they're using the whole month for CS2 but only 2 weeks for IS2? This wasn't clear in the manuscript until now, or in the abstract. I'd suggest repeating the analysis for just 2 weeks of CS2 so it's a like-for-like comparison even though I know this isn't ideal for coverage. If they really feel strongly that they shouldn't, then the averaging windows and reasoning needs to be very clear in Section 2 and the abstract.
The November CS-2 composite and distribution (in Figures 3 and 4) have been updated using only two weeks of CS-2 data – to be consistent with the availability of IS2.

P5L33: Would benefit from a more up-to-date reference than Lange & Eicken, 1991
Added Vernet et al. (2019): Vernet, M., Geibert, W., Hoppema, M., Brown, P. J., Haas, C., Hellmer, H. H., . . . Verdy, A. (2019). The Weddell Gyre, Southern Ocean: Present Knowledge and Future Challenges. Reviews of Geophysics, 57(3), 623-708. doi:10.1029/2018rg000604

P7L15-19: Although it's inferred, perhaps really spell it out here that wave propagation is more of an issue in the Pacific and Indian Ocean Sectors because of the small spread in extent. I appreciate that the authors are consistently transparent about the complexities of the signal.
We agree and added the following text: 'This effect is predominant in the Pacific and Indian Ocean sectors because of smaller sea ice extent'.

Section 4.1: What's the reference for a bulk density of 0.32 g/cm3 and uncertainty of

_0.07 g/cm3 for Antarctic sea ice?

There is no generally accepted average value of the bulk density of snow over Antarctic sea ice. Massom et al. (2001) suggest 200-300 kg.m^{-3} under cold/dry condition and higher density (350-500 kg.m^{-3}) for warm windy conditions – not unlike the Arctic. We elected to use the average winter bulk density of 320 kg.m^{-3} (like that of the Arctic) but increased the spread to 70 kg.m^{-3} to cover the range of average conditions. We have added this discussion to the text.

Section 4.1.2: I struggled with this description of the method. The way I understand it, they create daily snow depths only in grid cells where data are available. Therefore, the monthly composites should be weighted by the number of measurements in each grid cell. Please describe if/how this weighting was done. How do they account for anomalous cells, or cells that are only present for a few days and may bias averages (especially as they're allowing such large temporal separation)? This is a critical section, and the method should be made clearer.

For clarification purposes, we substituted the text P9L11-12 by: '…First, the daily along-track IS2 and CS2 freeboards are binned on a 25-km resolution grid. Gridded IS-2 freeboards are averages of the three strong IS-2 beams and thus provide a better sampling of the spatial mean (compared to CS-2 freeboards). In grid cells with available data, an average is computed while the other bins are assigned with a missing value. Freeboard differences are then computed at each valid IS2 grid cell using CS2 binned freeboards (weighted by ice concentration) with time separations |DT|<10 days and within a 75-km box. We find that this sampling strategy provides the best spatial coverage without sacrificing precision'.

P9L10-11: Are the IS2 thickness estimates also concentration weighted?

The IS2 estimates are not weighted by passive microwave ice concentration because the open water samples (i.e., H=0) are included in the population for computing thickness.

P9L32: "may be" or "is"? There's an important distinction!

We used "may be" because the results of the sensitivity analysis may not have sampled the range of conditions expected.

Section 4.3: I appreciate that they've included this section, but I think it's unnecessarily complicated. The same point could be made by just this final sentence on Page 10. That sentence does need rewording, for clarity, and I suggest something like "The negative intercepts observed in the scatterplots imply that h_f is an underestimate of true snow depth by +2.4 to +3.9 cm."

We think this section is useful, as it constitutes the basis of the discussion about the possible sources of biases in the snow depth estimates. The final sentence on page 10 has been rephrased as suggested.

P11L4: Reference for the -5C value? I'd really like to read this work.

Figure 5 of Winebrenner et al. (1994) - Instead of T=0C, the appearance of moisture in the snow layer from around -5 C would cause changes in bulk dielectric constant affecting penetration and backscatter at radar frequencies. This can be seen in the fluctuations in radar backscatter even before the air temperature reaches the melting temperature.

Winebrenner, D. P., Nelson, E. D., Colony, R., & West, R. D. (1994). Observation of Melt Onset on Multiyear Arctic Sea-Ice Using the Ers-1 Synthetic-Aperture-Radar. *Journal of Geophysical Research-Oceans, 99*(C11), 22425-22441. doi:Doi 10.1029/94jc01268

P12L33: A more accurate statement would be that "the ASPeCt data are biased towards thin and level ice types"

Revised as suggested.

—————————————- Technical comments ———————————

P4L7: "export" -> "exports"
P5L26" Remove "generally"
P5 L28: Delete "due"
P6L9: "on" -> "in"
*P6L13: "The tails **of** freeboard…"*
*P7L19: "…**but** some…"*
P11L31: Delete "viz"
P12L27: "data set" -> "data"
P13L37: "sector" -> "section"

The above have been corrected as suggested.

Responses to Reviewer 2's comments (*in blue):*

General comments: This is a challenging and valuable paper to attempt to map the distribution of snow depth, sea ice thickness, and ice volume for Antarctic sea ice on a hemispheric scale for the first time, by combining satellite lidar (ICESat-2) and radar (CryoSat-2) altimeters. The major motivation is to improve our understanding of the recent decreasing trend of Antarctic sea ice extents. For this purpose, the authors estimated the surface elevation with ICESat-2 and the ice freeboard with CryoSat-2 and obtained the snow depth distribution from the difference between these datasets and the ice thickness and ice volume distribution assuming isostatic balance. They also conducted the error estimates from uncertainties of various factors that contribute to the freeboard measurements. As a result, the geographical and seasonal properties of freeboard, snow depth, and ice thickness were revealed on a hemispheric for the first time. Besides, by comparting the two datasets, some unique features are suggested; such as more than 60-70% of the total freeboard is snow. It is well known that the behavior of the Antarctic sea ice extents has different characteristics from that of the Arctic sea ice extents. However, the mechanism has not been well understood due to the lack of the hemispheric scale information of the Antarctic sea ice so far. While Worby et al. (2008) showed the hemispheric ice thickness distribution of Antarctic sea ice by compiling the visual observations conducted according to the ASPeCt protocol, there has been a lot of uncertainties about the seasonality and the biases caused by the observational methods. I think many scientists have been waiting for the estimation of the hemispheric snow depth, ice thickness, and ice volume distribution based on the satellite datasets. This paper can provide a breakthrough about this topic and contain a lot of implications. Therefore, I recommend publication with minor revisions. Having said that, I have several concerns. I would appreciate it if the authors address them before publication.

We thank the reviewer for his/her time in reviewing the manuscript and providing helpful comments for improving the revised manuscript.

The major points are as follows:

1) The lack of discussion about the different footprints of the two satellite sensors. Since the distributions of snow depth and ice thickness are usually anisotropic especially at deformed ice area, I am wondering if difference in footprint might affect the results. Even though the precise discussion might be difficult, I recommend some discussion about this.

All our calculations are performed with 25-km averages to avoid some of the pitfalls of sampling disparities between the two altimeters. We will note this in the sampling description (Section 4) to alert the reader to the potential differences due to the resolution in freeboard retrievals from IS2 and CS2.

2) Units of parameters In the manuscript, the CGS unit (cm, g, g/cm3) and MKS unit (m, kg, kg/m3) are mixed, which might be confusing. I think it would be better to unify them to SI unit.

Because of difference in the magnitude of snow depth and ice thickness (a factor of ten) we have consistently kept snow depths in centimeters and thicknesses in meters. We believe the community (at least the remote sensing community) generally thinks in those units.

3) Discussions with the correlation between IS-2 and CS-2 (Fig. 4) There are several speculations about the dominant growth processes based on the correlation between the IS-2 derived and the CS-2 derived freeboards at each subsection in section 3.2 (for example, P6L39-P7L3, PL14-L19). However, I feel there are some other possible reasons for good correlations between them and the ground for their speculation is not necessarily strong. So further evidence might be needed. Please first explain in what kind situation the correlation becomes high, and then discuss the possible processes in each sector.

The key processes that affect the variability and co-variability of the total and ice freeboards are addressed in the Section 3.1. The discussion, where we examined the contribution of the processes that affect freeboards, provided the basis for our interpretation of the time-varying IS-2 and CS-2 freeboard estimates in subsequent section.

4) The suggestions of future field observation based on the results I would recommend the authors to suggest what kind of field observations will be required in the future to improve the accuracy of their estimations, based on their results, in the conclusion section. In the Antarctic sea ice area, there are complex snow-ice conditions, such as the presence of slush layers caused by flooding, a wide range of snow density caused by snow metamorphosis, the presence of void layers caused by deformation processes. Such suggestions would be very useful for the research community.

Our last bullet in the conclusion highlighted the need for field and other observations for validation of these satellite data sets. The suggestions of specific observations and spacetime sampling are quite beyond the scope of the current manuscript (which already is quite lengthy). However, we added that coordinated field/remote sensing observations are needed if large-scale satellite retrievals are to be validated and made more useful to the broader community.

Specific comments:

**(P2L23-24) "the first approach. . . The second. . .. The third method. . ." Please add citation.*

These different approaches are cited beforehand, P2L20-22.

**(P2, section 2) Please add the footprint of each sensor. *(P4L18) "signs indication" might be "signs indicate".*

Section 2 (page 2) describes the products used in this study. We added the size of the footprints of the sea ice retrievals in the ICESat-2 and CS-2 height estimates.

**(P4L19) "Snowfall adds to the snow layer" To be exact, "Snowfall precipitation minus evaporation (P-E)".*

Yes, we have clarified this in the text.

**(P4L20) "fvalue" might be "value"?*

Corrected.

**(P6L19-20) "Both the total and CS-2 freeboards⋯" What do you mean by "a balance of different processes"?*

We explain the rather low-variability of the total and radar freeboards by a balance of competing processes that affect them (thermodynamics and dynamics).

**(P6L25) "0.75x10^6 km^2" might be "0.75x10^6 km^2 per year"?*
The value of the average annual export (a 34-year average) – this has been clarified in the text.

**(P7L4) "160°W and 90°E" might be "160°E and 90°E"?*

Corrected.

**(P8L7) "one free parameter" Could you explain what this parameter means physically?*

The free parameter here is the refractive index of the medium, which is described P8L8-9. Physically, it describes the speed of light in the snow layer and, to first order, is dependent on the bulk density of snow.

**(P8L11) Please add ", respectively" after snow-ice interface".*

Corrected.

**(P9L2) What caused the uncertainty in snow density? Spatial variation, or measurement error?*

This is largely due to the spatial variability of the snow layer, which is dependent on age of the snow, the prevailing and weather conditions.

**(P9L3) What do you mean by "one free parameter"?*

The one free parameter in our approach is the snow density (that is used to compute the refractive index – see above). By free parameter we mean that all the other parameters in the equation are determined by observations and the only parameter left is the refractive index.

**(P9L5) I would recommend the authors to change the name of this subsection title to "sensitivity of the sampling frequency to calculations" or something like that. The current title might not be straightforward.*

We appreciate the reviewer's suggestion; we have added sensitivity to the title.

**(P9L30-32) I am wondering if this explanation is sufficient. I think more detailed discussion about the spatial scales of deformation and the sensor's footprint.*

See our comment above.

**(P10L6) "is likely due to.." You can add "and also smaller amount of P-E compared with other regions" The annual mean P-E distribution around the Antarctica is given by the following paper:*

Cullather, R.I., Bromwich, D.H., and Van Woert, M.L. (1998) Spatial and temporal variability of Antarctic precipitation from atmospheric methods. Journal of Climate, 11, 334-367.

Toyota T., Massom R., Lecomte O., Nomura D., Heil P., Tamura T. and Fraser A.D. (2016) On the extraordinary snow on the sea ice off East Antarctica in late winter, 2012. Deep-Sea Res. II, 131, 53-67.

We think that the largest contribution to the thin snow cover is the age of the ice produced in the polynya. Perhaps a higher order process is the smaller P-E in the region. We have cited the above as a potential explanation of the observed retrieval.

**(P10L7-8) "The spatial patterns show…" It might be possible that this is just because the ice-covered period becomes shorter toward the marginal ice zone. What do you think?*

Yes, this is what we meant to imply – the ice-covered period becomes progressively shorter on average towards the MIZ.

**(P10L14-15) "In all other sectors, we find. . ." The result is quite interesting. This might be a good evidence especially for the loss into leads, as suggested by the above paper.*

Yes, we agree although this is a different process compared to P-E.

**(P10L30-37) In the end, what du you think is the major reason for the negative bias?*

The discussion about the different reason for the observed biases are described P11L1-16.

