Author’s Response to Referee #1 comments on “Snow depth uncertainty and its implications on satellite derived Antarctic sea ice thickness” - Price et al.

We thank Referee #1 for their review and detailed comments. Our responses are below after each point made by the referee and are highlighted in bold.

General comments

The presentation of the different snow depths was pretty bad. I’m very surprised you didn’t even show maps of the evolution of the snow depth in SnowModel, AMSRE and the ERA-I precip. I really struggled to get a sense of what they were all doing through this accumulation season. You use passive microwave snow depths, snow depths converted from ERA-I precip, and snow depths from SnowModel. I was pleased to see such a comparison of different approaches, but the use of SnowModel seemed not well justified considering the uncertainty in precipitation over this study region. In the discussion you mention the benefits of having this sophisticated SnowModel framework, but then also highlight that actually just converting ERA-I precip to snow depth gives arguably better results (through comparisons of the means), so how do you reconcile that? I think you needed to do a lot more comparison of available precipitation/snowfall datasets to get a better idea of what the model is actually doing. How do the PWRF and ERA-I precip/snowfall data differ? It also wasn’t clear to me if you were using precip or snowfall in SnowModel and ERA-I..

Thank you for this comment, we appreciate that certain aspects need clarifying. The point of this study was not to prove that SnowModel was superior to other snow products in the Antarctic. This was a first attempt using SnowModel over Antarctic sea ice and the point of the investigation was to evaluate its usefulness by comparing it against other readily available snow products and in situ data. One of the problems with current snow products is that their resolution in comparison to the altimeter satellite footprint is too coarse. There are also accuracy issues associated with passive microwave techniques over rough and deformed sea ice, this of course typical of Antarctic pack ice. If a more comparable, higher resolution snow product was available this would be a step in the right direction, helping to facilitate the useful combination of satellite altimeter data and snow information. We do not see how the uncertainty in precipitation has anything to do with the research approach and if anything justifies the assessment of different snow products in the region, especially given the availability of a rare in situ measurement dataset.

Although the ERA-Interim reanalysis has provided a good resource for snow on sea ice in this study it doesn’t mean this applies across the wider Antarctic. This is discussed in section 6. Also ERA-Interim performs well with one precipitation value for the entire region and it was not possible to segment it by freeze up area. We do not feel there is a need to reconcile the differences between the models in this respect, we can only compare the pros and cons of each and discuss how they could be applied to a larger area. When the mean of Snow Model across the entire study area is used (so actually comparing to ERA-Interim – apples to apples) Snow Model is + 2 cm against in situ, while ERA-Interim is – 1 cm. We do not think these are colossal differences that the comment infers they are. We have added the sentence “The SnowModel mean swe for all areas at the end of the simulation is 2 cm higher than *in situ* swe mean.” in section 4 to reiterate this. This point is already in the abstract and discussion.

We understand the referee's point about not showing maps, but the authors don't think this would provide much additional information to the reader. Given the differing spatial resolution of different snow datasets, maps would not allow visualisation of differences (e.g. ERA-Interim a singular grid cell at 80 km resolution and SnowModel at 200 m resolution) and this is why the authors opted for a time series plot of snow depth for all of the snow products. However, we do see the value in showing the SnowModel swe and in situ swe on a map in November to compare how well SnowModel produces the in situ observed snow distribution pattern. We have added this as Fig. 4 (below) and added text to the results section:

"*This general overestimation is clearly seen in Figure 4. Values in the eastern most section of the sea ice cover in McMurdo Sound, adjacent to Ross Island are in the order of 20 to 45 cm swe. These values are all larger than the highest in situ measured swe of 17.7 cm and for large areas, they are over double the measured value. In the central area of the Sound, modelled swe decreases in agreement with measured swe with 5 in situ sites agreeing within ± 0.5 cm of SnowModel swe (Fig. 3 and Fig. 4). The extremes, where there is a lot of snow and where there is very little snow both seem to be exaggerated by the model.*"

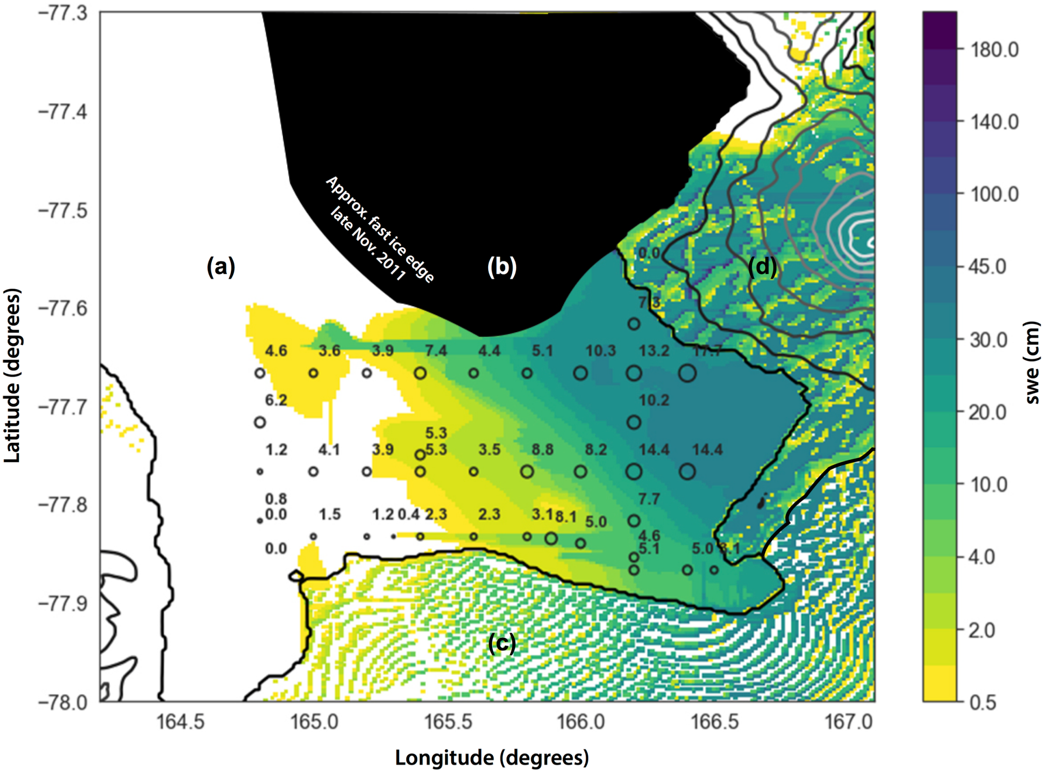


Figure 4. SnowModel distribution map displayed as swe over McMurdo Sound, (a) fast ice, (b) open water/pack ice, (c) McMurdo Ice Shelf, (d) Ross Island. The model swe distribution is the mean of the simulation over the *in situ* measurement period (25th November-1st December). The *in situ* measurements were converted to swe via the density measured at each site, if no measurement was taken (21 sites) the average *in situ* snow density was used (385 kgm^{-3}). *In situ* measurement locations are shown as black circles and are the mean of the 60 snow measurements taken at each site. The circle sizes are weighted for swe to allow visualisation of the decreasing swe distribution from east to west. Elevation contours are spaced at 400 m intervals; Mt Erebus is the dominant topographic feature on Ross Island to the east of the fast ice.

Only the temporal differences in precipitation between ERA-Interim and SnowModel can be compared given the low resolution of ERA. These differences can be visualised in Figure 2. The time series shows a gradual increase in ERA-Interim swe as this model includes no redistribution mechanism. SnowModel exhibits both increases and decreases in swe driven by both precipitation and transport respectively. These differences are described in the manuscript.

ERA-Interim used precipitation (water equivalent) which is clearly stated in the text. SnowModel was run to produce a swe product and a snow depth. This was not clear in the text and we have clarified this with "*SnowModel outputs snow depth and swe. The model has a varying density over time. The swe output is important as it allows comparison of the model to the other snow products which have different density assumptions.*" at the end of section 3.1.

I was also very confused by the SnowModel configuration and components needed to produce snow depths from this model. What is the Noah-LSM and why is this needed?

Noah-LSM is a Land Surface Model and one of the many components of the PolarWRF. The reason that this scheme has been highlighted in this paper is that LSMs are responsible for the near-surface exchanges between atmosphere-cryosphere and other climate sub-systems. Particularly the Noah LSM has adapted specific parameterizations that makes it ideal to be used over Arctic and Antarctic regions with varying sea ice thickness and snow distributions.

Seems like this is maybe running an entire atmospheric regional model without any real validation, so why not keep it simple and force this model with a reanalysis like ASR, which is based on Polar WRF?

ASR is only available over the Arctic and to the best knowledge of the authors no equivalent product for Antarctica exists. The WRF and PolarWRF models have been widely verified across the meteorological community and the results have been reflected in many peer reviewed articles, some of which have been cited in this paper. The main challenge with snow verification in this region is the lack of adequate in situ precipitation observations especially over the sea ice. Yet, the validity of the coupled PolarWRF-SnowModel outcomes are reflected in the sensible snow distribution across the area of study.

The use of Pd in this study seemed odd to me, and I think is the wrong way of thinking about this problem. The main issue here is that we have a distribution of returns across the snow layer, including likely some return from no penetration (the snow-air interface) to returns from various penetration depths into the snow layer. What you are showing is a simplification of this high complexity. I get that you need to do something, but how you've presented this was overly simplistic (a fixed value) in my view and needs to be better explained.

We understand this is a simplistic approach regarding the interaction of radar energy and the overlying snow pack but with the available information it is justified. Advancing this approach should be the subject of another, far more detailed study focusing on actual CS-2 waveforms over different types of snow and ice types with validation data. This is a future goal of the authors research group.

Further, the ESA retracker has already identified a surface, we are not attempting a retracking procedure ourselves in this study. Given that a surface height has already been identified we are simply evaluating which surface best represents the dominant backscattering surface by varying where this surface might be (using a penetration depth which is essentially just changing the thickness equation to account for different elevations above sea level) and comparing the results to the thickness measured in situ.

To make this immediately clear to the reader at the end of section 1, we have added the following to the manuscript: "*The interaction of radar energy with the snow pack is highly complex and here we take a simplified approach given the surface height has already been established by the ESA retracking procedure. Given the uncertainty of the position of the retracking point with reference to the height above sea level we alter the proportion of snow and ice in the thickness estimation assuming different penetration depths and compare the inferred CS-2 thicknesses with in situ information.*"

And this in section 2.4: "*Given this uncertainty we apply a simple methodology to discover the range of thicknesses as inferred via this CS-2 data.*"

I think you need to provide more context for the survey and the snow data that exists around Antarctica. You say snow depth data are lacking but then present this nice in-situ snow depth dataset. Are similar datasets available elsewhere to see how consistent these ideas are in other areas?

This is a first attempt at using SnowModel and a first attempt at combining multiple snow products with CS-2 data in the Antarctic. Therefore, the scope of this study is at the local scale. We understand the title may have been misleading in this respect and thank the reviewer for indicating this. We have made changes to the title and abstract as suggested by both reviewers.

We have a detailed knowledge of this region and with validation can develop ideas and methods for the combination of snow products and satellite altimetry data that could then be applied at the regional/hemispheric scale. We are not currently attempting this, these are early days for this work. The authors are unaware of other satellite validation datasets for CS-2 that would be appropriate for use with these snow products and if they are available we don't have collaborations with other partners for access to these datasets.

Your title needs changing as I don't really think the results here can help us say anything about snow depth uncertainty and satellite derived Antarctic sea ice other than it being a challenging topic!

Agreed, the title was misleading and has been changed to "*Antarctic fast ice thickness from CryoSat-2 using different snow product information*". We have slightly modified the abstract to better align with the new title.

The satellite data are described and introduced very crudely throughout. You need to provide better a description of these datasets, especially the Envisat data section.

Thanks for pointing out this weakness, we have added the following to the Envisat, CryoSat-2 and AMSR-E sections. We think this is enough relevant information for the reader.