**(P11L26) "by assuming that the snow depth is equal to the total (or IS-2) freeboard." Is this based on the observational facts? If so, please cite some papers which support this idea. If you can justify this assumption, it would be supportive of your results.*

There is no physical evidence that the total freeboard everywhere in the Antarctic is composed of snow. The calculation (in Equation 12) only allows us to obtain a lower bound of ice thickness by assuming that total freeboard to be equal to snow depth (i.e., lower density than ice).

**(P14L31) "an indication of total freeboard changes rather actual change in ice thickness" Then, what caused the change in freeboard?*

Due to a change in snow depth - we clarified this in the text.

**(Figure 4) "Total freeboard" might be changed to "Total (IS-2) freeboard" to avoid confusion. Please add the explanation about what the color means in Fig.4a.*

Changed and added the explanation of colors.

*****(Figure 5) It is hard to detect what the color means. The color bar should be placed at the bottom of the figure.*

Modified as suggested.

*****(Figure 6) Please add the explanation about what the thick solid line means.*

Added.

The Antarctic sea ice cover from ICESat-2 and CryoSat-2: freeboard, snow depth and ice thickness

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Abstract We offer a view of the Antarctic sea ice cover from lidar (ICESat-2) and radar (CryoSat-2) altimetry, with retrievals of freeboard, snow depth, and ice thickness that span an 8-month winter between April 1, 2019 and November 16, 2019. Snow depths are from freeboard differences. The multiyear ice observed in the West Weddell sector is the thickest with a mean sector thickness > 2 m. Thinnest ice is found near polynyas (Ross Sea and Ronne Ice Shelf) where new ice areas are exported seaward and entrained in the surrounding ice cover. For all months, the results suggest that ~65-70% of the total freeboard is comprised of snow. The remarkable mechanical convergence in coastal Amundsen Sea, associated with onshore winds, was captured by ICESat-2 and CryoSat-2. We observe a corresponding correlated increase in both freeboards, snow depth and ice thickness. While the spatial patterns in the freeboard, snow depth, and thickness composites are as expected, the observed seasonality in these variables is rather weak. This most likely results from competing processes (snowfall, snow redistribution, snow-ice formation, ice deformation, basal growth/melt) that contribute to uncorrelated changes in the total and radar freeboards. Evidence points to biases in CryoSat-2 estimates of ice freeboard of at least a few centimeters from high salinity snow (>10) in the basal layer resulting in lower/higher snow depth/ice thickness retrievals although the extent of these areas cannot be established in the current data set. Adjusting CryoSat-2 freeboards by 3/6 cm gives a circumpolar ice volume of 17,900/15,600 km^3 in October, for an average thickness of ~1.29/1.13 m. Validation of Antarctic sea ice parameters remains a challenge, there are no seasonally and regionally diverse data sets that could be used to assess these large-scale satellite retrievals.

*Now at the Applied Physics Laboratory, University of Washington, Seattle, Washington, USA.

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1 Introduction

The gradual increase in Antarctic sea ice extent in satellite records over the last four decades reversed in 2014, with subsequent rates of decrease in 2014–2019 exceeding the decay rates in the Arctic. For these past years, the Antarctic sea ice extents were reduced to their lowest levels in the 40-year satellite record (Parkinson, 2019). Our current understanding of the behavior of the Antarctic ice cover is largely informed by these ice coverage measurements from satellite passive microwave sensors. Ice extent, however, provides an incomplete picture of sea ice response to climate change and variability. But, even with the large observed changes, available measurements are still too few to be able to determine the long-term trend of ice production and volume of the of Antarctic sea ice cover (Vaughan et al., 2013)

Prior to the 2014 decline in Antarctic ice extent, coupled ice-ocean models have suggested that significant changes in ice volume and thickness are correlated to changes in ice extents (Massonnet et al., 2013; Holland et al., 2014), and increases in ice thickness may have been driven by the intensification of the wind field (Zhang, 2014) noted by Holland and Kwok (2012). As well, fully-coupled climate models generally fail to capture the observed trends and variability in ice coverage during the last few decades (e.g., Mahlstein et al., 2013; Polvani & Smith, 2013; Zunz et al., 2013; Hobbs et al., 2015; Turner et al., 2015). However, large-scale estimates of ice thickness and ice production necessary to improve attribution of change, model evaluation and improvements, and for projection of future behavior have been challenging to obtain. Retrievals of Antarctic ice thickness remain a research topic, largely due to uncertainties in snow depth and freeboard (Giles et al., 2008) required for computing snow loading in the conversion of freeboard to thickness.

Wide discrepancy between ice thickness estimates from recent approaches to determine sea ice thickness persists (Yi et al., 2011; Kurtz & Markus, 2012; Xie et al., 2013). Current algorithms to derive ice thickness from data collected by ICESat-1 (Ice, Cloud, and land Elevation Satellite) have to relied on the following simplifying assumptions: 1) an independent measure of snow depth (Yi et al., 2011); 2) the snow depth is equal to the total freeboard (Kurtz & Markus, 2012); or, 3) empirical relationships between total freeboard and ice thickness determined from field data (Xie et al., 2013). All these approaches have limitations. The first approach tends to underestimate of snow depth in areas of deformed ice. The second seems more appropriate for the thinner ice in the outer pack with low ice thickness. The third method may be most suitable for thicker ice, where knowledge of densities is subsumed into the regression coefficients. Such empirical relationships vary seasonally and regionally (Ozsoy-Cicek et al., 2013), and so the confidence in the derivations is reduced. Even so, these approaches have provided a large-scale depiction of the spatial variability of the ice and snow cover based on limited knowledge of the Antarctic ice cover.

With the launch of NASA's ICESat-2 (IS-2) in late 2018 and the extension of ESA's CryoSat-2 (CS-2) mission, we are now able to combine lidar and radar altimetry of the Arctic and Antarctic ice covers from IS-2 and CS-2 for understanding ice behavior. A recent paper by Kwok et al. (2020) demonstrated the retrieval of basin-scale estimates of both Arctic snow depth and sea ice thickness from differences in IS-2 and CS-2 freeboards. Here, we follow the same approaches to examine the large-scale seasonal cycle of Antarctic freeboards, retrieved snow depth and ice thickness from a joint analysis of IS-2 and CS-2 data (between April and November of 2019). At the outset, we note that the results from this study remains exploratory because of current understanding of the snow cover of Antarctic sea ice. There are many aspects of data quality, some of which will only be revealed by assessment with snow data acquired and processed by dedicated airborne campaigns (e.g., NASA's Operation IceBridge), field programs and when a longer IS-2/CS-2 time series becomes available.

The paper is organized as follows. The next section describes the IS-2 and CS-2 freeboard data sets used in our analysis. In Section 3, we first discuss the key processes that contribute to the time evolution of Antarctic freeboards, and then describe the observed evolution of the two freeboards during the eight winter months. Section 4 outlines the principle behind the derivation of snow depth from freeboard differences, the sampling of the satellite freeboards for calculation of snow depth, and the derived

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monthly estimates. Section 5 compares the thickness and volume of the Antarctic ice cover computed using the derived snow depth, and assuming that snow depth is equal to the IS-2 freeboard. Potential biases in the data are discussed. Section 6 concludes the paper by the highlighting these first observations and discuss challenges in having the appropriate data sets for assessment of the retrievals from the two altimeters.

2 Data description

The primary data sets are freeboards from IS-2 and CS-2. Their attributes are described below.

2.1 ICESat-2 (IS-2) freeboards

The Advanced Topographic Laser Altimeter System (ATLAS) onboard ICESat-2 uses three beam pairs to profile the surface. The pairs are separated by about 3.3 km cross track. Each pair consists of a strong and a weak beam with an inter-beam spacing of 90m. The pulse energies of the strong beams are ~4 times that of the weak. Each beam profiles the surface at a pulse repetition rate of 10 kHz and footprints of ~14 m (Neumann et al., 2019). Along-track freeboards are from the ICESat-2 ATL10 products (Release 002) from the National Snow and Ice Data Center (Kwok et al., 2019b). The ATL10 product provides sea ice freeboard estimates – with a variable along-track resolutions (~27 to 200 m) – in 10-km segments that contain a sea surface reference. Local sea surface references (h_{ref}) (i.e., the estimated local sea level) are from available sea ice leads within a 10-km segment. Freeboard heights (h_f) are the differences between surface heights (h_s) and the local sea surface reference (i.e., $h_f = h_s - h_{ref}$). For individual beams, freeboard profiles are calculated with sea surface references from that beam with no dependence on estimates from other beams. In ATL10, freeboards are calculated only where the ice concentration is >50% and where the height samples are at least 25 km away from the coast (to avoid uncertainties in coastal tide corrections). Details of the sea ice algorithms can be found in Kwok et al. (2019c) and an early assessment of surface heights are in Kwok et al. (2019a). Only the freeboards from the strong beams are used in the following analyses and also cloud contaminated retrievals are not used. We note that, in the IS-2 data set used here, there is a one-month gap in coverage (July), indicated in the figures due to a spacecraft anomaly and that data are only available for the first two weeks of November 2019 in this release of the IS-2 data set. Uncertainty in IS-2 freeboard retrievals is ~2-4 cm based on assessment in Kwok et al. (2019a).

2.2 CS-2 radar freeboards

Along-track CS-2 freeboards are derived using the procedure in Kwok and Cunningham (2015), which contains a detailed description of the retrievals and an assessment of these freeboard estimates in the Arctic. The pulse-limited footprint of the CryoSat-2 synthetic aperture radar altimeter is approximately 0.31 km by 1.67 km along- and across-track. Freeboards are retrieved for individual returns but the derived CS-2 freeboards used here have been averaged to 25-km resolution and weighted by AMSR-derived ice concentration. As there are no large-scale assessments of these freeboard estimates, only comparisons with available ice thickness measurements from variety of sensors (e.g., upward looking sonars, airborne lidars, and airborne electromagnetic profilers, etc.) provide an indirect measure of quality. Nothing that freeboard is approximately one-ninth of ice thickness (due to the density contrast between, ice and seawater) differences between CS-2 and various thickness measurements in the Arctic in Kwok and Cunningham (2015) are: 0.06±0.29 m (ice draft from moorings), 0.07±0.44 m (submarine ice draft), 0.12±0.82 m (airborne electromagnetic profiles), and -0.16±0.87 m (Operation IceBridge) .

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3 IS-2 and CS-2 freeboards

In this section, we first discuss expected time-variable changes in IS-2 and CS-2 freeboards based on our understanding of the key processes before examining the spatial patterns and distributions of the monthly freeboards. Here, we divide the circumpolar Southern Ocean into five sectors, namely: Weddell Sea, Amundsen Sea/Bellingshausen Sea, Ross Sea, Pacific Ocean, and Indian Ocean (Figure 1); these are typically used in ice extent analyses (Comiso & Nishio, 2008). Further, we sub-divide the Weddell sector into an east sector and west sector, and added a coastal Amundsen-Bellingshausen region to sample to impact of the remarkable ice convergence observed in 2019 (discussed below).

3.1 Interpretation of time-varying IS-2 and CS-2 freeboards

Since this is the first large-scale examination of the combined IS-2 and CS-2 freeboards of the Antarctic ice cover, it is worthwhile reviewing the key processes that contribute to regional-scale freeboard changes. This will aid in the interpretation of the observations. As a reminder, the changes in total freeboard (Δh_f) are the sum of the changes in thickness of the snow layer $(\Delta h_{fs})$and changes in ice freeboard (Δh_i), i.e. $\Delta h_f(t) = \Delta h_{fs}(t) + \Delta h_i(t)$ (Figure 2). In the winter Arctic, there are three key processes that contribute to the changes in total freeboard: basal growth, ice deformation, and snow accumulation/redistribution. Since the Arctic Basin exports only ~10% of its area annually (mainly through the Fram Strait - Kwok et al. (2013)), there is relatively little melt in winter away from the ice margins. Therefore, it is simpler to observe a coherent seasonal cycle of freeboard growth over a fixed region of the Arctic Basin (i.e.; the correlated increases in both the IS-2 and CS-2 freeboards seen in Kwok et al. (2020)). In the Antarctic, however, the heavier snowfall (Massom et al., 1997), ice production in large coastal polynyas (Drucker et al., 2011), formation of snow-ice (Jeffries et al., 2001; Maksym & Markus, 2008), larger ice divergence (i.e., production of areas of open water) than the Arctic, wind-blown redistribution of the snow cover including losses into leads (Andreas & Claffey, 1995; Massom et al., 1997; Massom et al., 1998) and the continuous large-scale export of sea ice towards the ice margins (where the ice melts) (Kwok et al., 2017) add complexity to the interpretation of the seasonal evolution of freeboards.

Below, we briefly summarize five key processes that contribute to the modification of the total freeboard (h_f) of a drifting ice parcel during the Antarctic winter. Separating the contributions from the snow (h_{fs}) and ice layers (h_{fi}), we write,

$$\begin{aligned}\Delta h_{fs}(t) &= \delta h_{snow} + \delta h_{\phi} - \delta h_{sti} + \delta h^{s}_{def} \\ \Delta h_i(t) &= -\alpha(\delta h_{snow} + \delta h_{\phi}) + \beta \delta h_{sti} + \delta h^{i}_{def} + \delta h_{gm}\end{aligned} \qquad (1)$$

α and β are scale factors, and signs indicate the addition or removal of height from these layers. The δh's are described below:

1) Snowfall (δh_{snow}) – precipitation minus evaporation (P-E) – adds to the snow layer and the loading depresses the ice freeboard by $-\alpha \delta h_{snow}$. α is a fractional value, and in this case is dependent on the densities of ice, snow, and seawater.
2) Spatial redistribution of snow including loss into leads (δh_{ϕ}): Snow is redistributed due to wind stress and is sometimes lost into open leads (δh_{ϕ}); the ice freeboard adjusts hydrostatically by $-\alpha \delta h_{\phi}$.

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3) Snow-ice formation: When sea water infiltrates the snow layer during flooding, the refrozen ice layer becomes part of the ice freeboard and this results in a loss of δh_{sti} from the snow layer (i.e., the snow pack settles when flooded) and a gain of $\beta\delta h_{sti}$ by the ice freeboard. β represents the fraction of the snow thickness that is converted to ice freeboard after the transformation process.

4) Ice deformation (convergence and divergence of the ice cover): Mechanical redistribution due to convergence/divergence of the ice cover tends to increase/decrease the area-averaged thickness of the snow layer (δh^{s}_{def}) and ice freeboard (δh^{i}_{def}). The relationship between δh^{s}_{def} and δh^{i}_{def} may be more complicated and hence written separately.

5) Basal ice growth/melt (δh_{gm}) of sea ice adds/removes from the ice freeboard and increases/decrease the total freeboard.

This brief summary is a simplification as there are higher order processes such as changes due to snow metamorphism but their area-averaged contributions to freeboard changes are likely to be small. Another factor (note above) to bear in mind in the interpretation of regional variability of freeboard (below) is the advective changes and sea ice melt at the margins.

3.2 Monthly composites IS-2 and CS-2 freeboards

Figure 3 shows the monthly composites of IS-2 and CS-2 freeboards, for April through November 2019. The associated freeboard distributions are shown in Figure 4. The numerical values and sample statistics of the monthly distributions are in Table 2. We examine freeboard distributions of the seven sectors in the following order: Amundsen-Bellingshausen (A-B), coastal Amundsen-Bellingshausen (CoA-B), East and West Weddell (E-Wedd, W-Wedd), Ross, Pacific Ocean, and Indian Ocean.

3.2.1 Amundsen and Bellingshausen Seas sectors (A-B and CoA-B)

The freeboard distributions of the Amundsen and Bellingshausen seas between the Antarctic Peninsula and 140°W, are constructed with samples from two sectors (Figures 4a and 4b): one that is between coastal Antarctica and 70°S (referred to as the CoA-B sector) and the other has an open boundary to include the seaward extent of the advancing winter ice edge (A-B sector).

For the eight winter months, the highest variability (amongst the seven sectors) is seen in the CoA-B sector, where the area-averaged IS-2 and CS-2 freeboards range from 29.2±16.6 (min) to 54.0±32.5 (max) cm, and 11.2±6.03 to 15.6±6.83 cm, respectively. The squared correlation (ρ^2) between the two freeboards of 0.90 (Figure 4c) – highest of all seven sectors – indicates that the co-variability may be attributable to responses to the same forcing. Indeed, examination of the monthly maps of ice drift (Figure 5) suggests that the correlated increases in the two freeboards is likely due to the persistent wind-driven convergence of sea ice against the Antarctic coast (west of 90°W). The resulting ridging in the coastal Amundsen Sea ice cover resulted in a redistribution of the thinner ice into thicker categories. This simultaneously increases both the lidar and radar freeboards. The anomalous on-shore ice drift in 2019 (Figure 5b) can be contrasted to the mean ice drift pattern for the period 2012-2019 (Figure 5a). The large-scale atmospheric pattern in 2019 shows the location and depth of the Amundsen Sea Low (ASL) centered in the northeast Ross Sea (Figure 5b). The atmospheric pattern in 2019 is such that on-shore wind is nearly perpendicular to the coast and the depth of the ASL can be seen in the density of the isobars. The longer tails of the freeboard distributions seen after May are also signatures of ice convergence, where snow accumulation would unlikely affect the tails of

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both distributions, i.e., ice freeboard tends to be anti-correlated to snow accumulation. Hence, the freeboard variability here seems to be dominated by wind-driven ice deformation, which masked the signal of other processes.

For the A-B sector (which includes the CoA-B sector), the seasonal signal is more muted. The IS-2 and CS-2 freeboards range from 25.3± 7.8 to 36.3± 28.5 cm, and 9.53± 5.78 to 11.1±6.26 cm, and are lower because of the thinner seasonal ice cover away from the coastal zone (CoA-B). The squared correlation (ρ^2) between the two freeboards of 0.43 (Figure 4c) is also likely connected to the large signal in the CoA-B sector in the south. In November, the increase in the IS-2 freeboard not seen in the CS-2 freeboard is potentially due the limited 2-week IS-2 coverage.

3.2.2 East and West Weddell Sea Sectors

The East (E-Wedd) and West Weddell (W-Wedd) sectors are located between 15°E and 40°W, and 40° and 62°W, respectively, both with boundaries that are open to the north. Generally, the W-Wedd sector is one of few regions in the Antarctic where multiyear sea ice is found (Lange & Eicken, 1991). Sea ice formed in the east (E-Wedd sector) is advected clockwise around the southern Weddell Sea (cyclonic gyre), and the older sea ice after its transit is subsequently exported at its northwestern boundary (Figure 5a). Along its drift trajectory, the ice cover becomes thicker and deformed (Lange & Eicken, 1991; Vernet et al., 2019). As well, younger/thinner ice areas added by mechanical divergence and formed seaward of the Ronne and Brunt ice shelves (Drucker et al., 2011). The average annual areal export from the southern Weddell Sea (along a flux gate along the 1000 m isobaths that parallels the ice fronts of the Ronne and Filchner ice shelves) is ~0.32×10^6 km^2 (Kwok et al., 2017), and is comparable to the area of ~0.28×10^6 km^2 enclosed by the flux gate of ~1100 km in length.

In the composite fields (Figure 3), the thicker ice with its higher IS-2 and CS-2 freeboards in the W-Wedd sector is a feature that stands out in the circumpolar Antarctic ice cover. In the 2019 composites, an area of lower IS-2 and CS-2 freeboards (likely of ice formed in Ronne Polynya) is present in the southwestern corner of the Weddell Sea. In the eight months of 2019 (Figures 4c), the CS-2 freeboard only varied over a narrow range of ~3 cm (i.e., between 10.8± 5.05 and 13.5± 5.73 cm). The squared correlation (ρ^2) between the two freeboards is 0.20 (Figure 4c). Unlike the clear convergence signal (correlated freeboard time series) in the A-B sectors (correlated freeboard time series), this behavior suggests a balance of different/competing processes discussed earlier (Section 3.1). Generally, the processes that would increase the IS-2 freeboards during this winter (e.g., precipitation, convergence, and growth) must have been overwhelmed by processes that would tend to lower the IS-2 freeboards (e.g., snow-ice formation, loss of snow into leads, divergence, and ice export). Similarly, contributions to increases in CS-2 freeboards (due to convergence, growth, snow-ice formation) are likely balanced by precipitation and divergence, even though the CS-2 freeboards tend to be less sensitive to these changes. The longer tails of monthly freeboard distributions in the W-Wedd (Figures 4a and 4b) also suggest active ice deformation. These processes cannot be resolved at the regional scale that the data is being examined in this paper.

In the E-Wedd, the higher total and CS-2 freeboards is likely due to the thicker ice present early in April and May that become a much smaller fraction of the area of growing ice cover as the sea ice edge advances seaward. As ice coverage grows (Figure 3), the thinner seasonal ice dominates the total area lowering the mean freeboards in the subsequent months. Both the total and CS-2 freeboards remained within a narrow range after May, again suggesting a balance of different processes that reduced their range of variability. The lowest area-averaged freeboards are found in this sector.

3.2.3 Ross Sea Sector

Significant ice production occurs in this sector (between 140°W and 160°E). New ice production in the Ross Sea is located primarily in the Ross Shelf Polynya, and the Terra Nova Bay (TNB) and McMurdo Sound polynyas. Annual ice production here

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(south of the 1000 m isobaths) is higher than that in the Weddell Sea (Drucker et al., 2011). The average annual ice area export in a 34-year record is 0.75×10^{6} km^{2} (at a flux gate along the 1000 m isobaths that parallels the ice front of the Ross Sea Ice Shelf). The ~1400 km flux gate encloses an area of ~490×10^{3} km^{2} to the south. On average, the southern Ross Sea exports more than its area of sea ice that is largely produced in the polynyas.

In all months of 2019, the signature of thinner sea ice with lower freeboards exported from the polynyas can be seen as a distinct tongue that extends seaward then westward beyond the Ross embayment in both the IS-2 and CS-2 freeboards composites (Figure 3). The spatial features are consistent with the cyclonic (clockwise) drift pattern, centered over the northeast Ross Sea associated with the ASL, in all months between June and September (Figure 5b). The drift pattern shows a coastal inflow of thicker sea ice into the Ross Sea from the Amundsen Sea in the east that is distinctly thicker than the outflow of thinner ice from the southern Ross Sea. North of Cape Adare in the northwest corner of the Ross Sea, the northward drift splits into two branches with one that moves westward into the Somov Sea and the other northeastward before it gets entrained in the Antarctic Circumpolar Current (ACC).

The IS-2 and CS-2 freeboards range from 13.8±6.45 to 23.0± 13.6 cm, and 6.78± 2.8 to 9.35± 4.00 cm, respectively (Figure 4c, Table 1), Both freeboards show a gradual increase with a peak in the IS-2 freeboard during August, likely due to overlapping coverage of the ice convergence events by the A-B (discussed above) and Ross sectors, and to inflow of the thicker deformed ice from the A-B sector. The squared correlation (ρ^2) between the two freeboards of 0.88 (Figure 4c), comparable to that in the CoA-B sector, is likely due to the continual production of thin ice in the polynyas, the growth of the thin ice as it is advected northward, and the northward drift and growth of the sea ice from the A-B sector.

3.2.4 Pacific and Indian Ocean Sectors

The Pacific and Indian Ocean sectors are located between 90ºE and 160ºW, and 15º and 90ºE, respectively. Except for the larger extent of the ice cover in Indian Ocean Sector (around 15ºE and 40ºE) where the winter edge extends into the South Atlantic and Indian Oceans, the ice cover occupies a very narrow band that extends only ~400 km seaward at maximum extent. In 2019, associated with the location of the Davis Strait Low (DSL) pressure pattern (Kwok et al., 2017) there is an average westward ice drift in both sectors in all months consistent with that seen in the mean 2012-2019 drift patterns (Figure 5a). The Pacific sector ice cover is composed of mainly seasonal ice formed locally and fed by coastal polynyas, and by outflows from the Ross Sea. Similarly, the Indian Ocean sector is largely seasonal ice grown locally and in coastal polynyas and from the Pacific Sector.

The behavior of the freeboards in both sectors is similar (except for magnitude) (Figure 4). The higher IS-2 and CS-2 freeboards (though less pronounced in the CS-2 freeboards) in April/May are from a small population of sea ice adjacent to the coast (see Figure 3). Broadly, we find it difficult to explain the source of higher freeboard sea ice in both sectors early in the growth season. The behavior of higher freeboards of both the IS-2 and CS-2 freeboards are consistent - the squared correlation (ρ^2) between them are 0.55 and 0.64, in the Pacific and Indian sectors, respectively. From a retrieval perspective, we also note that the heights of the local sea surface estimates near the ice edge are affected by sea state, likely due to scattering from the troughs of waves propagating into the ice cover. This effect is predominant in the Pacific and Indian Ocean sectors because of the smaller sea ice extent. The consequence is surface heights that may be tens of centimeters below the local mean sea level resulting in higher freeboards. We have filtered most of these anomalous freeboards (visually) in the IS-2 and CS-2 processing but some are still present.

In general, the behavior of the sea ice cover in the Pacific and Indian Ocean sectors resembles that of the E-Wedd sector, with the lowest end-of-season IS-2 and CS-2 freeboards. The thinner seasonal ice dominates the behavior of the mean freeboards

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in all months (Figure 3). The lowest CS-2 freeboards are found in the Indian Ocean sector in in November (5.77± 2.88 cm). The CS-2 freeboards remained within a narrow range after May, the lowering of the IS-2 freeboards over the winter months suggest a balance of different processes discussed above. Again, it is difficult to resolve these processes at the regional scale that the data is being examined in this paper.