Envisat: "*To identify the dates and the pattern in which the sea ice fastens across the study area, we use a string of C-band Advanced Synthetic Aperture Radar (ASAR) images from Envisat acquired in Wide Swath mode with a spatial resolution of 150 x 150 m.*"

CryoSat-2: "*CS-2 is a Ku-band (center frequency 13.6 GHz) radar altimeter launched in 2010. Its on-board altimeter has an approximate footprint size of 380 m x 1560 m and samples along-track at 300 m intervals. The instrument has three modes and operates its interferometric (SIN) mode in the coastal Antarctic. This mode uses both of the satellites antennas to identify the location of off-nadir returns accurately. This is not the dedicated sea ice mode but is still suitable for sea ice freeboard retrieval.*"

AMSR-E (reworded and additional information added): "*The snow depth product is gridded to a 12.5 x 12.5 km^2 polar stereographic projection and reported as a 5-day running mean, that mean inclusive of that day and the prior 4 days. We remove data where ice concentrations are lower than 20%. Gridded snow depth values are calculated using the spectral gradient ratio of the 18.7 and 36.5 GHz vertical polarisation channels. For snow free sea ice the emissivity is similar for both frequencies. Snow depth increases attenuation from scattering but is more pronounced at 36.5 GHz than at 18.7 GHz, resulting in higher brightness temperatures at 18.7 GHz (Comiso et al., 2003, Markus and Cavalieri, 1998). Using coefficients derived from a linear regression of in situ snow depth measurements on microwave data, and a 36.5-18.7 GHz ratio corrected for sea ice concentration, snow depth can be estimated (Comiso et al., 2003).*"

You mention in the discussion (finally!) the issue of initial conditions, but say are hindered by the fact you don't have good freeze-up info at high resolution, but I would think the passive microwave data is fine for this purpose, especially with the ERA-I analysis? You must have some idea of the bias you introduce if you don't start accumulating until the ice fastens, instead of simply forming.. Is the idea that the ice that forms before fastening is all transported northwards and away from the region? Are there no drift products available to understand that?

Passive microwave data could be used for freeze-up analysis but its resolution (at best AMSR-E sea ice drift at 6.25 km and concentration at 12.5 km) is too low to be used effectively with SnowModel. Passive microwave could be used for AMSR-E and ERA-Interim but given the paper is a comparison of the different snow products it does not make sense to consider earlier snowfall for one product and not the others as is suggested above. We also have other concerns which resulted in us deciding to use freeze-up instead. These concerns are explained in a paragraph that has now been added in section 2.2:

**"*The sea ice freeze-up provides a point from which snow can begin to accumulate on the sea ice surface. Freeze-up could be identified using passive microwave information, but this data*

***does not provide the spatial resolution to segment the sea ice area appropriately for SnowModel's 200 m resolution. Also, snowfall before fastening is subject to uncertainty from floe movement, flooding events and snow loss to leads, three influences on the eventual snow depth that we have no way of accurately monitoring. With these uncertainties, we have selected the sea ice fastening date to begin snow accumulation.*"**

This sentence has also been added to the discussion:

"*Early snowfall on more dynamic pack ice will also be subject to flooding, sea spray (both likely to result in snow-ice formation) and loss to leads. These uncertainties must all be considered in future work.*"

I think you should compare using meters, not SWE, as that is what is going into the thickness model. You also didn't even say what the in-situ snow density was.

The authors do not agree that using meters will provide a better comparison as the densities used in SnowModel and those used for ERA-Interim and AMSR-E are different. We reduce snow depth to swe when appropriate to remove the density bias.

As mentioned in an earlier response, the following has also been added to section 3.1 to help clarify this:

***"SnowModel outputs snow depth and swe. The model has a varying density over time. The swe output is important as it allows comparison of the model to the other snow products which have different density assumptions.*"**

AMSR-E provides a snow depth, we convert this to swe using the in situ measured density of 385 kgm^{-3}. The in situ measured snow density was mentioned (L173, L244 old manuscript) but not clearly enough, we have revised this and added more detail around all densities in section 2.4.

Specific comments

L27 Not sure I agree with the first line of the introduction!

We are not sure why the reviewer does not agree with this statement as it is not specified. The understanding of Antarctic sea ice processes and properties, extent, area, drift and roughness have all been greatly advanced over the satellite era. Some confusion could be introduced by the vague use of '*few decades*'. We also see how disagreement around advancements in satellite technology is justified. To be more specific we have amended the sentence to '*The knowledge of Antarctic sea ice extent, area, drift and roughness have been greatly improved over the last forty years, principally supported by satellite remote sensing.* '

L42 Decadal trends is pushing it considering we have data from 2003. I think you could be more specific here about the relevant altimetry missions from which thickness data is still lacking.

This sentence is referring to satellite altimetry information available from 1995 (Giles et al. 2008 – from ERS-2) to the present day (23 years). The authors agree that more advanced altimeters are only available from 2003 (ICESat). However, the Giles paper shows antecedent instruments are useful and work is also being carried out using Envisat altimetry (Paul et al. 2018). In light of this we feel the decadal time frame is justified. We do not feel it is necessary to name individual missions here especially as the relevant literature is cited prior.

L43 Completed is strange language to use here.

Agreed. '*have been completed*' amended to '*are available*'.

L54 I think what you want to say here is that there is a long, but old, record of in-situ data of Arctic snow depth from which a climatology has been produced.

End of sentence amended to "*longer period than the Antarctic so climatologies can be produced*"

L58-59 Reword. Passive microwave data of snow depth available over both poles (where we have FYI).

Sentence amended to "*The research community lacks snow climatology information in the Southern Ocean; to date only AMSR-E passive microwave data have been used in combination with altimetry to estimate sea ice thickness.*"

L73 This terminology doesn't make much sense to me. What is sea ice fast-day-zero?!

Fast-day-zero refers to the first day that the ice is identified as having fastened. This terminology is clearly confusing and has now been removed throughout the manuscript. We have amended this sentence to "*With a high-resolution snow accumulation model called SnowModel (Liston and Elder, 2006a) and the use of synthetic aperture radar imagery we are able to establish when the sea ice fastens and accumulate snow from those dates for three areas of fast ice in McMurdo Sound in the south-western Ross Sea.*"

L78 Maybe say you compare against in-situ data. Assess uncertainty sounds odd.

Sentence amended to "*With these different snow depth datasets we infer sea ice thickness via freeboard measurements from CryoSat-2 and compare these results with in situ information.*"

L99 Virtual weather station?! Is this not simply the location of an overlapping ERA-I grid cell?

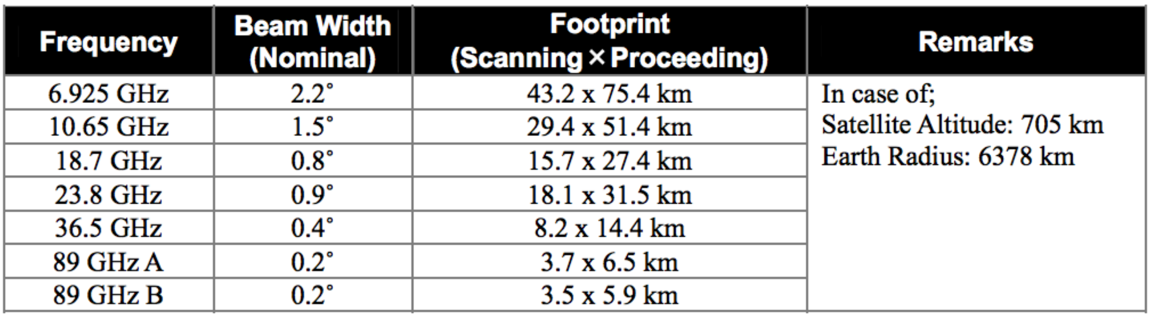
This terminology has been amended to "*The position at which ERA-Interim atmospheric reanalysis data are retrieved is identified by the black circle.*"

This sentence has also been added in section 3.2 for clarification: "*Splines were used to interpolate to this position from the three-dimensional ERA-Interim grid.*"

L114 I don't get this gridding discussion. Is this true? It's produced at 25 km then down sampled??

For AMSR-E the spatial resolution at observation frequencies of 18.7GHz and 36.5GHz are reported as 25 km and 15 km respectively. The spatial resolution is variable as determined by the footprint which is influenced by satellite altitude, off-nadir angle and beamwidth (Please see table 2.3-12 below from the JAXA AMSR-E Data Users Handbook below).

Table 2.3-12 Beam Width and Footprint

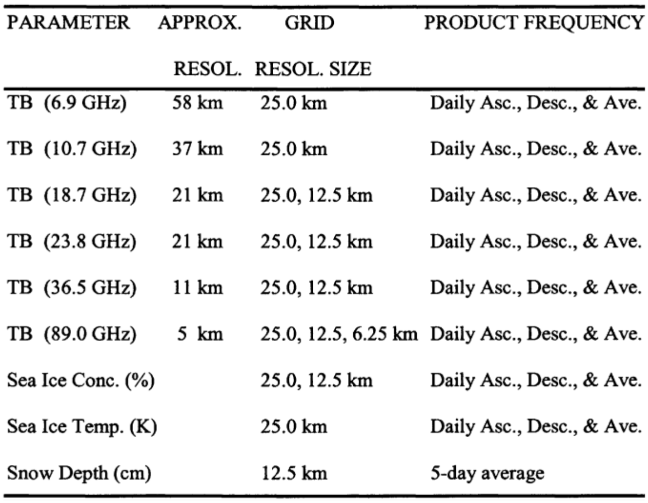


Frequency	Beam Width (Nominal)	Footprint (Scanning × Proceeding)	Remarks
6.925 GHz	2.2°	43.2 x 75.4 km	In case of; Satellite Altitude: 705 km Earth Radius: 6378 km
10.65 GHz	1.5°	29.4 x 51.4 km	
18.7 GHz	0.8°	15.7 x 27.4 km	
23.8 GHz	0.9°	18.1 x 31.5 km	
36.5 GHz	0.4°	8.2 x 14.4 km	
89 GHz A	0.2°	3.7 x 6.5 km	
89 GHz B	0.2°	3.5 x 5.9 km	

Please refer to the JAXA AMSR-E Data Users Handbook for more detail (http://www.eorc.jaxa.jp/en/hatoyama/amsr-e/amsr-e_handbook_e.pdf)

The 25 km to 12.5 km downsizing is described in Worby et al. (2008) - '*Snow depth on sea ice is a standard product of the EOS Aqua Advanced Microwave Scanning Radiometer (AMSR-E) instrument. This represents an average over an area of about 25 × 25 km2, gridded to a 12.5 × 12.5 km2 polar stereographic grid [Comiso et al., 2003].*' But little detail is provided beyond this. Comiso et al. (2003) describe the spatial resolution of AMSR-E with the following table:

TABLE I
AMSR-E LEVEL 3 T_B AND SEA ICE DATASETS



PARAMETER	APPROX. RESOL.	GRID RESOL. SIZE	PRODUCT FREQUENCY
TB (6.9 GHz)	58 km	25.0 km	Daily Asc., Desc., & Ave.
TB (10.7 GHz)	37 km	25.0 km	Daily Asc., Desc., & Ave.
TB (18.7 GHz)	21 km	25.0, 12.5 km	Daily Asc., Desc., & Ave.
TB (23.8 GHz)	21 km	25.0, 12.5 km	Daily Asc., Desc., & Ave.
TB (36.5 GHz)	11 km	25.0, 12.5 km	Daily Asc., Desc., & Ave.
TB (89.0 GHz)	5 km	25.0, 12.5, 6.25 km	Daily Asc., Desc., & Ave.
Sea Ice Conc. (%)		25.0, 12.5 km	Daily Asc., Desc., & Ave.
Sea Ice Temp. (K)		25.0 km	Daily Asc., Desc., & Ave.
Snow Depth (cm)		12.5 km	5-day average

The snow depth derived via the equations in Comiso et al. (2003) combine brightness temperatures from the 18.7 and 36.5 channels at 21 km and 11 km resolution respectively. With the information provided in the JAXA document and supporting literature there must be some downscaling or mechanism to combine the 21 km and 11 km data resolution to the 12.5 km x 12.5 km^2 grid spacing. We do not feel this detail is required here as the grid cell size is all that is relevant to the reader to understand our analysis. The AMSR-E section has been reorganised (see amended manuscript) and we have simplified the resolution sentence to: "*The snow depth product is gridded to a 12.5 x 12.5 km^2 polar stereographic projection and reported as a 5-day running mean, that mean inclusive of that day and the prior 4 days.*"

L116 You don't need to state the flag number here..

Agreed, not immediately relevant to the reader. The reference to flag number has been removed.

L133 You need to reword this! Strange sentence structure at the start.