4 Snow depth estimates

In this section, we first briefly summarize the calculation of snow depth from freeboard differences, and the sensitivity of the retrieved snow depths to uncertainties in bulk density. Second, we discuss the procedure used to construct monthly composites with freeboards from the two altimeters, and the expected uncertainties from the lack of coincidence between the two measurements. Third, the 2019 spatial patterns of snow depths are examined. Last, we discuss the large-scale relationship between snow depth and IS-2 freeboard in the monthly composites.

4.1 Snow depth from freeboard differences

We follow the procedure detailed in Kwok et al. (2020) (henceforth *K20*) using a layered geometry depicted in Figure 2. A layer of snow-ice, an important component of the Southern Ocean ice cover, is included and assumed to have the same bulk density as sea ice. In our simplification, the snow-ice layer is considered to be part of ice layer (h_i) and indistinguishable from sea ice insofar as mechanical loading or hydrostatic equilibrium is concerned; this is necessitated by our lack of knowledge on how to effectively model the snow-ice formation process. The snow depth (h_{fs}) can thus be expressed as the difference between the total freeboard (h_f), from IS-2 estimates, and sea ice freeboard (h_{fi}):

$$h_{fs} = h_f^{IS2} - h_{fi}. \qquad (2)$$

The snow depth ($h_{fs}^{\Delta f}$) is then given by,

$$h_{fs}^{\Delta f} = \frac{(h_f^{IS2} - h_{fi}^{CS2})}{\eta_s}. \qquad (3)$$

assuming that the scattering from the snow-ice interface dominates the returns at K_u-band wavelengths (CS-2 altimeter). With one free parameter, η_s, this equation relates snow depth to the IS-2 and CS-2 freeboard differences (i.e., the two observables here) – η_s is the refractive index at K_u-band, $\eta_s = c/c_s(\rho_s)$ (Ulaby et al., 1986), *c* is the speed of light in free space, and ρ_s is the bulk snow density.. Equation (3) accounts for the reduced propagation speed of the radar wave (c_s) in a snow layer with bulk density ρ_s. At temperatures below freezing, the lidar and radar returns can be assumed to be from the air-snow and the snow-ice interfaces respectively and thus provide observations of total and ice freeboards. The validity and shortcomings of this assumption and its implications are discussed in Section 6. A bulk snow density of 320 kg/m^3 is used in all our calculations. There is no generally accepted value for the bulk density of snow in the Antarctic. Massom et al. (2001) suggest 200-300 kg/m^3 under cold/dry condition and higher density (320-500 kg/m^3) for warm windy conditions, which is not unlike the Arctic. Below, we elected to use an average winter bulk density of 320 kg/m^3 (like that of the Arctic) but with a higher variability of 70 kg/m^3 to cover the range of conditions.

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4.1.1 Sensitivity of snow depth and ice thickness to snow density

Similarly, following *K20*, we write the sensitivity of $h_{fs}^{\Delta f}$ to bulk density (for the parameterization of η_s given above) as:

$$\frac{\partial h_{fs}^{\Delta f}}{\partial \rho_s} = -0.77(1+0.51\times10^{-3}\rho_s)^{-2.5}(h_f^{IS2}-h_{fi}^{CS2}). \qquad (4)$$

which gives the fractional change in snow depth associated with a change in density as,

$$\frac{\Delta h_{fs}^{\Delta f}}{(h_f^{IS2}-h_{fi}^{CS2})} = -0.53\times10^{-3}\Delta\rho_s \quad for \quad \rho_s = 320\,kg/m^3. \qquad (5)$$

Relative to a nominal density of 320 kg/m³ and an uncertainty in density of ±70 kg/m³, the uncertainty in the snow depth is ~4% of the difference in freeboard. In effect, this represents ~1 cm uncertainty in snow depth for freeboard differences of 30 cm, suggesting that snow depth is relatively insensitive to uncertainties in the bulk density. The sign indicates that snow depth will be underestimated if the density is overestimated.

As well, the sensitivity of thickness estimates to uncertainties in snow density in *K20* (for a fixed total freeboard) is written as,

$$\left.\frac{\partial h_i}{\partial \rho_s}\right|_{h_f} = (h_f^{IS2}-h_{fi}^{CS2})\frac{1-0.77\eta_s^{-5/3}(\rho_s-\rho_w)}{\eta_s(\rho_w-\rho_i)}. \qquad (6)$$

The fractional change in ice thickness associated with a change in density is,

$$\left.\frac{\Delta h_i}{(h_f^{IS2}-h_{fi}^{CS2})}\right|_{h_f} \sim 10.5\times10^{-3}\Delta\rho_s. \quad for \quad \rho_s = 320kg/m^3. \qquad (7)$$

Again, relative to a nominal density of 320±70 kg/m³, the calculated thickness uncertainty is ~70% of the difference in freeboards. For a 30-cm freeboard difference (typically winter value used as an example), this translates into ~0.2 m uncertainty in thickness. If the density is overestimated, the snow depth is underestimated (see above) and the ice thickness is overestimated – a larger fraction of the total freeboard is now assigned to the higher density sea ice. The above values serve as bounds on the expected density-induced errors in the retrieval estimates if a $\Delta\rho_s$ of ±70 kg/m³ is indeed representative of the density variability Antarctic snow cover. In our simple model to convert freeboard differences to snow depth, the above analysis quantifies the expected sensitivity of the calculations to snow density.

4.1.2 Sensitivity of freeboard sampling for snow depth calculations

The sampling of the IS-2 and CS-2 freeboards for snow depth calculations follows the procedure in *K20*. Since Antarctic sea ice is found at lower latitudes, coverage is challenging due to the lower density of ground tracks from polar orbiting satellites. First, daily along-track IS-2 and CS-2 freeboards are averaged separately onto their own 25-km grid. Gridded IS-2 freeboards are averages of the three strong IS-2 beams and thus provide a better sampling of the spatial mean (compared to single-track profiles of CS-2 freeboards). Freeboard differences are then computed at each IS-2 grid cell using CS-2 freeboards (weighted by ice concentration) with time separations |ΔT|<10 days and within a 75-km box. We find that this sampling strategy provides the best spatial coverage without sacrificing precision.

We examined the sensitivity to space-time sampling (as in *K20*), by assessing differences in calculated snow depths with time separations of |ΔT| <1 day, <10 days and <15 days, using CS-2 freeboards at collocated grid cells only and then freeboards within a 75-km box (i.e., including the eight neighboring grids cells); this provides six space-time combinations. The standard

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deviation of the differences in calculated snow depths (for the six combinations) were all less than 1 cm. This suggests that the spatial variability of the CS-2 freeboards is lower than IS-2 freeboards. As seen in the Section 4.2, the range of the area-averaged IS-2 freeboard between April and November (18.9 to 50.4 cm) is more than double the range of the CS-2 freeboards (6.6 to 15.6 cm). The added advantage of longer time separations and looking over longer distances for CS-2 freeboards is the improved coverage for constructing full composites. In fact, a time-separation of 10 days (i.e., |ΔT|<10 days) provides the best coverage (see Table 1).

4.1.3 Ice deformation

The episodic and localized nature of ice deformation and the impact of this process on differencing freeboards separated in time are discussed in *K20*. Here, we provide a brief summary. The time order of freeboard sampling has an asymmetric effect, i.e., the impact of a convergence or divergence event separating the freeboard samples would be different. If the selected CS-2 freeboard precedes an IS-2 freeboard in time, the snow depth would be overestimated (underestimated) if a convergence (divergence) event occurred in the interim. If the selected CS-2 freeboard is from a later time and a convergence (divergence) event occurred in between, the snow depths would be underestimated (overestimated). Also note is that the loss of snow during a convergence event may have a confounding effect. Here, the selected CS-2 freeboards are centered on the time of the IS-2 samples; hence, random events around that center time would increase the snow depth variance but would have a small impact on the average monthly snow depth. These results, discussed in the previous section, suggest that the effect of sea-ice deformation in biasing the snow depth estimates may be small. For the six combinations of space-time sampling of the two freeboards, the variability in retrieved snow depths were less than a centimeter.

4.2 Snow depth estimates in 2019

The monthly snow depth composites and their distributions are shown in Figure 3 and Figure 6a, respectively. Table 2 shows the numerical values. Due to the low variability of the CS-2 freeboards, the spatial pattern of the snow depth estimates and the IS-2 freeboards are highly correlated in all the sectors ($\rho > 0.95$ - see Figure 7). Here, we summarize the spatial features of note. A more in-depth discussion of the relationship between snow depth and freeboard can be found in the next section and an assessment of the quality of the snow depth estimates (whether they are biased) are given the following section and Section 5, where these estimates were used to calculate ice thickness.

The thickest snow is seen in the W-Wedd sector (sector mean = 22.8± 12.4 cm in May) and the CoA-B sectors (31.4± 23.1 cm in September). With the multiyear sea ice cover in the W-Wedd sector, thicker snow is expected. The thinnest snow is found in the Ross (7.35± 4.30 cm in April) and E-Wedd (8.21± 5.81 cm in June) sectors. The thinner snow depth in the Ross sector is likely due to the extensive coverage by thin/young ice exported from the active Ross Sea polynyas, and in the E-Wedd sector due to the large seasonal ice cover. Lower snowfall rates may also contribute to these results (Cullather et al., 1998; Toyota et al., 2016). The spatial patterns show consistent thinning of the snow cover towards the ice margins almost everywhere and in all months; we see no spatial anomalies in snow depth near the ice edge expected of higher precipitation. Except for coastal zones with active polynyas (e.g., southern Ross and Weddell seas), snow depth is generally higher in coastal zones.

Seasonal increases in the monthly mean snow depth are seen only in the A-B and CoA-B sectors. In the CoA-B sector, the increase is ~13 cm (approximately half that of the IS-2 freeboard increase) over the eight months. This is likely due to precipitation delivered by the on-shore wind pattern linked to the location and depth of the Amundsen Sea Low (ASL) discussed earlier. In all other sectors, we find slowly varying snow covers between April and November, similar to the observed behavior of IS-2 and CS-2 freeboards. This is quite remarkable and suggests the processes that remove snow from the surface (e.g., snow-ice transformation, loss into leads, divergence, etc.) must be significant and overwhelm all precipitation signals in all months.

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Consequently, an in-depth study of these processes will be important for understanding of the behavior of the Antarctic snow cover.

4.3 Relationship between freeboard and snow depth

K20 examined the relationship between freeboard and retrieved snow depth for the Arctic ice cover. This of geophysical interest as the connection could be potentially utilized to provide rough estimates of snow depths where there are gaps in CS-2 observation. Figure 7 shows the monthly scatterplots of $h_{fs}^{\Delta f}$ and Antarctic IS-2 freeboard for the eight months between April and November. At the length scale of 25 km, the regression analysis (slope, intercept, and standard error in each plot) of the monthly fields shows that the two values are highly correlated (with the freeboard explaining >95% of the variance in snow depth); this is not entirely surprising as snow depth is derived from IS-2 freeboard. The regression slopes vary between 0.66 and 0.70 between April and November. For this Antarctic winter at least, the results suggest that between 66 and 70% of the IS-2 freeboard is snow. This can be contrasted with the 2019 Arctic winter (*K20*) where snow occupies a lower fraction or ~50-55% of the IS-2 freeboard.

The negative intercepts of between -3.4 and -4.5 cm are worth noting, as one should expect –by definition – zero snow depth at near zero IS-2 freeboard. The consistent values of the monthly intercepts suggest that one of the estimates may be biased. Here, we write:

$$\hat{h}_{fs} = \alpha h_f + \beta = f(h_f) \qquad (8)$$

where $\hat{h}_{fs}$ is the snow depth estimate, and α and β are the regression slope and intercept. If zero snow depth is expected at zero total freeboard, then an unbiased estimate of snow depth (h_{fs}) can be written as,

$$h_{fs} = \hat{h}_{fs} + \delta = f(h_f) + \delta \quad and \quad \delta = -\beta \quad if \quad h_{fs} = f(0) = 0 \qquad (9)$$

where δ is the bias. To obtain the true unbiased estimate of snow depth (h_{fs}), an adjustment of $\hat{h}_{fs}$ by δ (or $-\beta$) is needed. The negative intercepts observed in the scatterplots imply that $\hat{h}_{fs}$ is overestimated by +3.4 and +4.5 cm.

One likely source of these biases is the displacement of retracking point (RP) of the radar altimeter (CS-2) away from the snow-ice interface resulting in higher CS-freeboards (Kwok, 2014). At K_u-band frequencies (CS-2), the RP's are displaced from the true ice surface when elevated snow salinities (due to brine-wicking, flooding) are found near the snow-ice interface, or the changes in scattering the presence of moisture in the snow layer when air temperature warms (Winebrenner et al., 1994). For Antarctic sea ice, in particular, the salinity of snow layer was characterized by Massom et al. (1997) to include two components: 1) a "background" salinity <1 in the upper part of the snow column, likely contributed by blowing snow due to wicked salt or aerosol or sea spray transported during strong winds over adjacent leads and polynyas; and, 2) a high-salinity (> 10) basal component (0–3 cm), sometimes damp due to brine wicking when the snow is thin or associated with flooding of the snow-interface. It is the basal layer salinity that has a large impact on CS-2 freeboards. Massom et al. (1997) also noted that basal salinities exceeding 10 commonly occur under relatively thin snow covers when brine is available at their surface for vertical uptake into an accumulating snow layer.

The displacement of the RP's above the snow-ice interface from radar penetration experiments in the field has been reported in a number of publications (Willatt et al., 2010; Willatt et al., 2011). Using salinity profiles from snow pits (collected in the Canadian Arctic Archipelago) to drive a scattering model, Nandan et al. (2017) and Nandan et al. (2020) prescribed a nominal adjustment (δ) of ~7 cm of the RP from first-year ice throughout most of the year. Kwok and Kacimi (2018), in an

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analysis of data from CS-2 and OIB, also reported consistently higher CS-2 radar freeboards along an airborne transect of the Weddell Sea.

K20 showed that an adjustment of the snow depth (δ), due to the displacement of the scattering surface, would decrease the ice thickness estimates by

$$\Delta h_i = \left(\frac{\rho_s - \rho_w}{\rho_w - \rho_i}\right)\frac{\delta}{\eta_s} \sim -5.26\delta \quad for\, \rho_s = 320 kg \cdot m^{-3}. \tag{10}$$

A 7 cm adjustment results in a reduction in the estimated ice thickness of -0.37 m. The physical basis of a displacement of the RP due to brine wicking is sound, but a better understanding of the time-evolution of these processes and the magnitude of this adjustment is needed if these corrections were to be applied to individual freeboard estimates. This will be addressed in more detail in the discussion of thickness calculations in the next section.

5 Ice thickness and volume

In this section, we first describe the calculation of ice thickness and volume by using snow depths from freeboard differences, and by assuming that the snow depth is equal to the total (or IS-2) freeboard. Second, we discuss briefly the spatial statistics of the composites and address the potential biases due to effects of the snow layer on CS-2 freeboard retrievals. Last, the volume of the Antarctic ice cover is discussed.

5.1 Ice thickness and sector volume

We calculate two ice thicknesses: 1) h_i – with snow depth from altimeter freeboards and 2) h_i^0 – by setting snow depth equal to the total freeboard,

$$h_i(h_f, h_{fs}) = \left(\frac{\rho_w}{\rho_w - \rho_i}\right)h_f + \left(\frac{\rho_s - \rho_w}{\rho_w - \rho_i}\right)h_{fs} \tag{11}$$

$$h_i^0(h_f) = \left(\frac{\rho_w}{\rho_w - \rho_i}\right)h_f \quad for \quad h_{fs} = h_f. \tag{12}$$

In the first equation, we assume that the radar derived surface is from the snow-ice interface. The ice thickness, h_i^0, in the second equation sets a lower bound on the thickness estimates for a given total freeboard of h_f – with assumed densities of water, snow, and ice ($\rho_w = 1024 kg \cdot m^{-3}$, $\rho_s = 320 kg \cdot m^{-3}$, $\rho_i = 917 kg \cdot m^{-3}$). When flooding and snow-ice formation occur and the ice freeboard is zero, an estimate of snow depth can be used to estimate ice thickness (given reasonable values for snow and ice densities).

Ice volume for each Antarctic sector is simply the product of the average thickness $\bar{h}_i$ and area A_{sec} of each sector,

$$V_{sec} = A_{sec}\bar{h}_i. \tag{13}$$

To examine the potential impact on ice volume due to biases in CS-2 freeboards due to salinity effects, we write,

$$V_{sec}(\delta) = A_{sec}(\bar{h}_i - 5.26\delta) \quad m^3 \tag{14}$$

where δ is the adjustment factor that accounts for the displacement of the CS-freeboard above the snow-ice interface discussed in Section 4.3.

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5.2 Monthly ice thickness (April-November)

The monthly thickness composites (h_i and h_i^0) and their distributions are shown in Figure 8 and Figure 9, respectively, and the numerical averages are in Table 2. Again, the spatial patterns of the thickness composites are very similar to that of the freeboards and snow depth, and so here we note only the features and differences.

As expected, the thickest ice is found in the W-Wedd sector (mean 2.50±1.08 m in May) and the CoA-B sector (3.25± 1.71m in September). These are also sectors where the highest snow depths are found. The thinnest ice is in the Ross (0.90± 0.41 m in April) and E-Wedd (<1.5 m for all months) sectors. The tongue of lower ice thickness in the Ross sector (Figure 8) is a clear signature of the outflow of thin/young ice produced in the Ross Sea polynyas. Similarly, for the E-Wedd sector, the large expanse of thinner seasonal ice is also evident. Consistent thinning towards the ice margins is seen almost everywhere and in all months.

The seasonal cycle of ice thickness is surprisingly weak. Seasonal increases in the monthly mean ice thickness are only evident in the A-B and CoA-B sectors. Notably, in the CoA-B sector, the increase in ~1 m (from 1.85± 1.11 m in April to 2.94± 1.43 m in November) over the eight months, discussed earlier, is connected to coastal ice convergence (the mechanical redistribution of thin to thicker ice) associated with persistent on-shore wind pattern in 2019. In all other sectors, we find either decreases or relatively unchanging thicknesses (i.e., weak seasonality) from April to November.

There are no seasonally and regionally diverse data set from field observations that could be used to assess the large-scale satellite retrievals. Field observations of ice thickness are from two main sources – shipborne observations and mechanical drilling profiles. The most extensive compilation of Antarctic ice thickness is from the ASPeCt database reported in Worby et al. (2008) – it contains data from 83 voyages and 2 helicopter flights for the period 1980 - 2005. Figure 10 compares our thickness estimates with the ASPeCt data summarized in Worby et al. (2008). For all seasons and sectors, the overall ice thickness in the ASPeCt data (circles in Figure 10) are less than half the mean thickness in our estimates (solid blue line). There are two reasons these data sets are not comparable: 1) the ASPeCt data are biased towards thin and level ice types; and, 2) few of the ASPeCt data have been collected at a similar time and location; indeed, ASPeCt observations of the coastal southern Bellingshausen and Amundsen seas in spring are not available. Underway shipboard observations made while traversing the pack ice (in ASPeCt database) favor sampling the thinner end of the thickness distribution due to physical, navigational, and logistical constraints. Hence, the sample population in the ASPeCt database is not likely to represent the regional statistics needed for assessment of the satellite retrievals. Drilling data may be more comparable, as they provide a better sampling of the thickness distribution and of ice thick enough to stand on — but this limits the sampling of very thin ice. However, almost all drilling data to date are from thinner floes (Ozsoy-Cicek et al., 2013) and the thickest ice is often avoided. Even though drilling measurements have provided locations on where one should expect thicker ice (e.g., Lange & Eicken, 1991; Massom et al., 2001; Williams et al., 2015), they rarely provide averages at spatial scales compatible with satellite averages.

Ice thickness estimates from Operation IceBridge provide averages at a larger scale but they are still limited in terms of seasonal coverage. In an examination of three years of OIB ice thickness, Kwok and Kacimi (2018) report October ice thicknesses that ranges from 2.40 to 2.60 m over a transect across the Weddell Sea (from the tip of the Antarctic Peninsula to Cap Norvegia. This is more compatible with the averages in the W-Wedd sector in Figure 10a (solid blue line). In a north-south OIB transect of the Ross Sea in November, Tian et al. (2020) found ice thicknesses between 0.48 and 0.99 m, again more compatible with that seen in Figure 10d (solid blue line). In any case, a more exhaustive evaluation of the present data set remains a challenge.

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5.3 Are the thickness estimates high?

In sectors where there is predominantly seasonal ice (Ross, Pacific, Indian, E-Wedd) the ice thickness in the early winter months of April and May, at close to ~ 1.5 m, seems to be too high. In these sectors, the growth of 1 m of sea ice in the 1-2 months between freeze-up (in February, March) and April/May is unlikely. With ice drift that is largely seaward and divergent during these months (Figure 5), the only two processes that contribute significantly to increases in thickness are basal growth and snow-ice formation. In the short 1-2 months from freeze-up, basal thermodynamic growth of 1 m is unlikely given the oceanic conditions (ocean heat flux in a weakly stratified ocean compared to the Arctic). As well, it would require high snowfall rates to create a significant thickness of snow-ice in that amount of time. Thus, this points strongly to biases in the CS-2 freeboards as the estimated thicknesses are highly sensitive to these biases (due to large 3:1 contrast between ice and snow densities in Equation 11).

Clearly, if ice freeboard were zero everywhere, then h_i^0 (Equation 12) would be the best estimate of ice thickness given measurements of total freeboard. However, this is unlikely the case especially in the W-Wedd and CoA-B sectors where thicker ice is known to be present (see discussion above). If there were a large-scale bias in the CS-2 freeboards (assuming the processes that contribute to the radar biases are the same everywhere) then areas with the lowest CS-2 freeboards provide a rough guidance on the magnitude of that bias. In the four sectors of largely seasonal ice (Ross, Pacific, Indian, E-Wedd), the sector-averaged CS-2 freeboards have the lowest values and low seasonal variability that ranges from 5.86± 2.50 cm (minimum) to 10.3± 3.67 cm for all months. This suggests a bias (δ) of ~6 cm if we assumed that early-season ice freeboards have to be near zero. This value can be compared to reported biases from different studies, for example:

- The thickness of the high salinity basal layer of 0-3 cm (> 10) reported by Massom et al. (1997).
- Suggested adjustment (δ) of ~7 cm on first-year ice in the Arctic based on a scattering study using profiles of basal salinities (Nandan et al. (2017); Nandan et al. (2020)).
- Observed CS-2 biases of up to 8 cm in the Weddell Sea in an assessment of the IceBridge and CS-2 derived ice thicknesses (Kwok & Kacimi, 2018).
- 3.4 - 4.5 cm estimated in Section 4.3.

In the following section, we examine the sensitivity of thickness and volume if these biases were generally representative over the entire ice cover.

5.4 Thickness and volume estimates – with and without adjustments

As discussed above, sea ice would be too thick using the CS-2 freeboards directly and too thin if ice freeboard were assumed to be zero everywhere. Guided by the potential range of CS-2 freeboard biases above, we calculate the regional thickness and volume of the Antarctic ice cover with adjustments (δ) of 3 and 6 cm (Equation 13) to assess the variability of sector ice volume between the two extremes of thicknesses (i.e., h_i and h_i^0) over the winter of 2019. The monthly h_i^0 composites and the sector thicknesses (with δ = 0, 3, 6 cm) can be seen in Figure 10 and Table 3, and the monthly ice volumes are shown in Figure 11.

The adjustments to CS-2 freeboards, as expected, lower the thickness (5 cm per 1 cm of adjustment – based on Equation 10); at δ = 6 cm the sector mean would be reduced by 0.32 m. The impact is higher – in terms of fractional change in total thickness – in sectors with thinner ice (e.g., E-Wedd). The range of thicknesses in Figure 10 gives us at least an indication of the potential range of variability between assuming zero ice freeboard and the rough estimates of δ (applied as a sector wide bias).

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Even though current knowledge does not allow us to adjust individual thickness retrievals, these large-scale adjustments likely provide a better estimate than those calculated using h_i or h_i^0.

The end-of-season ice volume in each sector is proportional to the area production (Figure 11h) with the largest ice volume in the E-Wedd sector. This, of course, is not the ice volume production in a particular sector. In order to calculate seasonal ice production, one has to account for volume exchanges at the sector boundaries and volume lost to melt at the ice edge. Of interest here is the ice volume and its sensitivity to δ. At the end of the season, the difference in total Antarctic ice volume between assuming δ=0 and $h_{fs} = h_f$ is ~10,000 km^3, or one-third of the total volume. Adjustments with δ=3 and δ=6 cm reduce the differences by ~2000 and 4000 km^3, respectively. As with ice thickness, in sectors where the ice is thicker (W-Wedd, Figure 10) the fractional changes are smaller. An adjustment of 6 cm gives a circumpolar ice volume of 15,600 km^3 in October, for an average thickness of ~1.13 m.

These volume estimates can be compared to volume estimates from ICESat-1 freeboards. Using AMSR snow depths, Zwally et al. (2008) estimated the average October-November (2004 and 2005) Weddell Sea ice volume to be ~8750 km^3, comparable to our 2019 estimate of 7264 km^3 (without any adjustments). Here, differences are expected as the efficacy of the AMSR snow depths has yet to be demonstrated.