Sentence amended to: "*CS-2 was launched in 2010 and houses a Ku-band radar altimeter (centre frequency 13.6 GHz).*"

L135 Provide a citation to the CS2 L2 data.

Citation not appropriate but we have added a URL for the CS-2 data after 'SIR_SIN_L2' "- available at: http://science-pds.cryosat.esa.int/"

L143 Is this max freeboard based on anything? Surprised this is so low..

Yes, this is based on in situ measurements in 2011. The largest measured total freeboard (ice-plus-snow) was 0.46 m.

L155 Reword Beyond Wingham etc..

Amended to: "***Wingham et al. (2006) indicate the snow-ice interface is represented by the ESA retracked height. No other information is available about the assumptions made here, only that for diffuse echoes in SAR processing, for baseline C, a new retracker was implemented (Bouffard, 2015).***"

L172 Which investigations? Are these the same as other altimetry studies?

We have added more detail about our density values and amended this section to: "*where ρw (1027 kgm^{-3}), ρi (925 kgm^{-3}) and ρs (385 kgm^{-3}) are the densities of water, sea ice and snow respectively. ρw is informed by an unpublished time series of surface salinity measurements taken from October 2008 to October 2009 along the front of the McMurdo Ice Shelf. The range in ρw during this period is less than 1 kgm^{-3}. The ρi value used here is in the middle of the measured range in McMurdo Sound, the use of which is discussed in Price et al. (2014). ρs is the mean of snow pit measurements at 18 of the in situ measurement sites in 2011.*"

L173 Need to reword this. What do you mean by when required? When is this required?!

This refers to the correction for the speed of light in snow. This only applies when snow is present and/or some penetration is assumed. If no snow is present the correction is not applied and equally if the air-snow interface is assumed i.e. *Pd* = 0 then no correction is applied.

We have amended this sentence to: "*When snow is present and penetration is assumed (i.e. Pd > 0), reduction of the speed of the radar wave through the snow pack is corrected following the procedure described in Kurtz et al (2014).*"

L191 Has it ever been used for Antarctic snow on sea ice?

No and this is mentioned in the sentence beginning L235 (old manuscript). We have moved this sentence earlier to L233 (new manuscript) as it establishes this earlier to avoid confusion.

L241 Aren't you using snowfall, not precip? Why can't you also comapre this with the precip from pWRF (or ASR as suggested)

No the original data from ERA-Interim is precipitation water equivalent. We convert this to snow depth with the average snow density measured in situ. The objective here is to advance PWRF with SnowModel, so simply comparing precipitation from PWRF would not advance the study.

L244-245 So this is the location of the only ERA-I grid-cell in the study area?

ERA-Interim is only available on a 0.75° x 0.75° grid which results in an approximate spatial resolution of 80 km. This is larger than the sea ice area in question and is too coarse to resolve at a higher resolution in the study area. Data was extracted from the reanalysis product at 77.7S 165.8E via a spline interpolation and more detail has been included about this in section 3.2 – "*Splines were used to interpolate to this position from the three-dimensional ERA-Interim grid*". Therefore, the resultant ERA-Interim value at this position represents the spline interpolation value with respect to the local ERA-Interim grid cells.

Figure 2 Pretty unclear figure with no legend and lines that are hard to distinguish.

We are not sure why the reviewer finds this plot unclear. It is a time series of swe for each of the products with clearly distinguishable lines. The figure caption describes these lines.

L315-318 Ok so two provide snow depth and ERA-I is converted using in-situ density. Reword.

Amended to "*Snow depths for each CS-2 freeboard measurement are retrieved from the SnowModel and AMSR-E products directly, while ERA-Interim swe is converted to snow depth using the mean in situ measured density.*"

Figure 4 I can't even work out what is being shown here.

This is a key figure to the paper and shows the range in inferred sea ice thickness assuming different heights represented by the ESA retracker between the air-snow and snow-ice interface. These varying penetration depths are plotted for each snow product. We have moved the penetration depth information (*Pd*) off the plot for clarity and attempted to provide the reader with better information about the figure by reworking the text. We have reworded section 5 to try and make it clearer what is going on in this Figure (please see in new manuscript).

L424 I'm not sure what you mean here.

This sentence is referring to the fact it is a perfect study area for AMSR-E with no interference from open water, or leads and that most of the fast ice is flat. However, this sentence isn't really necessary and has been removed.

L480 Good point, was ice density not measured directly in this study?!

Yes, the value we have used for sea ice density has been measured and is supported by the literature and previous work by the lead author of this work (expanded upon section 2.4 – L210 – new manuscript). The sentence in the discussion is referring to the fact that if the sea ice density was varied through a given range it would change the sea ice thickness estimated from CS-2 freeboard. We have decided to ignore this in this investigation as we are focusing on the combination of snow depth information and altimeter data, but mention it here as it is an additional source of uncertainty in the eventual sea ice thickness estimate.

The sentence in the discussion has been amended to: "*As this analysis was focused on the combination of independent snow products and CS-2 altimeter data, the range in sea ice density has not been taken into account. We have confidence in the middle ground ρi value used from previous work in McMurdo Sound (Price et al., 2014).*"

L485 Unclear how these results indicate accurate snow depths.

This sentence states that "*The snow distribution from SnowModel <u>accurately captures the measured distribution in November 2011</u> and produces a swe mean value that is 0.02 m above the mean of in situ validation, but when sea ice is segmented by fastening date large deviations of up to 0.05 m are present in the east where the model has overestimated snow depth.*"

'*Accurately*' only refers to the snow distribution produced by SnowModel which is correct. We then directly state actual means for comparisons after this statement. We have clarified this accurate representation of the snow distribution and other concerns with the addition of a snow distribution map – see response to first 'General comment'. We have added a map as Fig.4 to help visualise this.

Figure 3 and 4 showed big differences (especially as a percentage), and ERA-I perhaps performing better..?

SnowModel does exhibit large differences from in situ measurements and the entire snow data set is biased high, likely driven by too much accumulation in the east driven by the topographic barrier of Ross Island in the model. This captures reality but the result is exaggerated in the model. This is all stated in the text. The focus of this paper was to compare SnowModel against existing snow datasets, not to prove it was better.

Also to reiterate when the SnowModel mean across all areas is taken it is only 2 cm higher than the in situ mean (ERA-Interim) is 1 cm lower. These are not huge differences and do not justify the elevation of ERA-Interim as a superior product.

It would be clearer if you used centimeter units for the snow depth results throughout!

We have changed the units to centimeters for all snow plots in the manuscript. Sea ice thickness, related plots and references in the text remain in meters.

References

Giles, K. A., S. W. Laxon, and A. P. Worby (2008), Antarctic sea ice elevation from satellite radar altimetry, *Geophys. Res. Lett.*, 35, L03503, doi: 10.1029/2007GL031572.

Paul, S., Hendricks, S., Ricker, R., Kern, S., and Rinne, E.: Empirical parametrization of Envisat freeboard retrieval of Arctic and Antarctic sea ice based on CryoSat-2: progress in the ESA Climate Change Initiative, The Cryosphere, 12, 2437-2460, https://doi.org/10.5194/tc-12-2437-2018, 2018.

Worby, A. P., T. Markus, A. D. Steer, V. I. Lytle, and R. A. Massom (2008), Evaluation of AMSR-E snow depth product over East Antarctic sea ice using in situ measurements and aerial photography, *J. Geophys. Res.*, 113, C05S94, doi: 10.1029/2007JC004181.

Author's Response to Referee #2 comments on "Snow depth uncertainty and its implications on satellite derived Antarctic sea ice thickness" - Price et al.

We thank Referee #2 for their review and detailed comments. Our responses are below after each point made by the referee and are highlighted in bold.

1. What the authors are producing is unlikely to be true sea ice thickness, but rather some representative parameter. The factors influencing radar penetration and freeboard in the Antarctic are numerous and are still not well understood (the Willatt et al. (2010) paper remains the key study on this subject). This is partly addressed this by applying different snow penetration depths in their freeboard to thickness conversion, but this solution which will not capture spatial variation in penetration, or temporal variation if the solution were to be used in different months. More transparency is needed that the retrieval of "thickness" is still highly problematic, and there are limitations in this approach. It should be stated early in the manuscript that "freeboard" is radar freeboard rather than ice freeboard, as this may not be obvious to the wide readership that the paper will attract.

We thank the reviewer for this comment and other detailed considerations about radar altimetry through the paper. We agree that the paper does not sufficiently describe the complexity of microwave interaction over Antarctic sea ice but have suitably pointed to the literature that does and have now included references to surface roughness studies (see response to point P2 L51-53). We agree that the freeboard terminology was loose and have amended it accordingly developing the terminology from the initial 'radar freeboard' to the freeboard we are using to derive thickness (see response to point P4 L135).

We have attempted to cater for the range of sea ice thicknesses that the ESA radar freeboard could represent by altering the surfaces it could be in the thickness equations. We understand that this is a simple approach regarding the complex interaction of the radar energy with the surface, but seeing as the Level 2 product is actually only a surface height there is little else that can be done, except vary where this surface height might be. We agree that if we were approaching this from an earlier stage in the processing we would need to take account of all the variables in our own retracking procedure, however we are not doing this. Here, it is simply not required. Please see responses to 'P2 L51-53' and 'P5 equations' for more detail.

2. The comparison of the various CS-2 sea ice thickness results with in situ data is not sufficient to conclude that any of the CS-2 data show good agreement with in situ data (as suggested on P11 final sentence). Figures 4 and 5 and related discussion provide an initial and basic comparison of sea ice thickness results, but cannot be considered an evaluation of the product in any way. In general, some clarification is needed for this analysis:

We disagree with the reviewer which could be based on a misunderstanding. We attempt to clarify below:

We have taken the retracked elevation provided by ESA which provides us with surface height. To assess the range in inferred thickness, as a result of the uncertainty surrounding what surface the radar freeboard represents, we used different assumptions about where this surface is and vary these assumptions between the air-snow and snow-ice interfaces. Our analysis (Fig. 5 (in new manuscript)) shows this range of thicknesses

as trends through the year and essentially shows the uncertainty in the CS-2 inferred thickness from the ESA product from both the freeboard uncertainty and a snow product uncertainty. We argue that this is an evaluation of a sea ice thickness product as derived from CS-2 measurements. The study does not attempt to build a retracking procedure of its own, but is simply using the information available from the ESA L2 product. As there is no more information on what the radar freeboard represents, there is nothing else that can be done. However, by varying the penetration depth (or the range of surfaces the ESA retracked heights could represent) we find using the interpolated in situ dataset (the best available 'snow product') that CS-2 derived thickness, assuming a penetration of 0.07 m, agrees with in situ mass equivalent thickness within 0.02 m. This is a very good result, but we are not suggesting that this can be universally applied but do argue that it is an evaluation of the ESA L2 product. We are open to further discussion about what else the reviewer suggests can be done with the L2 product, or why it is not considered an evaluation of the L2 height product.

P10 final sentence: Wording suggests that all CS-2 and in situ thicknesses are mass equivalent thickness. However, it doesn't appear this way from Figure 4 which shows in situ measurements in November falling below the mean mass equivalent thickness. It should be clear in the text what thickness is being plotted/compared. If in situ (red) and CS-2 thicknesses are not equivalent than this assessment needs to be repeated.

The referee is correct to identify the difference between these two different thicknesses. In Figure 4 both these types of thicknesses are plotted, the mass-equivalent thickness (inclusive of the influence of the sub-ice platelet layer) represented by the black plus-sign and actual solid sea ice thickness represented by the red line. This red line is a linear fit between measurements taken of solid sea ice thickness in July and November. This will be thinner than mass-equivalent thickness as it does not account for the sub-ice platelet layer and is a direct measure using a tape measure of the consolidated solid sea ice. CS-2 thickness is only comparable to mass-equivalent thickness (black plus-sign) as the freeboard measurement will be influenced by the buoyant force of the sub-ice platelet layer (Price et al. 2014). Therefore, for comparison of in situ thickness to CS-2 thickness the reader should only take note of the difference between the black plus-sign and different CS-2 thickness with varying *Pd* values. The red line is an additional resource to give the reader an idea of the expected sea ice growth rate as an additional comparison to the CS-2 thickness trends.

We have made the following changes to give clarity on the different thicknesses:

End of the first paragraph in section 5: "*The only exception to this is the red line in Fig.4 which is a linear fit between two measurements of consolidated sea ice thickness in July and November 2011 used here to show an expected sea ice thickness growth rate for comparison to CS-2 thickness trends.*"

Figure 4 caption, sentences amended to: "*The red line shows sea ice thickness from in situ measurements of consolidated sea ice thickness with a tape measure taken in July and November in one location in the south of McMurdo Sound joined assuming a constant growth rate. The black plus sign is the mean 'mass-equivalent thickness' from all in situ measurements in November. This is slightly thicker than the end of season thickness indicated by the red line given it takes account of the influence of the sub-ice platelet too.*"

***This is what CS-2 derived thickness should be compared to as the freeboard measurement from the satellite will also be affected by the buoyant influenced of the sub-ice platelet layer.*”**

I assume that July and November in situ thicknesses are spatial means for those months, but it’s not stated in the text.

This needed clarification. The line is simply a linear fit between measured sea ice thickness in July and measured sea ice thickness at one location in McMurdo Sound. This has been used in the plot to show the growth rate during this period for comparison to the CS-2 thickness trends. This has been clarified with the amendments made in response to the previous comment.

Figure 4: The caption gives the first mention of in situ sea ice thickness measurements being taken in July. This should be included briefly in section 2.1, as surely the July and November data are not being averaged over the same area.

In addition to the amendments above this has been included in section 2.1: “*Two more in situ measurements of sea ice thickness are included in the analysis. These are two measurements taken at one location in McMurdo Sound in July and November. Assuming a constant growth rate between these measurements they are used in section 5 as a comparison to CS-2 inferred sea ice growth rates. More detail on how the in situ thickness measurements are used and how they should be interpreted is provided in section 5.* ”

Further comments:

Title and abstract: The title is too broad – it suggests that the scope and study area of the paper are far wider than what is presented. The abstract also needs to state that the study was limited to fast ice in McMurdo Sound.

We agree the title is too broad and have changed it to:

‘*Antarctic fast ice thickness from CryoSat-2 using different snow product information*’

McMurdo Sound and fast ice are now included in the abstract.

P1 L27: Understanding of what?

This sentence has been amended to: “*The knowledge of Antarctic sea ice extent, area, drift and roughness have been greatly improved over the last forty years, principally supported by satellite remote sensing.*”

P1 L42-43: Move all discussion on snow depth assessments to next paragraph, which addresses it in more detail. Seems out of place here.

Moved sentence “*Dedicated basin-scale snow depth assessments are available (Markus and Cavalieri, 2006) but continual improvements in our monitoring ability are key to support the current ESA satellite altimeter missions, CryoSat-2 (CS-2) and Sentinel-3 and NASA’s planned ICESat-2 expected to be operational in late 2018.*” to next paragraph.

P2 L51-53: I disagree with point 2, that the retracking procedure is a principal source of error in thickness estimates via snow. The presence of snow will slow radar propagation but the waveform shape will be dictated by the roughness of the reflecting surface. The principle of retracking is to select a given location on this waveform that corresponds to "the surface" at nadir without knowledge of its exact location. This is why the ESA L2 product is considered radar freeboard rather than ice freeboard. Therefore, it is the assumed radar penetration that contributes to the error (up to the user), rather than the waveform retracking procedure applied.

We agree with the reviewer that this needed re-wording. The sentence has been amended to: "*2. Uncertainty about what surface the retracking point on the radar waveform actually represents between the ice freeboard and snow freeboard. This initial measurement is commonly referred to as radar freeboard.*"

We have added a statement and reference directed at surface roughness in section 2.4:

"*It is clear that the presence of snow influences the CS-2 height retrieval but precisely how is dependent on the surface roughness (Kurtz et al., 2014; Hendricks et al., 2010; Drinkwater, 1991), its depth (Kwok, 2014) and its dielectric properties (Hallikainen et al., 1986).*"

References added for surface roughness inclusion:

Hendricks, S, Stenseng, L, Helm, V and Haas, C (2010) Effects of surface roughness on sea ice freeboard retrieval with an Airborne *Ku*-Band SAR radar altimeter. In *International Geoscience and Remote Sensing Symposium (IGARSS 2010), 25–30 July 2010. Proceedings*. Institute of Electrical and Electronics Engineers, Piscataway, NJ, 3126–3129. doi: 10.1109/IGARSS.2010.5654350.

Drinkwater, M. (1991) *Ku*-band airborne radar altimeter observations of marginal sea ice during the 1984 Marginal Ice Zone Experiment. *J. Geophys. Res.*, 96(C3), 4555–4572, doi: doi.org/10.1029/90JC01954.

The reviewers comment supports the method of the paper. As "the surface" at nadir is undefined in the ESA product (i.e. no indication is given of where it might be) and it is essentially left to the user. The only way for the user to establish what it represents is to compare it against in situ measured freeboard and thickness. In the manuscript we alter the possible positions at which it could be between the air-snow and ice-snow interface and estimate thickness accordingly. This analysis presents the range of uncertainty as presented by the ambiguity of the radar freeboard and the current inability to accurately define at what point above sea level the retracked surface height represents.

P2 L62-66: It is not clear from the author's description that the assumption of zero ice freeboard is only applicable to laser altimetry, where the snow surface is believed to be the dominant scattering horizon. There is no evidence for this being true with radar altimetry, which is why no hemisphere-wide Antarctic sea ice thickness results have been published for CS-2.

Good point, "*Using laser altimetry*" added at the beginning of the sentence.

P2 L74-76: Confusing sentence structure.

Sentence amended to: "*The high-resolution model results are compared to snow products from two other independent datasets, the first ERA-Interim precipitation and the second satellite passive microwave snow depth from AMSR-E.*"

P2 L78: "CryoSat-2" to "CS-2"

Amended.

Section 2.1: Please provide comment on how many snow density, ice freeboard and ice thickness measurements were made at each site

Sentence amended to: "*This involved sea ice thickness, freeboard and snow depth/snow density measurements at 39 sites. Freeboard was measured 5 times in a cross profile at each site, once at the centre of the cross and once at the terminus of each line, as was thickness. Mean snow depths for each in situ site represent 60 individual snow depth measurements over that same cross-profile at 0.5 m intervals. Snow density was measured at 18 sites, well distributed across the area, the mean of these sites is used for this analysis. A full overview of the measurement procedure is provided in Price et al. (2014).*"

Section 2.2: Not all ice comprising the "large areas" will appear on the same day, so how is the exact date of fast-day-zero established?

We have added this sentence to provide more detail in section 2.2: "*By comparing motion and patterns between sequential images we are able to identify three areas that froze independently of one another.*"

The reviewer is right to question the accuracy of the fastening dates and we have addressed this by including this in section 2.2 "*The largest gap in the Envisat image string is 8 days but no large gaps are around key fastening dates. The typical spacing is 1-2 days so we have confidence we have reduced our error in the fastening date to less than 2 days.*"

The term fast-day-zero has been removed from the paper as this just caused confusion.

P4 L1117-118: Provide a brief (just a sentence will do) summary of how gridded snow depth values are calculated from spectral gradient ratio

More detail provided and this section has been reworded as: "*Gridded snow depth values are calculated using the spectral gradient ratio of the 18.7 and 36.5 GHz vertical polarisation channels. For snow free sea ice the emissivity is similar for both frequencies. Snow depth increases attenuation from scattering and it is greater at 36.5 GHz than at 18.7 GHz, resulting in increased brightness temperatures at 18.7 GHz (Comiso et al., 2003, Markus and Cavalieri, 1998). Using coefficients derived from a linear regression of in situ snow depth measurements on microwave data and a 36.5-18.7 GHz ratio corrected for sea ice concentration snow depth can be estimated (Comiso et al., 2003).*"

P4 L135: Define “SIN” for readers who may not be familiar with CS-2 data

Sentence amended and new sentence added: “*The instrument has three modes and operates its interferometric (SIN) mode in the coastal Antarctic. This mode uses both of the satellites antennas to identify the location of off-nadir returns accurately.*”

P4 L135: “. . . **radar** freeboard measurements. . .” Here would be a good place to highlight that freeboard is radar freeboard, rather than sea ice freeboard. Therefore, “thickness” is just a representative parameter rather than true sea ice thickness.

We have provided more clarity on exactly what is being represented by our references to freeboard through the paper. Here we have started with: “*The ESA L2 baseline C SIN mode (SIR_SIN_L2 – available at: http://science-pds.cryosat.esa.int/) data set provides a retracked height for the surface over sea ice and this initial measurement is termed radar freeboard.*”

Following this in the same section (2.4):

“*Each CS-2 radar freeboard measurement is cross-referenced to freeze-up areas 1, 2 and 3 and assigned a snow depth (Ts) value from the described snow products.*”

“Given this uncertainty we apply a simple methodology to discover the range of thicknesses as inferred via this CS-2 data. We explore this possible range by using a varying penetration depth (Pd) into the snowpack. Equation 1 assumes that the snow surface is detected, equation 2 that the sea ice surface is detected and equation 3 that an arbitrary surface at incremental Pd values into the snow pack represents the retracking point varying from 0.02 m to 0.50 m (or to the snow-ice interface, whichever criteria is met first). The radar freeboard is corrected when snow is present and penetration is assumed (i.e. Pd > 0) for the reduction of the speed of the radar wave through the snow pack following the procedure described in Kurtz et al (2014). We derive sea ice thickness (Ti) using the newly corrected freeboard (Fb) and the described equations;”

All the following references to freeboard follow the same logic i.e. they are corrected radar freeboard (*Fb*).

It should also be noted that ‘true sea ice thickness’ is essentially always a representative parameter (within the error of all inputs) from altimetry. This is absolutely the case if the mean backscattering horizon represented by the radar freeboard is unknown. That is the main purpose for trying different horizons in this paper and establishing the range in this representative parameter of sea ice thickness.

P4 L143: Was 0.5 m chosen from in situ measurements or otherwise?

Yes, it was selected from in situ information in 2011. “*(as measured in situ in 2011)*” added to the end of this sentence.

P4 L145: Again, the authors can’t be sure

We have included a description of what we mean by freeboard earlier in the paper as suggested in the comment above (comment P4 L135). What freeboard is in the paper is now established throughout.

P5 L157: See comment on P2 L51-53. The suggestion that the retracking procedure itself introduces uncertainty is misleading. The purpose of the ESA product is to provide range and freeboard to the “surface” at nadir. It is up to the user to decide what that surface is.

See response to P2 L51-53.

P5 equations: I appreciate the authors consideration of differing penetration depths on Antarctic sea ice retrievals. However, a large number of factors influence radar propagation over Antarctic sea ice (flooding, icy layers, depth hoar, snow ice, crust, sea ´ water wicking etc). Which of these factors has the dominant impact on radar reflection will depend on the age and depth of snow on sea ice. Therefore, penetration depth is unlikely to be constant even over relatively small areas and a more representative way to vary penetration would be through varying penetration depth by a percentage of snow depth (say 25%, 50%, 75%). Why did the authors not choose that approach for this study?

If we have understood the question correctly, we absolutely agree with the reviewer about the complexity of radar interaction and that penetration depth will be variable, even over small areas. However, we do not agree with the proposed percentage approach.

If we take a given percentage then penetration universally increases into the snowpack with increasing snow thickness. This is contrary to evidence in the literature, especially if the surface roughness and complexity of the snow structure are increasing over time (i.e. grain size, layering). We could vary the penetration through the season, starting at 75% and decreasing toward 25% at the end of the season but we have no data to support at what rate these percentages should decrease, so we choose a fixed depth. There are pros and cons to each approach but we think a percentage approach could actually introduce additional uncertainty, whereas a fixed depth gives us the range in sea ice thickness through the growth season through many of the potential horizons.

In further support of our approach our observations show that the snow surface and volume in the area of investigation are very uniform. We therefore believe that the radar penetration over larger areas is relatively constant (certainly in comparison to pack ice) and given the high latitude and non-summer months included in the analysis maybe even shows little change over time. We appreciate the need for more comprehensive interpretation of the waveform and the use of detailed statistics from the ground to aid this procedure, but that is beyond the scope of this study and requires better data to inform the procedure. Surface roughness information at the radar wavelength scale is required (radiometric roughness) and larger surface roughness features (geometric roughness) along with detailed information on snow depth, layering, grain size and wetness. Ideally this would all be completed and compiled as statistics that represent each CS-2 radar footprint specifically (i.e. georeferenced to the full 380 m x 1560 m footprint).