Assuming snow depth to be the total freeboard (i.e., zero ice freeboard) Kurtz and Markus (2012) estimated an average circumpolar ice volume of 11,111 km^3 in the spring (2003 through 2008) with an average thickness of 0.83 m; this can be compared to our October estimate of 10062 km^3 and 0.72 m using the same assumption. Our lower volume estimates may be partly attributable to the retreat in Antarctic ice coverage (Parkinson, 2019) since the ICESat-1 mission of >10^6 km^2. With the same assumption of zero ice freeboard, the change of 0.11 m between ICESat-1 and IS-2 in 2019 may be of interest but this is more of an indication of decrease in total freeboard rather than an actual change in ice thickness.

6 Conclusions

In this study, we offer a view of the Antarctic sea ice cover from lidar (ICESat-2) and radar (CryoSat-2) altimetry. This is a first joint examination of the IS-2 and CS-2 freeboards, the snow depth derived from their differences, and the calculated sea ice thickness/volume. Our analysis spans an 8-month winter between April, 2019 and November 16, 2019. We characterize the behavior of the circumpolar ice cover in seven geographic sectors. The limitations in our current knowledge in the retrieval of snow depth, thickness, and volume are addressed. Below we highlight some of the results and discuss future opportunities for validation and assessment of this retrieval approach:

- Highest freeboards are seen in the CoA-B and W-Wedd sectors. The remarkable ice convergence due to on-shore wind and ice drift along the coastal Amundsen Sea – associated with the depth, location, and persistence of Amundsen Sea Low pattern – is captured in the correlated changes in IS-2 and CS-2 freeboards with extremes of 54.0±32.5 cm (in September) and 15.6±6.83 cm (in October), respectively, and derived thickness of 3.25±1.71 m (in September). The multiyear ice in the W-Wedd sector, as expected, also stands out with high freeboards and thickness (sector mean thickness of 2.50±1.08 m in May).
- Lowest freeboards, snow depth, and thickness are seen in the proximity of the Ross Sea and Ronne polynyas. In the Ross Sea sector, the lowest sector-averaged IS-2 and CS-2 freeboards of 13.8±6.45 cm, and 6.78±2.81 cm, respectively, can be contrasted with those in the CoA-B and W-Wedd above.

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- With the extremely low variability in CS-2 freeboards in the Antarctic snow depth estimates are highly correlated with IS-2 freeboards, with the IS-2 freeboard explaining >90% of the variance in snow depth. Our results suggest that more than 60-70% of the IS-2 freeboard is snow.
- In 2019, the observed seasonality in the sector-averaged freeboards, snow depth, and thickness is surprisingly weak. These sector averages do not follow the expected seasonal increases due to ice growth and snow accumulation seen in the Arctic. We attribute this to the mixture of competing processes (snowfall, snow redistribution, snow-ice formation, ice deformation, basal growth/melt) in different parts of the divergent Antarctic ice cover, and the continuous export of sea ice to the margins, where they subsequently melt.
- Evidence points to biases in CS-2 freeboards that is associated with displacement of the retracking points to a height above the snow-ice interface resulting in snow depths that are too low and ice thicknesses that are too high in the present retrievals. Based on field measurements, a contributing source to the bias is the salinity at the base of the snow layer due to wicking and flooding, the physical basis of expected biases in CS-2 freeboards from basal-layer salinity is sound. The question is the range of the biases and whether a correction factor could be applied for retrievals at the highest spatial resolution.
- Our calculations show the sector-scale variability of snow depth, thickness and computed ice volume given biases of 3 cm and 6 cm in radar freeboard, and assuming zero ice freeboard. At the sector scale, the adjusted estimates seem to be more credible although better assessment of these parameter awaits better field measurements. An adjustment of 3/6 cm gives a circumpolar ice volume of 17,900/15,700 km^3 in October, for an average thickness of ~1.29/1.13 m.
- Validation of Antarctic sea ice parameters remain a challenge. There are no seasonally and regionally diverse data set from field records that could be used to the assess the large-scale satellite retrievals, especially in areas that are inaccessible to ships. The overall ice thickness in the ASPeCt data in all seasons and locations are less than half the mean thickness in the present data and points to the sampling biases from underway shipboard observations. There is an urgent need for sustained and extensive field measurements.

The present analysis, however, is only a first step in the examination of the Antarctic ice cover using both the IS-2 and CS-2 altimeters. There are many aspects of data quality, some of which will only be revealed by assessment with data acquired and processed by dedicated airborne campaigns (e.g., NASA's Operation IceBridge), field programs, and when a longer IS-2/CS-2 time series becomes available. An adjustment of the CS-2 orbits (by ESA) – CRYO2ICE – to provide improved coincidence in space-time sampling of the two altimeters has been successfully implemented. We anticipate that the data acquired by CRYO2ICE will provide a crucial and valuable data set for not only understanding current retrievals but also the design of future instruments tasked to understand the development of the Arctic and Antarctic sea ice covers.

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Acknowledgments

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Table 1. Dependence of number of retrievals on space-time separation. November is not included here because the IS-2 data (Release 002) covered only half a month.

Space/ Time	25-km/ 1 day	25-km/ 10 day	25-km/ 15 day	75-km/ 1 day	75-km/ 10 day	75-km/ 15 day
Apr	774	2967	3476	2107	4246	4433
May	1023	4461	5543	1980	6898	7405
Jun	1413	5895	7293	3968	9243	9941
Jul						
Aug	2108	9516	11783	6253	15782	16673
Sep	2073	8556	10716	5751	14581	15536
Oct	1818	8270	10127	5291	13125	13928

Table 2. Monthly mean (standard deviation) of IS-2 freeboard (h_f), CS-2 freeboard (h_{fi}^{CS2}), and derived snow depth $(h_{fs}^{\Delta f})$.

(cm)		Apr	May	Jun	Jul	Aug	Sep	Oct	Nov
E-Wedd	h_f	25.4±10.9	19.0±9.72	15.6±8.12	-	17.5±6.02	18.7±6.10	17.8±5.82	16.4±6.50
	h_{fi}^{CS2}	8.37±3.14	7.14±2.74	7.00±2.16	6.60±2.00	7.07±1.86	7.63±2.20	7.36±2.16	5.86±2.50
	$h_{fs}^{\Delta f}$	14.7±8.90	13.1±10.6	8.21±5.81	-	8.90±4.30	9.45±4.05	9.24±3.96	8.76±4.63
W-Wedd	h_f	36.5±20.3	41.1±19.2	36.2±16.9	-	38.7±19.7	38.0±19.2	38.2±20.5	39.5±18.7
	h_{fi}^{CS2}	11.8±4.56	13.5±5.73	12.5±5.00	11.5±5.43	11.4±5.68	10.8±5.05	11.3±5.36	12.4±5.03
	$h_{fs}^{\Delta f}$	20.7±13.8	22.8±12.4	20.3±12.3	-	22.5±14.3	22.5±14.1	22.7±16.2	22.1±13.0
A-B	h_f	29.5±21.8	25.3±17.8	26.7±18.8	-	31.1±23.6	36.3±28.5	32.1±23.7	38.2±25.0
	h_{fi}^{CS2}	11.0±5.65	9.53±5.78	10.0±6.21	9.56±6.23	10.2±6.04	11.1±6.26	10.6±6.54	10.5±6.54
	$h_{fs}^{\Delta f}$	17.3±14.0	14.8±11.0	16.4±14.7	-	18.6±17.5	21.7±19.7	19.7±17.3	23.6±16.5
CoA-B	h_f	29.7±19.2	29.2±16.6	33.6±19.3	-	46.3±26.2	54.0±32.5	49.1±24.7	50.4±25.5
	h_{fi}^{CS2}	11.5±5.88	11.2±6.03	13.1±7.00	13.3±7.46	14.9±6.36	15.3±6.68	15.6±6.83	14.6±6.73
	$h_{fs}^{\Delta f}$	17.1±11.6	16.6±10.3	18.0±11.1	-	27.5±19.4	31.4±23.1	30.0±18.5	30.8±17.0
Ross	h_f	13.8±6.45	15.2±6.50	17.7±7.93	-	21.0±10.2	22.7±13.1	22.2±12.7	23.0±13.6
	h_{fi}^{CS2}	6.95±3.32	6.78±2.81	7.62±2.48	8.25±3.78	8.81±3.72	9.35±4.00	8.83±4.30	8.45±4.87
	$h_{fs}^{\Delta f}$	7.35±4.30	7.50±4.21	9.10±5.37	-	11.1±6.21	11.8±8.35	12.0±9.44	12.4±8.48
Pacific	h_f	34.8±30.1	22.3±16.6	27.9±14.4	-	26.5±16.5	25.7±15.7	27.8±18.5	27.0±20.0
	h_{fi}^{CS2}	10.3±3.67	8.13±2.11	8.35±2.80	8.18±2.88	8.06±2.97	7.36±2.91	7.43±2.96	7.28±3.16
	$h_{fs}^{\Delta f}$	24.5±23.0	18.4±15.3	19.3±13.7	-	19.8±14.7	19.3±13.8	21.3±17.5	19.0±12.4
Indian	h_f	27.5±22.4	19.0±14.1	25.3±26.7	-	17.9±8.55	16.8±8.45	18.3±9.55	18.0±9.86
	h_{fi}^{CS2}	10.1±4.00	7.71±2.48	7.46±2.55	7.40±2.55	6.74±2.06	7.00±2.17	6.85±2.55	5.77±2.88
	$h_{fs}^{\Delta f}$	19.8±20.4	16.6±17.2	17.3±19.8	-	12.0±9.51	9.27±6.61	11.0±7.60	10.3±6.71

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Table 3. Monthly mean (standard deviation) of estimated ice thickness: 1) h_i, with derived snow depth (h_i); 2); h_i^0, assuming $h_{fs} = h_f$; 3) h_i^3, with δ= 3 cm; and, 4) h_i^6, with δ= 6 cm.

(m)		Apr	May	Jun	Jul	Aug	Sep	Oct	Nov
E-Wedd	h_i	1.46± 0.56	1.21± 0.53	1.02±0.46		1.14±0.32	1.23±0.34	1.16±0.32	1.08±0.35
	h_i^0	0.78±0.33	0.58±0.30	0.48±0.20		0.54±0.18	0.57±0.18	0.55±0.18	0.50±0.20
	h_i^3	1.30	1.05	0.86		0.98	1.07	1.00	0.92
	h_i^6	1.14	0.89	0.70		0.82	0.91	0.84	0.76
W-Wedd	h_i	2.21± 1.11	2.50± 1.08	2.22± 0.90		2.29± 1.05	2.22± 1.02	2.24± 1.04	2.43± 1.01
	h_i^0	1.13±0.63	1.26±0.60	1.12±0.52		1.20±0.60	1.17± 0.60	1.17± 0.63	1.21± 0.57
	h_i^3	2.05	2.34	2.06		2.13	2.06	2.08	2.27
	h_i^6	1.89	2.18	1.90		1.97	1.90	1.92	2.11
A-B	h_i	1.85± 1.22	1.58± 1.04	1.70± 1.13		1.93± 1.28	2.31± 1.56	1.96± 1.28	2.32± 1.38
	h_i^0	0.91±0.67	0.77±0.55	0.82±0.58		0.95±0.73	1.12± 0.88	0.98± 0.73	1.17± 0.77
	h_i^3	1.69	1.42	1.54		1.77	2.15	1.80	2.16
	h_i^6	1.53	1.26	1.38		1.61	1.99	1.64	2.00
CoA-B	h_i	1.85± 1.11	1.79± 1.00	2.10± 1.20		2.72± 1.34	3.25± 1.71	2.83± 1.33	2.94± 1.43
	h_i^0	0.91±0.60	0.89±0.51	1.03±0.59		1.42±0.80	1.66± 1.00	1.51± 0.76	1.55± 0.78
	h_i^3	1.69	1.63	1.94		2.56	3.09	2.67	2.78
	h_i^6	1.53	1.47	1.78		2.40	2.93	2.51	2.62
Ross	h_i	0.90± 0.41	1.0± 0.40	1.14± 0.47		1.37± 0.62	1.51± 0.75	1.45± 0.74	1.48± 0.83
	h_i^0	0.42±0.20	0.47±0.20	0.55±0.24		0.65±0.31	0.70± 0.40	0.68± 0.40	0.70± 0.42
	h_i^3	0.74	0.84	0.98		1.21	1.35	1.29	1.32
	h_i^6	0.58	0.68	0.82		1.05	1.19	1.13	1.16
Pacific	h_i	2.00± 1.55	1.32± 0.87	1.62± 0.83		1.53± 0.90	1.52± 0.88	1.52± 0.96	1.58± 1.11
	h_i^0	1.07±0.93	0.68±0.51	0.86±0.44		0.82±0.51	0.80± 0.48	0.86± 0.57	0.83± 0.61
	h_i^3	1.84	1.16	1.46		1.37	1.36	1.36	1.42
	h_i^6	1.68	1.00	1.30		1.21	1.20	1.20	1.26
Indian	h_i	1.58± 1.16	1.13± 0.72	1.36± 1.13		1.10± 0.47	1.11± 0.47	1.10± 0.49	1.12± 0.57
	h_i^0	0.85±0.68	0.58 0.43	0.77±0.82		0.55±0.26	0.53± 0.26	0.56± 0.30	0.55± 0.30
	h_i^3	1.42	0.97	1.20		0.94	0.95	0.94	0.96
	h_i^6	1.26	0.81	1.04		0.78	0.79	0.78	0.80
Antarctic	h_i	1.58	1.41	1.40		1.44	1.50	1.45	
	h_i^0	0.81	0.68	0.70		0.71	0.72	0.72	
	h_i^3	1.42	1.25	1.24		1.28	1.34	1.29	
	h_i^6	1.26	1.09	1.08		1.12	1.18	1.13	

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Figure Captions

Figure 1. Naming of the sea ice sectors around Antarctica.

Figure 2. Relationship between the different height quantities.

Figure 3. Monthly composites of IS-2 freeboard (h_f), CS-2 freeboard (h_{fi}^{CS2}), derived snow depth ($h_{fs}^{\Delta f}$) for the period between April 2019 and November 2019. (25-km grid; Units: centimeters)

Figure 4. Monthly distributions of (a) IS-2 (h_f) and (b) CS-2 (h_{fi}^{CS2}) freeboards for the period between April 2019 and November 2019. Their monthly means are compared in (c). Numerical values in the line plots show the squared correlation between the two freeboards (distributions are normalized).

Figure 5. Monthly mean (April through November) ice drift in the Southern Ocean for (a) 2012-2019 and (b) 2019.

Figure 6. Monthly distributions of (a) derived snow depth ($h_{fs}^{\Delta f}$) and (b) ice thickness (h_i) for the period between April 2019 and November 2019 (distributions are normalized).

Figure 7. Monthly relationship between snow depth and freeboard. Parameters from the regression analysis (slope, intercept, correlation coefficient, and standard error) are shown in the top left corner of each panel.

Figure 8. Monthly composites of calculated ice thicknesses: (a) h_i – using snow depth from freeboard differences ($h_{fs}^{\Delta f}$), and (b) h_i^0 – assuming zero ice freeboard, i.e., $h_{fs} = h_f$, for the period between April 2019 and November 2019. (25-km grid; Units: meters)

Figure 9. Monthly distributions of calculated ice thicknesses: (a) h_i – using snow depth from freeboard differences ($h_{fs}^{\Delta f}$), and (b) h_i^0 – assuming zero ice freeboard, i.e., $h_{fs} = h_f$, for the period between April 2019 and November 2019. Their monthly means are compared in (c) (distributions are normalized).

Figure 10. Comparison of seasonal ice thickness calculated with δ = 0, 3, and 6 cm, and assuming zero ice freeboard (i.e., $h_{fs} = h_f$) with shipborne measurements in Worby et al. (2008).

Figure 11. Evolution of the volume and area of the Antarctic sea ice cover between April and October 2019.

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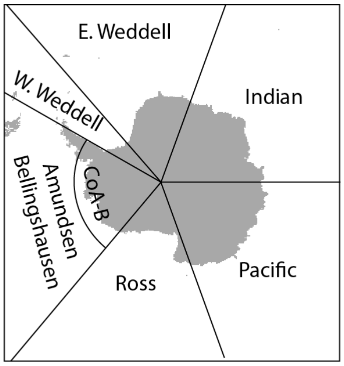

Figure 1. Naming of the sea ice sectors around Antarctica.

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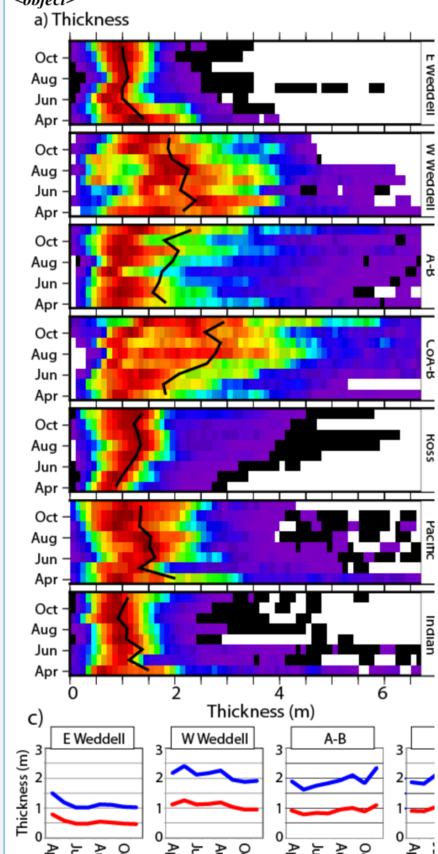

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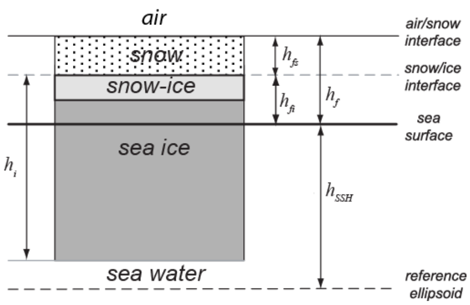
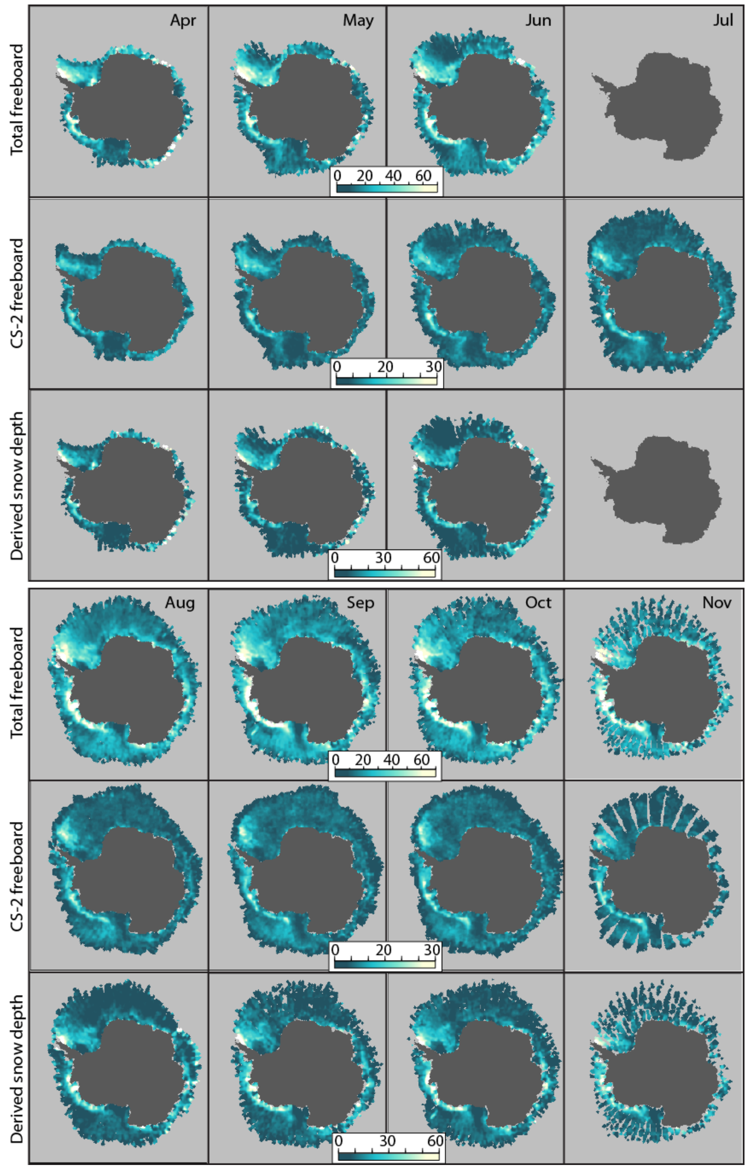


Figure 2. Relationship between the different height quantities in Equation (1).



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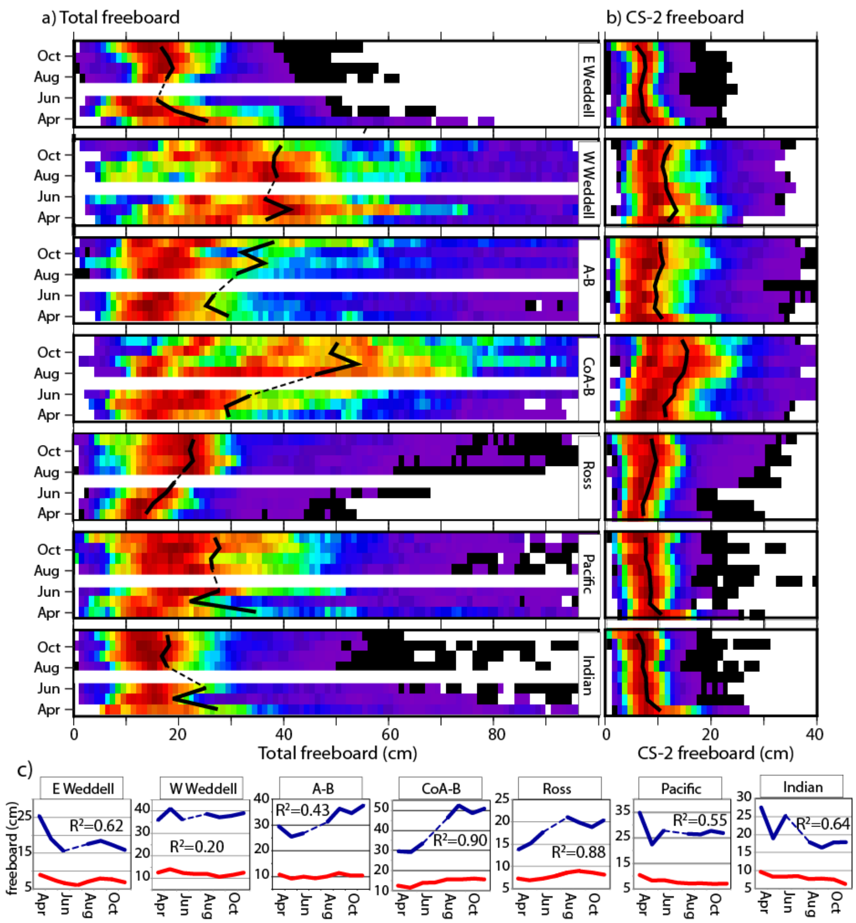
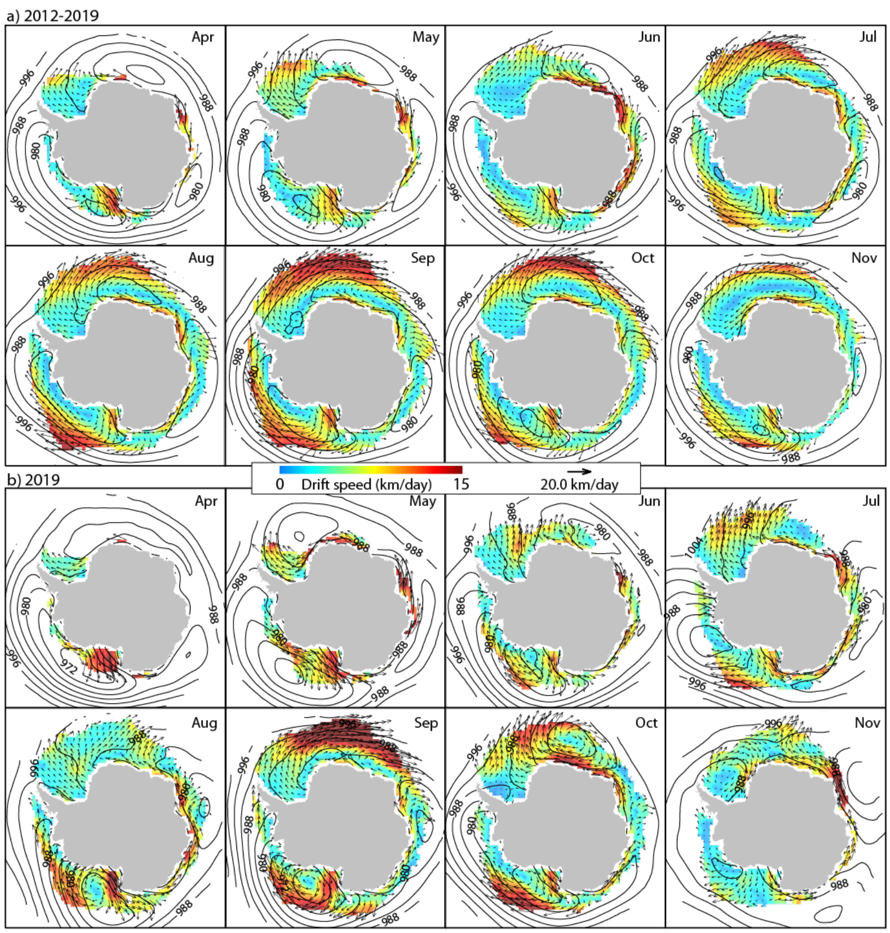


Figure 4. Monthly distributions of (a) IS-2 (h_f) and (b) CS-2 (h_{fi}^{CS2}) freeboards for the period between April 2019 and November 2019. Their monthly means are compared in (c). Numerical values in the line plots show the squared correlation between the two freeboards (distributions are normalized).