All that the user has to work with from the level 2 product is surface height. The authors do not see the value in attempting to include the complex variables that influence the

waveform at this stage. This should all be considered when the retracking is done. All we are doing here is varying where the surface height could be between the air-snow and snow-ice interfaces (inclusive). We compare the assumptions to the in situ thickness and establish (i) the range in thickness estimates associated with the uncertainty and user based interpretation of the ESA radar freeboard and (ii) identify at what assumed freeboard interface produces the thickness closest to in situ measured thickness.

Also as the snow depth principally influences the width of the waveform and trailing edge an algorithm based on a percentage of snow depth isn't ideal either (but this isn't even relevant because the retracking is already complete i.e. all we have is a surface height).

With the percentage approach our time series assessment (new Fig. 5) will have a constantly changing penetration which will make the analysis more difficult to interpret.

In section 2.4 we have also added a sentence which clarifies that if the *Pd* is higher than the snow depth, then we assume full penetration to the snow-ice interface as this needed clarification.

"*We explore this possible range by using a varying penetration depth (Pd) into the snowpack. Equation 1 assumes that the snow surface is detected, equation 2 that the sea ice surface is detected and equation 3 that an arbitrary surface at incremental Pd values into the snow pack varying from 0.02 m to 0.50 m (or to snow-ice interface, whichever criteria is met first).*"

Section 3.1: Provides a very nice, clear introduction to SnowModel

No action taken.

Section 3.2: More information required on the use of ERA-Interim reanalysis data. 1.) Is this the total precipitation 2.) Are there any temperature constraints on what falls as snow 3.) Why is evaporation not considered

This is total precipitation reported in mm water equivalent. We have not considered temperature in the ERA-Interim precipitation analysis. From April, at this latitude we have assumed all precipitation is snow. We have not considered evaporation as we expect it to be non-existent from April-November or certainly negligible. We have only observed melting on snow on sea ice in McMurdo in December and this month is not included in the analysis. Sublimation is possible and expected once the sun rises in austral spring (first sunrise 19th August) but we have no way of accurately including this in the snow mass balance analysis for ERA-Interim data.

Figure 4: Make penetration depth labels larger

Label sizes increased and also moved off the plot for easier interpretation. Dashed lines also changed to solid line with colour gradient between the two extremes of air-snow and snow-ice interface. See all changes in amended Fig. 5 in the new manuscript.

P14 L405: Specify ICESsat-2 footprint, and CS-2 footprint earlier in the manuscript

CS-2 footprint now given in section 2.4.

ICESat-2 footprint mentioned in the discussion as it is not relevant when the satellite is described earlier in the manuscript. Sentence in discussion amended to "*These meter-scale features will be important to capture, especially to support compatibility with smaller satellite altimeter footprints, in particularly ICESat-2 with an expected 0.7 m along-track sampling rate (Abdalati et al., 2010).*"

Reference added: Abdalati, W., Zwally, H.J., Bindschadler, R., Csatho, B., Farrell, S.L., Fricker, H.A., Harding, D., Kwok, R., Lefsky, M., Markus, T., Marshak, A., Neumann, T., Palm, S., Schutz, B., Smith, B., Spinhirne, J and Webb C. 2010. The ICESat-2 laser altimetry mission, Proceedings of the IEEE, 98(5), 735-751. doi:10.1109/JPROC.2009.2034765.

P15 L478: Penetration can also vary spatially over small study areas (see Willatt et al., 2010), which is why a percentage penetration factor may be more applicable than fixed depth.

See response to 'P5 equations' above.

L506-507: "at least as reliable" is a strong statement, and not proved in the manuscript, considering the authors did not show overlap of AMSR-E snow depths compared with in situ.

Agreed this statement is too strong, amended to: "*With improvements to redistribution mechanisms and adequate representation of the effect of topographic features atmospheric models could be used as an alternative to contemporary passive microwave algorithms.*"

Conclusion: It would be good to finish with a statement regarding the potential for Antarctic-wide application of SnowModel (and limitations) for sea ice thickness retrievals, as the paper title suggests.

Sentence added: "*If these two variables can be adequately incorporated SnowModel could provide a valuable resource for snow and sea ice thickness investigations over the wider Antarctic sea ice area.*"

References

Price, D., Rack, W., Langhorne, P. J., Haas, C., Leonard, G., and Barnsdale, K.: The sub-ice platelet layer and its influence on freeboard to thickness conversion of Antarctic sea ice, The Cryosphere, 8, 1031-1039, https://doi.org/10.5194/tc-8-1031-2014, 2014.

Antarctic fast ice thickness from CryoSat-2 using different snow product information

Comment [DP1]: Title change from 'Snow depth uncertainty and its implications on satellite derived Antarctic sea ice thickness' to 'Antarctic fast ice thickness from CryoSat-2 using different snow product information'

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Abstract. Knowledge of the snow depth distribution on Antarctic sea ice is poor but is critical to obtaining sea ice thickness from satellite altimetry measurements of freeboard. We examine the usefulness of various snow products to provide snow depth information over Antarctic fast ice in McMurdo Sound with a focus on a novel approach using a high-resolution numerical snow accumulation model (SnowModel). We compare this model to results from ECMWF ERA-Interim precipitation, EOS Aqua AMSR-E passive microwave snow depths and *in situ* measurements at the end of the sea ice growth season in 2011. The fast ice was segmented into three areas by fastening date and the onset of snow accumulation was calibrated to these dates. SnowModel falls within 2 cm snow water equivalent (swe) of *in situ* measurements across the entire study area, but exhibits deviations of 5 cm swe from these measurements in the east where the effect of local topographic features has caused an overestimate of snow depth in the model. AMSR-E provides swe values half that of SnowModel for the majority of the sea ice growth season. The coarser resolution ERA-Interim, not segmented for sea ice freeze up area reveals a mean swe value 1 cm higher than *in situ* measurements. These various snow datasets and *in situ* information are used to infer sea ice thickness in combination with CryoSat-2 (CS-2) freeboard data. CS-2 is capable of capturing the seasonal trend of sea ice freeboard growth but thickness results are highly dependent on what interface the retracked CS-2 height is assumed to represent. By varying the reference interface between the air-snow and snow-ice interface we assess this uncertainty. The sea ice thickness estimates vary by up to 2 m through this range. However, we find the best agreement between CS-2 derived and *in situ* thickness when this surface is assumed to be 0.07 m below the snow surface.

Comment [DP2]: Added McMurdo Sound

Comment [DP3]: 2011 added.

Comment [DP4]: m changed to cm on snow references throughout.

Comment [DP5]: Changed from 'large topographic features'

Comment [DP6]: Instead of positive bias.

Comment [DP7]: Amended from 'the assumptions involved in separating snow and ice freeboard'

Comment [DP8]: Sentence amended for clarity.

Comment [DP9]: Specifically refer to 0.07 m as opposed to 0.05-0.10 m range. This Pd provides the best agreement with in situ thickness and provides the most useful information to the community.

1 Introduction

The knowledge of Antarctic sea ice extent, area, drift and roughness have been greatly improved over the last forty years, principally supported by satellite remote sensing. Nevertheless, many knowledge gaps remain which restrict further developments. A foremost concern is inadequate data for the snow depth distribution on Antarctic sea ice (Pope et al., 2016) as the presence of snow has many important implications for the sea ice cover (Massom et al., 2001, Wu et al., 1999, Fichefet and Maqueda, 1999). The thermal conductivity of snow is almost an order of magnitude less than sea ice (Maykut and Untersteiner, 1971) and as snow accumulates, it reduces the conductive heat flux from the ocean to the atmosphere, slowing growth rates, but also leads to thickening of the ice cover through snow-ice formation (Maksym and Markus, 2008). Snow significantly increases the albedo of the sea ice cover and in the austral spring and summer snow melt drives fresh water input to the Southern Ocean (Massom et al., 2001). Perhaps most crucially from a satellite observation perspective our inability to accurately monitor its depth and distribution causes difficulty when estimating sea ice thickness. Sea ice thickness measurements as inferred via satellite freeboard estimates (Schwegmann et al., 2016, Kurtz and Markus, 2012, Giles et al., 2008) currently present the the best opportunity to establish yet unpublished datasets on decadal trends in Antarctic sea ice volume. Without improved snow depth measurements, it is impossible to discern meaningful

Comment [DP10]: Amended in response to clarity issues highlighted by both reviewers, previously 'The understanding of Antarctic sea ice has greatly improved over the last few decades, 28 principally supported by advancements in satellite capability.'

Comment [DP11]: Previously 'Crucially it is highly influential from an observational perspective given our restricted ability 39 to combine reliable snow depth information with altimetric measurements from satellites.'

trends in Antarctic sea ice thickness. Errors are introduced to thickness estimates via the snow cover for two principal reasons:

1. Snow depth information is inaccurate/not available and therefore the ratio of ice and snow above the waterline is poorly quantified or unknown.
2. Uncertainty about what surface the retracking point on the radar waveform actually represents between the ice freeboard and snow freeboard. This initial measurement is commonly referred to as radar freeboard.

Comment [DP12]: Amended after reviewer 2 correctly pointed out the wording was not accurate. Previously 'The presence of snow influences incident radar energy which manifests itself in 52 the radar waveform. If the retracking procedure does not accurately account for 53 this, the retracked surface, assumed to be freeboard, will be incorrect.'

Arctic sea ice has been investigated in more detail and over a longer period than the Antarctic so climatologies can be produced (Warren et al., 1999). These datasets in combination with satellite altimetry, and suitable airborne investigations have permitted the completion of pan-Arctic thickness assessments (Kurtz et al., 2014, Laxon et al., 2013, Kwok and Cunningham, 2008). The research community lacks snow climatology information in the Southern Ocean, though dedicated basin-scale snow depth assessments are available (Markus and Cavalieri, 2006). Continual improvements in our monitoring ability are key to support the current ESA satellite altimeter missions, CryoSat-2 (CS-2) and Sentinel-3 and NASA's planned ICESat-2, which is expected to be operational in late 2018. To date only AMSR-E passive microwave data have been used in combination with altimetry to estimate sea ice thickness. The AMSR-E algorithm's accuracy is decreased by rough sea ice and deep and complex snow (Kern and Ozsoy-Çiçek, 2016, Kern et al., 2011, Worby et al., 2008b, Stroeve et al., 2006), both typical characteristics of the Antarctic sea ice cover. Using laser altimetry, some investigators have assumed zero ice freeboard (Kurtz and Markus, 2012), that is, the snow loading forces the ice surface to the waterline, negating the need for snow depth data. Thickness estimates using this approach are likely biased low and although this simplification provides valuable insights, it does not provide sea ice thickness at the desired accuracy. This work is motivated by the necessity for a comprehensive understanding of the usefulness of snow products in the Southern Ocean, and the need to investigate new avenues for producing snow depth products over Antarctic sea ice. Here we make use of a detailed *in situ* dataset to assess modelling and satellite approaches to construct snow depth over the 2011 sea ice growth season. In a first attempt over Antarctic fast ice, using a high-resolution snow accumulation model called SnowModel (Liston and Elder, 2006a) and synthetic aperture radar imagery, we are able to establish when the sea ice fastens and accumulate snow from those dates for three areas of fast ice in McMurdo Sound in the south-western Ross Sea. The high-resolution model results are compared to snow products from two other independent datasets, the first ERA-Interim precipitation and the second satellite passive microwave snow depth from AMSR-E. With these different snow depth datasets we infer sea ice thickness via freeboard measurements from CS-2. The interaction of radar energy with the snow pack is highly complex and here we take a simplified approach given the surface height has already been established by the ESA retracking procedure. Given the uncertainty of the position of the retracking point with reference to the height above sea level, we assume different penetration depths into the snowpack, and compare the inferred CS-2 thicknesses with *in situ* information.

Comment [DP13]: Simplified from 'permitting the compilation of snowfall climatologies'.

Comment [DP14]: Same sentences but shifted around. Sentences referring to snow depth assessments and different altimeter missions have been moved here from the previous paragraph.

Comment [DP15]: Added.

Comment [DP16]: Modelling and satellite switched around.

Comment [DP17]: Added to inform reader it is first use over Antarctic sea ice .

Comment [DP18]: Instead of fast-day-zero.