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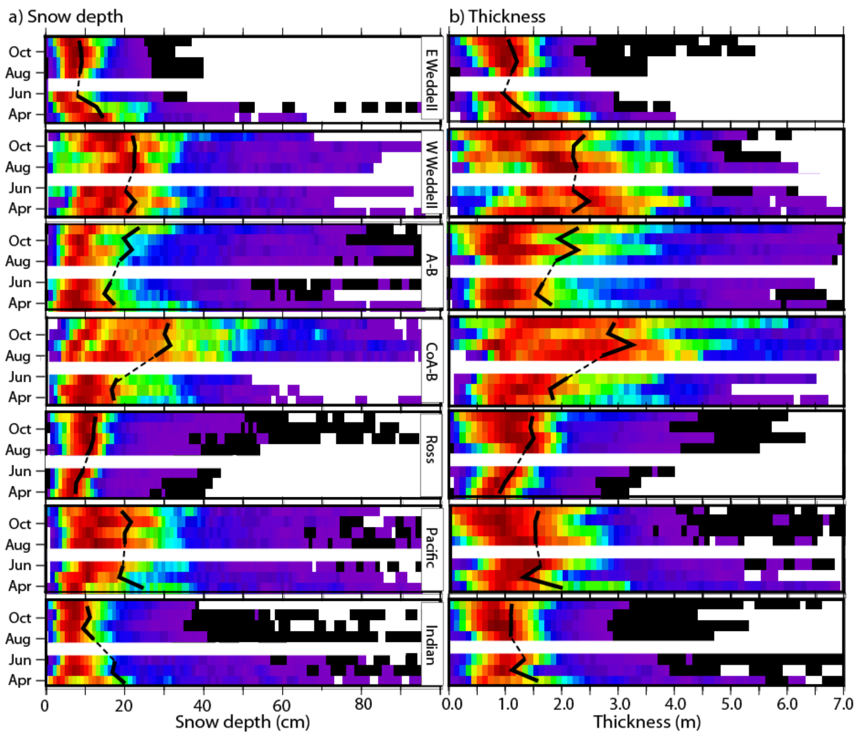

Figure 6. Monthly distributions of (a) derived snow depth ($h_{fs}^{\Delta f}$) and (b) ice thickness (h_i) for the period between April 2019 and November 2019 (distributions are normalized)..

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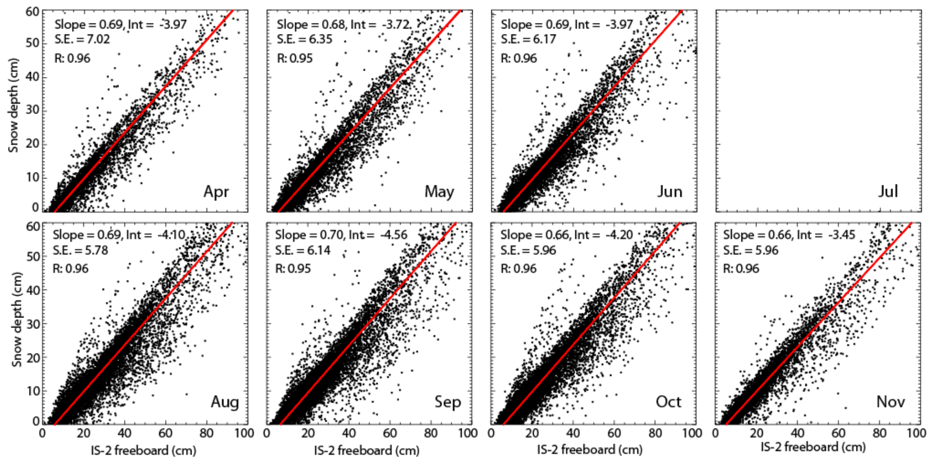

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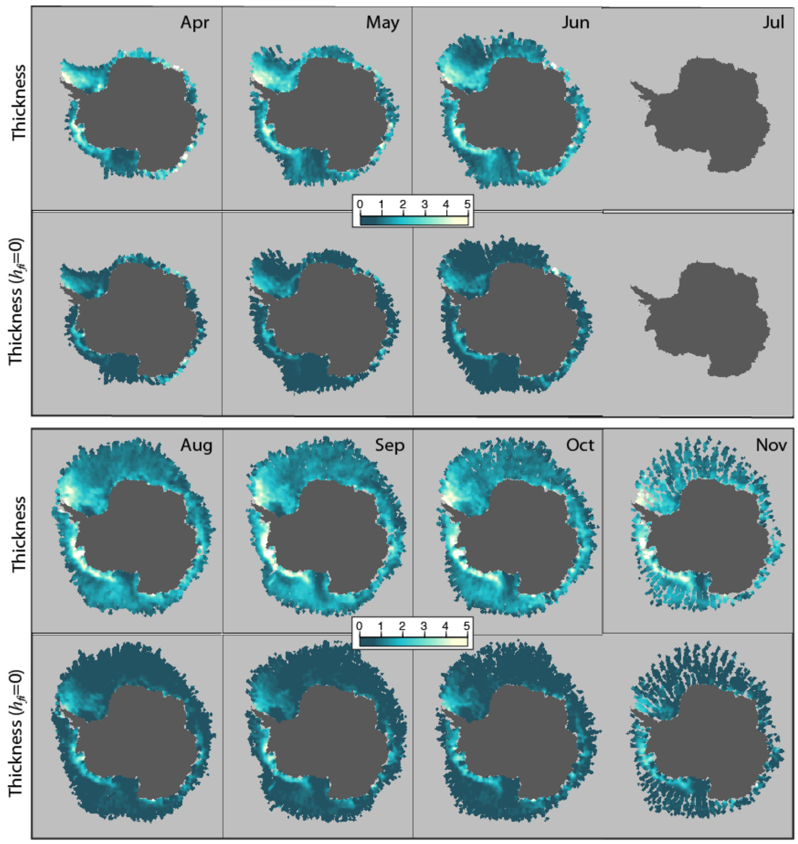

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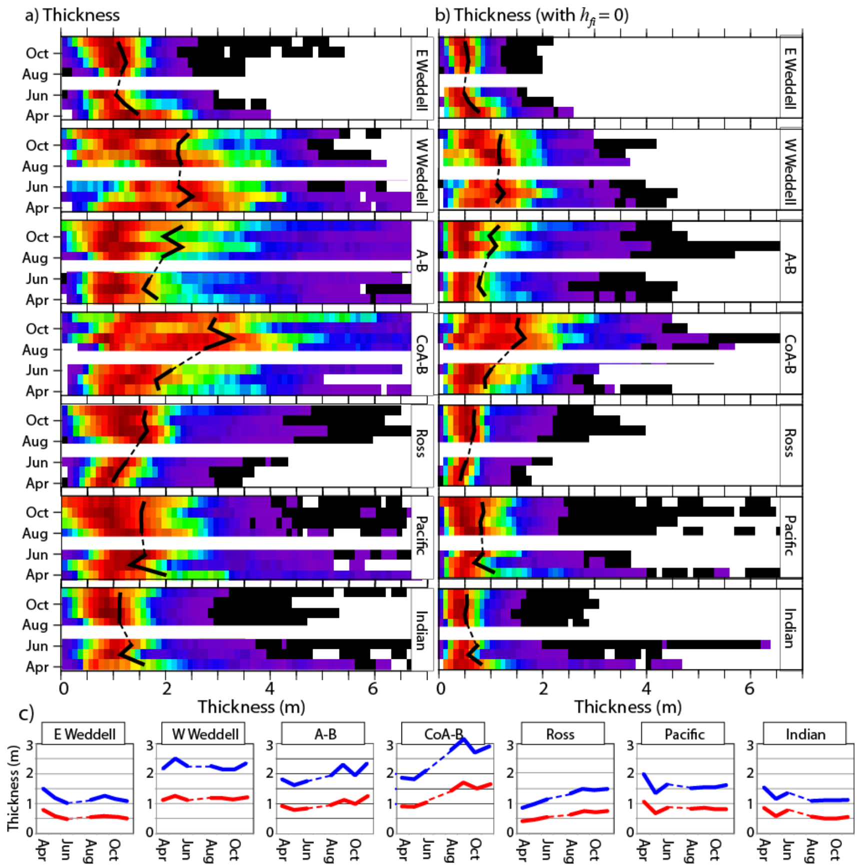

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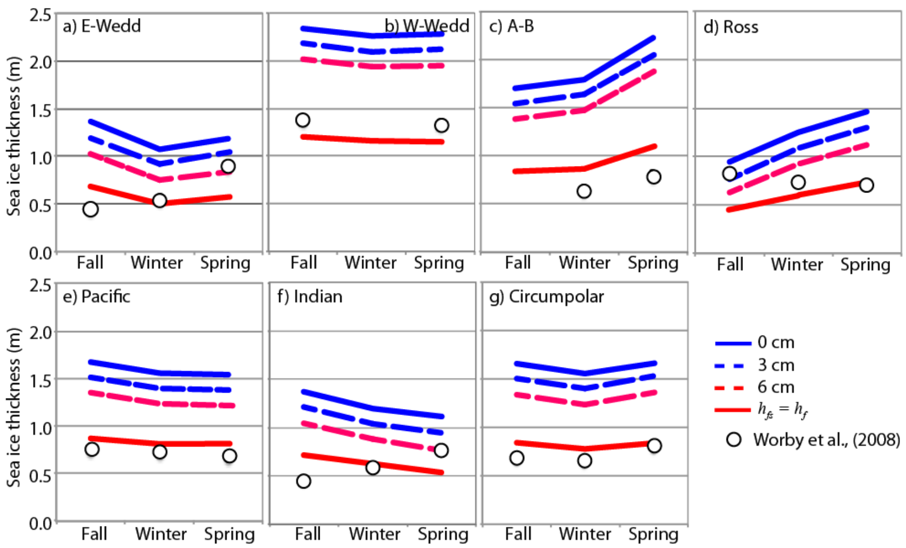

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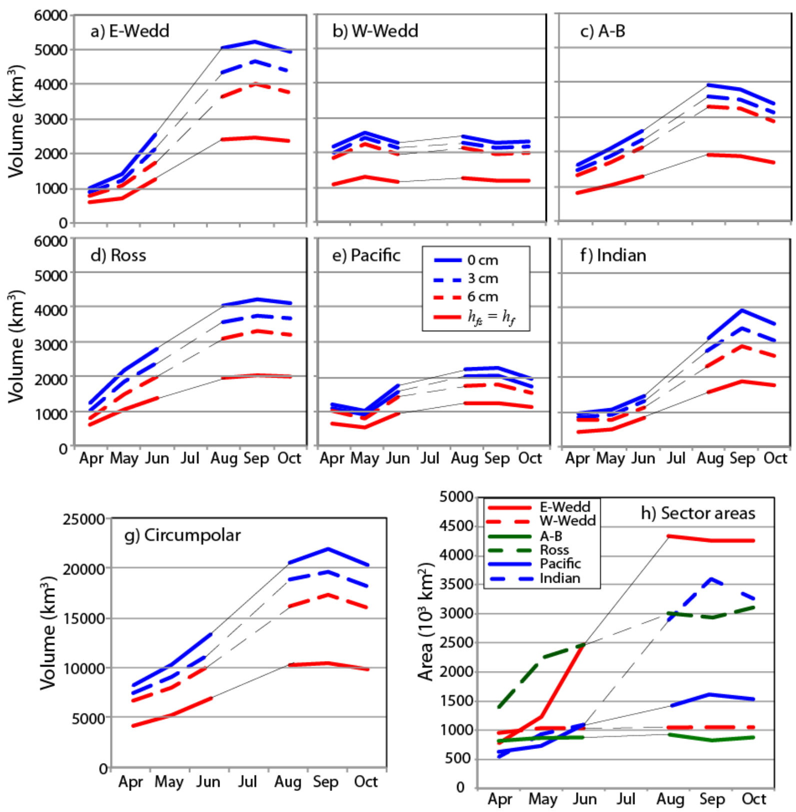

Figure 11. Evolution of the volume and area of the Antarctic sea ice cover between April and October 2019. November is not included here because the IS-2 data covered only half a month.

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