Comment [DP19]: Restructured.

Comment [DP20]: Added to establish the scope of the paper early. This also addresses Reviewer 2's concerns about neglecting the complexity of radar altimetry in the previous version of the manuscript.

2 Study area, field and satellite data

2.1 McMurdo Sound and field data

A detailed *in situ* sea ice measurement campaign was carried out in November 2011 on the fast ice in McMurdo Sound (Fig. 1). This involved sea ice thickness, freeboard and snow depth/snow density measurements at 39 sites. Freeboard was measured 5 times in a cross profile at each site, once at the centre of the cross and once at the terminus of each line, as was thickness. Mean snow depths for each *in situ* site represent 60 individual snow depth measurements over that same cross-profile at 50 cm intervals. Snow density was measured at 18 sites, well distributed across the area, the mean of these sites is used for this analysis unless stated otherwise. A full overview of the measurement procedure is provided in Price et al. (2014). Two more *in situ* measurements of sea ice thickness are included in the analysis. These are two measurements taken at one location in McMurdo Sound in July and November. Assuming a constant growth rate between these measurements they are used in section 5 as a comparison to CS-2 inferred sea ice growth rates. More detail on how the *in situ* thickness measurements are used and how they should be interpreted is provided in section 5.

Comment [DP21]: Detail provided on in situ measurements.

Comment [DP22]: Additional information.

Comment [DP23]: More detail on snow density measurements.

Comment [DP24]: Added to provide detail on red line and additional sea ice thickness measurements shown in Fig. 5.

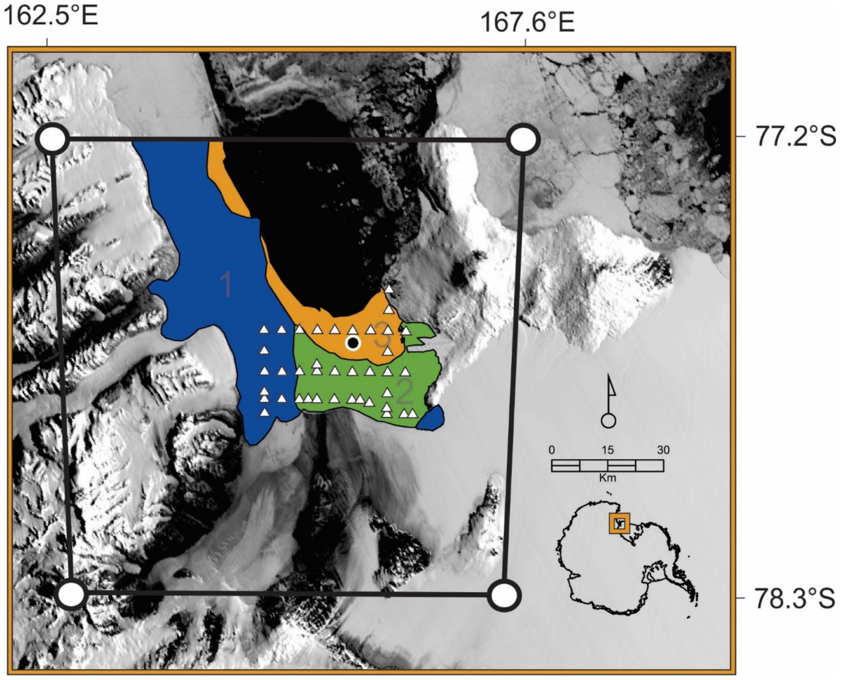


Figure 1. McMurdo Sound study area with each freeze-up area as identified by Envisat radar imagery: area 1 – 01/04/2011 (Blue), area 2 – 29/04/2011 (Green), area 3 – 01/06/2011 (Orange) and SnowModel domain bounded by black box. Freeze-up areas are superimposed on a MODIS image acquired on 15 November at the time of maximum fast ice extent in 2011. The locations of 39 measurement sites used to produce the *in situ* snow and sea ice statistics are shown as white triangles. The position at which ERA-Interim atmospheric reanalysis data are retrieved is identified by the black circle.

Comment [DP25]: Virtual weather station terminology removed and replaced with 'data are retrieved'.

2.2 Envisat

The sea ice freeze-up provides a point from which snow can begin to accumulate on the sea ice surface. Freeze-up could be identified using passive microwave information, but this data does not provide the spatial resolution to segment the sea ice area appropriately for SnowModel's 200 m resolution. Also, snowfall, before fastening occurs, is subject to uncertainty from floe movement, flooding events and snow loss to leads, three influences on the eventual snow depth that we have no way of accurately monitoring. With the resolution restriction in mind and these uncertainties, we have selected the sea ice fastening date to begin snow accumulation. To identify the dates and the pattern in which the sea ice fastens across the study area, we use a string of *C*-band Advanced Synthetic Aperture Radar (ASAR) images from Envisat acquired in Wide Swath mode with a spatial resolution of 150 x 150 m. By comparing motion and patterns between sequential images we are able to identify three areas that froze independently of one another. The first area of fast ice was established by 1 April (area 1 – Fig. 1), by the end of April, a second area of fast ice had formed along the southern extremity of the Sound (area 2 – Fig. 1), and by the beginning of June, a third area had fastened (area 3 – Fig. 1). The largest gap in the Envisat image string is 8 days but no large gaps are around key fastening dates. The typical spacing is 1-2 days so we have confidence we have reduced our error in the fastening date to less than 2 days. These three areas persisted for the winter and when combined, made up the fast ice area present in late November when *in situ* measurements were made.

Comment [DP26]: New sentence added.

Comment [DP27]: Replaces fast-day-zero.

Comment [DP28]: Here we provide a justification for the use of Envisat data as opposed to other data from which we could monitor sea ice freeze up.

Comment [DP29]: Envisat description has been given more detail and information is provided about the expected error in the established fastening dates.

2.3 AMSR-E

The EOS Aqua Advanced Microwave Scanning Radiometer (AMSR-E) was operational from December 2002 until 4 October 2011. The snow depth product is gridded to a 12.5 x 12.5 km^2 polar stereographic projection and reported as a 5-day running mean, that mean inclusive of that day and the prior 4 days. We remove data where ice concentrations are lower than 20%. Gridded snow depth values are calculated using the spectral gradient ratio of the 18.7 and 36.5 GHz vertical polarisation channels. For snow free sea ice the emissivity is similar for both frequencies. Snow depth increases attenuation from scattering but is more pronounced at 36.5 GHz than at 18.7 GHz, resulting in higher brightness temperatures at 18.7 GHz (Comiso et al., 2003, Markus and Cavalieri, 1998). Using coefficients derived from a linear regression of *in situ* snow depth measurements on microwave data, and a 36.5-18.7 GHz ratio corrected for sea ice concentration, snow depth can be estimated (Comiso et al., 2003). Snow depth retrievals are restricted to dry snow only and to a depth of less than 50 cm. Variable snow properties including snow grain size, snow density and liquid water content influence microwave emissivity from the sea ice surface and the algorithm is reported to have a precision of 5 cm (Comiso et al., 2003) . Given the extreme southern latitude of the study area, snow conditions throughout this study were very dry, supported by snow pit analysis on the sea ice in November with no wet snow or lensing observed. AMSR-E cells are included in the analysis if over 50% of the cell lies within the fast ice mask, and segmented into each freeze up area by that same criteria. 22 AMSR-E cells are used and due to the instrument failure in early October 2011, data for the last two months of this investigation are unavailable.

Comment [DP30]: Description of data simplified for reader, justification provided in the response to the specific comment to the reviewer.

Comment [DP31]: More detail provided on AMSR-E snow depth algorithm.

2.4 CryoSat-2

CS-2 was launched in 2010 and houses a *Ku*-band radar altimeter (centre frequency 13.6 GHz). The altimeter has an approximate footprint size of 380 m x 1560 m and samples along-track at 300 m intervals. The instrument has three modes and operates its interferometric (SIN) mode in the coastal Antarctic. This mode uses both of the satellite's antennas to identify the location of off-nadir returns accurately. This is not the dedicated sea ice mode, but it is still suitable for sea ice freeboard retrieval (Price et al., 2015; Armitage and Davidson, 2014). In section 6, to assess the usefulness of the evaluated snow products, we infer sea ice thickness from CS-2 freeboard measurements.

Comment [DP32]: Sentence restructured at request of reviewer 1.

Comment [DP33]: More detail provided on CS-2 and SIN mode is explained.

The ESA L2 baseline C SIN mode (SIR_SIN_L2 – available at: http://science-pds.cryosat.esa.int/) data set provides a retracked height for the surface over sea ice and this initial measurement is termed radar freeboard. The processing closely follows that described in Price et al. (2015), but to reduce noise, two modifications are made to achieve more detailed scrutiny of the CS-2 height retrievals. The first is a more stringent exclusion of off-nadir elevation retrievals, the threshold is halved from ± 750 m to ± 375 m; data located at greater distances from nadir are discarded. The second is the rejection of freeboard measurements of less than -0.24 m and greater than 0.74 m. Following Schwegmann et al (2016) the ± 0.24 m accounts for speckle range noise in the CS-2 data and the + 0.5 m threshold additionally incorporates an expected maximum sea ice freeboard of 0.5 m for fast ice in McMurdo Sound (as measured *in situ* in 2011). Each CS-2 radar freeboard measurement is cross-referenced to freeze-up areas 1, 2 and 3 and assigned a snow depth (*Ts*) value from the described snow products. From the ESA retracked product there is currently no consensus on what surface the radar freeboard represents over sea ice, the air-snow interface, the snow-ice interface or an 1undefined interface between the two. Laboratory experiments (Beaven et al., 1995) and comparisons of other radar altimeter systems with *in situ* measurements (Laxon et al., 2003) suggest the snow-ice interface is detected. It is clear that the presence of snow influences the CS-2 height retrieval but precisely how is dependent on the surface roughness (Kurtz et al., 2014; Hendricks et al., 2010; Drinkwater, 1991), its depth (Kwok, 2014) and its dielectric properties (Hallikainen et al., 1986). The mean depth of the dominant backscattering surface measured using a surface based *Ku*-band radar over snow covered Antarctic sea ice was around 50% of the mean measured snow depth, and the snow-ice interface only dominated when morphological features or flooding were absent (Willatt et al., 2010). Wingham et al. (2006) indicate the snow-ice interface is represented by the ESA retracked height. No other information is available about the assumptions made here, only that for diffuse echoes in SAR processing, for baseline C, a new retracker was implemented (Bouffard, 2015). It is unclear what the original retracking assumptions are for any retrieval mode and if any changes were made to SIN mode for baseline C. A prior study of CS-2 waveform behaviour over the same study area found ESA L2 freeboard to be located between the air-snow and snow-ice interface (Price et al., 2015). Given this uncertainty we apply a simple methodology to discover the range of thicknesses as inferred via this CS-2 data. We explore this possible range by using a varying penetration depth (*Pd*) into the snowpack. Equation 1 assumes that the snow surface is detected, equation 2 that the sea ice surface is detected and equation 3 that an arbitrary surface at incremental *Pd* values into the snow pack represents the retracking point varying from 0.02 m to 0.50 m (or to the snow-ice interface, whichever criteria is met first). The radar freeboard is corrected when snow is present and penetration is assumed (i.e. *Pd* > 0) for the reduction of

Comment [DP34]: Data source added.

Comment [DP35]: Radar freeboard introduced.

Comment [DP36]: Reference to in situ maximum freeboard provided.

Comment [DP37]: Clarity provided on attribution of snow depths.

Comment [DP38]: Surface roughness and related references now included.

Comment [DP39]: Sentence restructured.

Comment [DP40]: Two sentences added to further describe methodology.

Comment [DP41]: Clarification on exactly what equation 3 is doing.

the speed of the radar wave through the snow pack following the procedure described in Kurtz et al (2014). We derive sea ice thickness (*Ti*) using the newly corrected freeboard (*Fb*) and the described equations;

Comment [DP42]: Clarification is provided and sentence expanded upon about the correction for the radar propagation through the snow pack, was previously just 'When required'.

$$T_i = \frac{\rho_w}{\rho_w - \rho_i} Fb - \frac{\rho_w - \rho_s}{\rho_w - \rho_i} T_s \quad (1)$$

$$T_i = \frac{\rho_w}{\rho_w - \rho_i} Fb + \frac{\rho_s}{\rho_w - \rho_i} T_s \quad (2)$$

$$T_i = \frac{\rho_w}{\rho_w - \rho_i} Fb - \frac{\rho_w - \rho_s}{\rho_w - \rho_i} T_s + \frac{\rho_w}{\rho_w - \rho_i} Pd \quad (3)$$

where ρ_w (1027 kgm^{-3}), ρ_i (925 kgm^{-3}) and ρ_s (385 kgm^{-3}) are the densities of water, sea ice and snow respectively. ρ_w is informed by an unpublished time series of surface salinity measurements taken from October 2008 to October 2009 along the front of the McMurdo Ice Shelf. The range in p_w during this period is less than 1 kgm^{-3}. The ρ_i value used here is in the middle of the measured range in McMurdo Sound, the use of which is discussed in Price et al. (2014). ρ_s is the mean of snow pit measurements at 18 of the *in situ* measurement sites in 2011.

Comment [DP43]: References/origins of density values used in the analysis have been expanded upon.

3 Atmospheric models for snow accumulation

3.1 High resolution model

SnowModel is a numerical modelling system with four main components: (1) MicroMet, a quasi-physically-based, high-resolution meteorological distribution model (Liston and Elder, 2006b) (2) Enbal, a surface energy balance and snowmelt model (Liston et al., 1999) (3) SnowTran-3D, a wind driven snow redistribution routine (Liston et al., 2007, Liston and Sturm, 1998) and (4) SnowPack, a multilayer snow depth and water-equivalent model (Liston and Sturm, 1998). The main objective of MicroMet is to provide seamless atmospheric forcing data, both temporally and spatially to the other SnowModel components. MicroMet is capable of downscaling the fundamental atmospheric forcing such as air temperature, relative humidity, wind speed, wind direction, incoming solar radiation, incoming longwave radiation, surface pressure, and precipitation. Other SnowModel submodels simulate surface energy balance, and moisture exchanges including snow melt, snow redistribution and sublimation. SnowModel also incorporates multilayer heat-and mass-transfer processes within the snow (e.g. snow density evolution).

SnowModel is capable of initializing with both *in situ* and gridded model data and has been evaluated in many geographical locations including Greenland and Antarctica (Liston and Hiemstra, 2011; Liston and Hiemstra, 2008; Liston and Winther, 2005; Mernild et al., 2006). To the authors knowledge, and at the time of writing this is only the second application of SnowModel in a sea ice environment. Liston et al. (2018) applied SnowModel with an additional component that accounted for snowdrifts and snow dunes, at very high spatial resolution over Arctic sea ice with positive results.

Comment [DP44]: Moved from later in the manuscript to establish early that this is the first known application of SnowModel over Antarctic sea ice. Liston et al. (2018) reference also moved from the end of section 3.1.

SnowModel requires topography, land cover and various atmospheric forcing. The minimum meteorological requirements of the model are near-surface air temperature, precipitation, relative humidity, wind speed and direction data from Automatic Weather Stations (AWS) and/or gridded numerical models. Determining the influence of wind and other atmospheric forcing on snow distribution in a complex terrain requires the use of numerical atmospheric models. Many studies have demonstrated that high-resolution models are vital for simulating topographic and land-use impacts on wind, hydraulic jump and associated turbulence (Olafsson and Agustsson, 2009; Agustsson and Olafsson, 2007). For this research, hourly atmospheric forcing were generated by version 3.5 of the polar-optimized version of the Advanced Research Weather Research and Forecasting Model (WRF-ARW; Skamarock et al., 2008) known as Polar WRF (Bromwich et al., 2009) or PWRF (http://polarmet.osu.edu/PWRF) at 3 km horizontal resolution.

Comment [DP45]: Changed from 'Atmospheric'.

The WRF-ARW (hereafter, WRF) is a state-of-the-art model that is equipped with a fully compressible, Eulerian and nonhydrostatic dynamic core. This model uses Arakawa C-grid staggering in the horizontal and utilises a mass terrain-following coordinate vertically. Several physical parameterization schemes are available in WRF, and some of those used for this work are described below. The WRF single-moment 6-class microphysics scheme (WSM6; (Hong and Lim, 2006)) is a cloud microphysics scheme, which includes various water phases including graupel. This likely improves precipitation and cloud related predictions at higher spatial resolution. For radiation, the rapid radiative transfer model (RRTM;(Mlawer et al., 1997)) and the empirically based Dudhia short-wave radiation scheme (Dudhia, 1989) are used as the long and short wave radiation schemes, respectively. The Mellor–Yamada–Nakanishi–Niino (MYNN; Nakanishi and Niino, 2006, Nakanishi and Niino, 2004, Nakanishi, 2001) level-2.5 scheme is used to take into account subgrid-scale turbulent fluxes.

The Noah LSM (Chen and Dudhia, 2001) with four soil layers, which is able to handle sea-ice and polar conditions through modifications described below was chosen as the land surface model. Generally, mesoscale numerical models including WRF have simple representations for sea ice thickness and snow depth on sea ice. This shortcoming leads to an outstanding error in the simulation of the snow and mass balance in the polar regions. To address this issue, PWRF improved the representation of heat fluxes through snow and ice in the Noah LSM. Further, this version of PWRF modified sea ice and snow albedos and made it accessible to define spatially varying sea ice thickness and snow depth on sea ice [for further detailed information about PWRF see (Hines et al., 2015)].

The models, PWRF and SnowModel are coupled in an off-line manner. This means that the PWRF model ran for the entire study period first, then SnowModel initiated based on the PWRF simulated atmospheric forcing and there is no feedback from SnowModel to the atmospheric model. In order to increase the spatial resolution of the PWRF outputs, before ingesting the atmospheric forcing to the SnowModel, PWRF gridded data are interpolated to a new grid, and then corrected physically according to topography using the MicroMet submodel. The spatial resolution of SnowModel is 200 m and its output is segmented into sea ice fastening areas as indicated by the Envisat imagery (Fig. 1). These are reported as hourly means beginning at 00:00 1st April 2011 and ending at 00:00 1st December 2011. SnowModel outputs snow depth and swe. The model has a varying density over time. The swe output is important as it allows comparison of the model to the other snow products which have different density assumptions.

Comment [DP46]: Outputs of SnowModel now described.

3.2 Low resolution model

ERA-Interim is a global atmospheric reanalysis product on a 0.75° x 0.75° grid available from 1 January 1989 (Dee et al., 2011). Precipitation data (mm water equivalent) are available at three hourly intervals and are converted to snow depth when required using the average snow density of 385 kgm^{-3} measured *in situ* in 2011. Data are retrieved from ERA-Interim at 77.7°S 165.8°E (Fig. 1) and accumulated through the assessment period. Splines were used to interpolate to this position from the three-dimensional ERA-Interim grid. The reanalysis does not account for snow transport and does not have a high enough resolution to segregate snow accumulation by freeze up date. Therefore, the reported ERA-Interim data are daily averages for the entire study area.

Comment [DP47]: Extraction method for ERA-Interim data added.

4 Snow product evaluation

When the three snow products are compared to one another, or to *in situ* measurements, all snow depths are reduced to snow water equivalent (swe) via their respective densities to remove any bias associated with varying density between snow datasets. SnowModel provides a swe output via a time varying snow density during the model run, AMSR-E snow depths are reduced to swe using average *in situ* measured snow density in November, and ERA-Interim precipitation is provided as swe in its original format. The SnowModel evaluation is split into three parts, firstly, an accumulation time-series is presented for SnowModel and AMSR-E segmented by each freeze-up area, 1-3, this time series is the mean snow depth for each product within in each area (Fig. 2). ERA-Interim is a single daily value for the entire study area. Secondly, selected SnowModel grid cells are directly compared to spatially coincident *in situ* measurement sites in November (Fig. 3) and thirdly, the SnowModel distribution is plotted as a map at the end of the model run for spatial comparison to the in situ dataset (Fig. 4). The model swe values used for direct comparison to in situ measurements in Figures 3 and 4 are the mean at each site between 25th November and 1st December, the period over which *in situ* measurements were made.

Comment [DP48]: Amended to be inclusive of the addition of Fig. 4

The SnowModel mean swe for all areas at the end of the simulation is 2 cm higher than *in situ* swe mean. However, SnowModel clearly presents two very different snow accumulation patterns, one in the west covering area 1 and one in the east covering areas 2 and 3. Mean swe values in area 1 reach a maximum of 2 cm during the 8-month study period while in areas 2 and 3 they are in excess of 10 cm. This distribution compares well with *in situ* measurements and general observations during fieldwork in November 2011, which recorded an increasing gradient in snow depth from west to east (Fig. 4). However, when each freeze-up area is directly compared to *in situ* means for those areas, swe is underestimated in area 1 (2 cm < *in situ*), slightly overestimated in area 3 (1 cm > *in situ*) and substantially overestimated in area 2 (5 cm > *in situ*) (Fig. 2). Only modelled swe in area 3 falls within the standard deviation of the *in situ* mean. In the east, snow depth increases are noted in mid-May, mid-June, early-July, early and mid-August and late-September. The snow depth evolution in the west of the Sound over area 1 follows a separate pattern with negligible increases in mid/late April, mid-May, mid-July, late-September and early-November. When directly compared to *in situ* data (Fig. 3) SnowModel overestimates swe snow depth in the study area and therefore the model has better agreement with *in situ* maximum values ($r^2 = 0.56$) than with the mean ($r^2 = 0.53$) or minimum ($r^2 = 0.30$) values (Fig. 3). This general overestimation is clearly seen in Figure 4. Values in the eastern most section of the sea ice cover in McMurdo Sound, adjacent to Ross Island are in

Comment [DP49]: Added to clearly establish the mean deviation of the entire SnowModel domain over the sea ice from in situ. This was not clear to the reviewers.

Comment [DP50]: Simplified from ‘Although the model captures the snow distribution on the fast ice’.

Comment [DP51]: Figure reference added.

the order of 20 to 45 cm swe. These values are all larger than the highest *in situ* measured swe of 17.7 cm and for large areas, they are over double the measured value. In the central area of the Sound, modelled swe decreases in agreement with measured swe with 5 *in situ* sites agreeing within ± 0.5 cm of SnowModel swe (Fig. 3 and Fig. 4). The extremes, where there is a lot of snow and where there is very little snow both seem to be exaggerated by the model.

ERA-Interim swe for the entire study area steadily increases after the first-third of April and falls within + 1 cm of the mean of all *in situ* measurements made in November. ERA-Interim swe is lower than swe for SnowModel for areas 2 and 3 after the first large increase in swe in these areas in mid-June. ERA-Interim shows better agreement with AMSR-E during this time period. Unlike SnowModel or the *in situ* distribution in late November AMSR-E swe follows a similar pattern over time in all freeze-up areas. For areas 2 and 3, May through June, AMSR-E and SnowModel produce similar swe values, agreeing within 1.5 cm in areas 2 and 3. In area 1 AMSR-E swe fluctuates but is typically about 2.5-3 cm higher than SnowModel. As the growth season progresses AMSR-E remains significantly lower than SnowModel swe in areas 2 and 3, by up to 10 cm. swe values are higher in area 2 than area 3 in agreement with SnowModel. However, in area 1 swe values are four times larger than SnowModel. Most importantly, the longitudinal swe gradient indicated by SnowModel and supported by *in situ* data is opposite when measured using AMSR-E (i.e. swe is higher in the west than in the east for the duration of the times series). As the AMSR-E instrument failed in early October, we are unable to validate it with *in situ* measurements.

Comment [DP52]: Sentences added to the text in reference to addition of map as Fig.4.

Moved down [1]: Unlike SnowModel or the *in situ* distribution in late November AMSR-E swe follows a similar pattern over time in all freeze-up areas. For areas 2 and 3, May through June, AMSR-E and SnowModel produce similar swe values, agreeing within 1.5 cm in areas 2 and 3. In area 1 AMSR-E swe fluctuates but is typically about 2.5-3 cm higher than SnowModel. As the growth season progresses AMSR-E remains significantly lower than SnowModel swe in areas 2 and 3, by up to 10 cm. swe values are higher in area 2 than area 3 in agreement with SnowModel. However, in area 1 swe values are four times larger than SnowModel. Most importantly, the longitudinal swe gradient indicated by SnowModel and supported by *in situ* data is opposite when measured using AMSR-E (i.e. swe is higher in the west than in the east for the duration of the times series). As the AMSR-E instrument failed in early October, we are unable to validate it with *in situ* measurements.

Comment [DP53]: Additional sentences added about ERA-Interim.

Moved (insertion) [1]

Comment [DP54]: More detail added to AMSR-E evaluation.

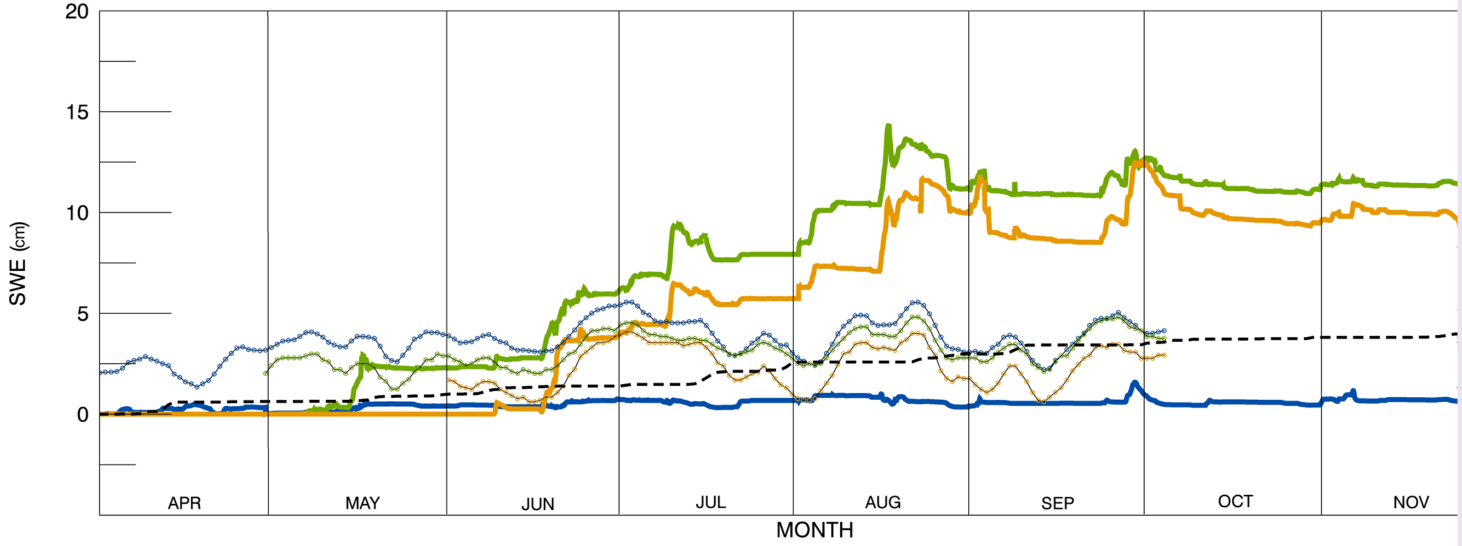
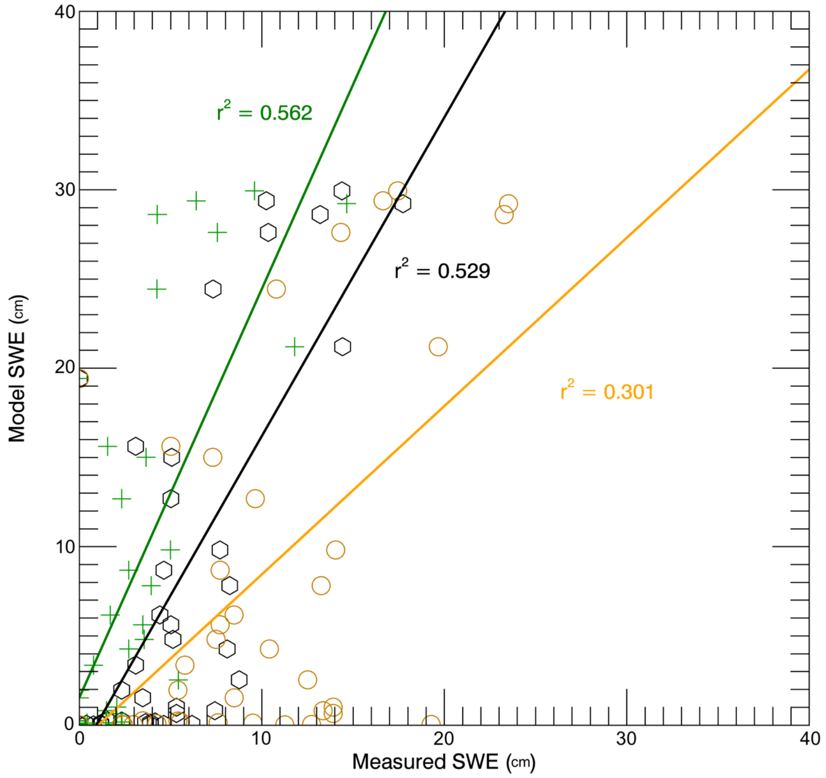


Figure 2. SnowModel (solid lines) hourly accumulation and AMSR-E daily snow depth (solid lines with circles) converted to snow water equivalent (swe) for freeze-up areas 1 (blue), 2 (green) and 3 (orange) plotted with ERA-Interim swe (hashed black line) for the entire study area. The mean *in situ* swe and standard deviations for each area are displayed as circles at the end of November and colour coded to their respective freeze-up areas.

Comment [DP55]: m to cm on scale.



Comment [DP56]: m to cm on scale.

Figure 3. Mean (black), maximum (green) and minimum (orange) *in situ* measured snow water equivalent (swe) for each site against mean SnowModel swe at each coincident model cell for the *in situ* measurement period.

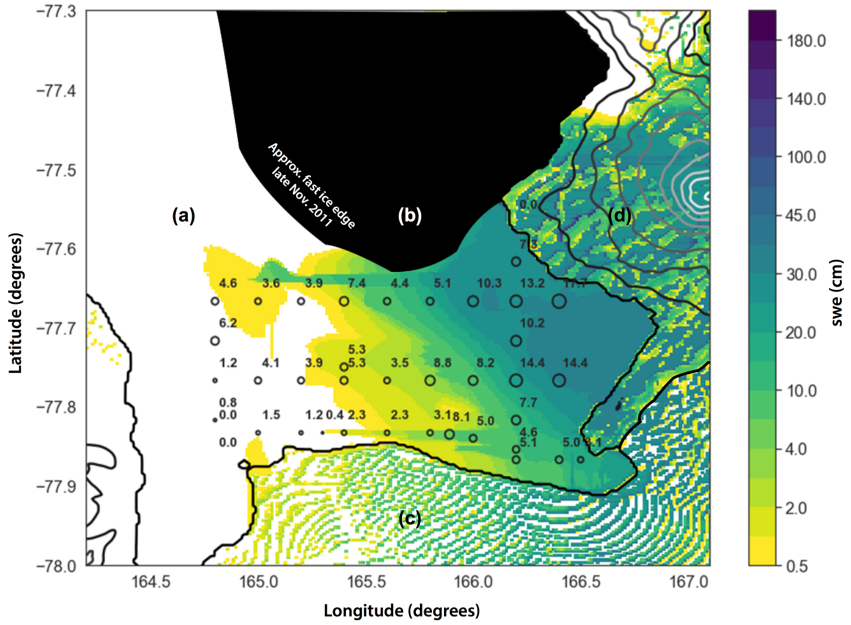


Figure 4. SnowModel distribution map displayed as swe over McMurdo Sound, (a) fast ice, (b) open water/pack ice, (c) McMurdo Ice Shelf, (d) Ross Island. The model swe distribution is the mean of the simulation over the *in situ* measurement period (25th November-1st December). The *in situ* measurements were converted to swe via the density measured at each site, if no measurement was taken (21 sites) the average *in situ* snow density was used (385 kgm^{-3}). *In situ* measurement locations are shown as black circles and are the mean of the 60 snow measurements taken at each site. The circle sizes are weighted for swe to allow visualisation of the decreasing swe distribution from east to west. Elevation contours are spaced at 400 m intervals; Mt Erebus is the dominant topographic feature on Ross Island to the east of the fast ice.

5 Sea ice thickness

In this section, we review the usefulness of the snow products by using them as inputs to equations 1-3 and infer sea ice thickness in McMurdo Sound through the growth season. Snow information, coincident in space and time for each CS-2 measurement is retrieved from the SnowModel and AMSR-E products as snow depth, while ERA-Interim swe is converted to snow depth using the mean *in situ* measured density. Sea ice thickness inferred from altimetry in McMurdo Sound will be influenced by the buoyant sub-ice platelet layer (Price et al., 2014). The *Fb* measurement used to infer thickness is representative of the solid sea ice and the layer of sub-ice platelets attached below. Therefore, comparisons to *in situ* thickness referenced in this work actually refer to the 'mass-equivalent thickness', that is, the resultant thickness taking account of both the solid sea ice and the sub-ice platelet layer (sub-ice platelet layer multiplied by the solid fraction). The only exception to this is the red line in Fig. 5 which is a linear fit between two measurements of consolidated sea ice thickness in July and November 2011 used here to show the sea ice thickness growth rate for comparison to CS-2 thickness trends.

Comment [DP57]: New figure added.

Comment [DP58]: Reworded to provide clarity on where from and how snow information is being used in equations 1-3.

Comment [DP59]: Sentence added for clarification on what the in situ measurements are used for the red line in Fig. 5.

From equations 1-3, sea ice thickness is highly sensitive to the snow-ice ratio for the measured freeboard. This results in a large range in sea ice thickness for all snow products through the growth season (Fig. 5). Using modelled snow depths (Fig. 5a and b) sea ice thickness can vary by over 2 m from assuming the air-snow interface or snow-ice interface is measured. The AMSR-E derived thickness trend is not comparable to the model output trends as the last two months are missing. However, it is useful to highlight the importance of the snow-ice freeboard ratio. AMSR-E snow depths are high in comparison to the model snow depths at the beginning of the growth season and they remain relatively stable for its duration. Because of this, the ratio of ice to snow above the waterline remains very similar. The modelled snow depths gradually increase and snow makes up an ever increasing proportion of mass above the waterline. If the air-snow interface is taken to represent *Fb* then the trend in sea ice thickness through the growth season is negative for SnowModel and ERA-Interim derived thicknesses. The trend is more negative for the SnowModel estimate simply because the snow loading is greater. If the snow-ice interface (equation 2) is assumed to represent *Fb*, thickness trends are too positive. The mean CS-2 thickness values for November are 2.62 m and 2.77 m for SnowModel and ERA-Interim respectively compared to an *in situ* thickness of 2.4 m. The trends that result in a November thickness supported by the *in situ* measurements are those that assume penetration into the snow cover, analogous with the retracked surface representing a surface between the air-snow and snow ice interfaces. For thicknesses derived using SnowModel to match *in situ* thickness a large *Pd* of 0.5 m is required given the higher snow depth values, while for ERA-Interim *Pd* values of 0.1 to 0.15 m place CS-2 thickness estimates closer to *in situ* thickness.

Comment [DP60]: More detail provided here about results if a penetration factor is assumed.

The differences in the snow depths from each model result make if difficult to constrain what *Pd* value provides CS-2 thicknesses that agree best with measured thickness. To narrow down the range of most representative *Pd* values we use interpolated *in situ* measurements for snow depth as input to the sea ice thickness calculation. We reduce the CS-2 measurements used in this comparison to the same area bounded by situ measurements. The total range in estimated sea ice thickness using interpolated *in situ* snow depth between equations 1 and 2 is 1.7 m. For *Pd* values 0.02 m through 0.20 m the best agreement between *in situ* thickness and CS-2 derived thickness is found between 0.05 and 0.10 m (Fig. 6 – third column, 'In situ'). The CS-2 thickness is only 0.02 m thicker than *in situ* thickness for this particular dataset when *Pd* = 0.07 m. The range in SnowModel derived thickness between equations 1 and 2 is nearly 4 m while the range when using the ERA-Interim data set is almost half that of SnowModel, showing good agreement with the *in situ* dataset (Fig. 6). Again this large range in thickness reflects the higher average snow depth produced by SnowModel. The deeper snow creates a larger range of snow-to-ice ratios.

Comment [DP61]: Sentence reworded to help explain logic of using interpolated in situ snow depth as input to CS-2 thickness estimates.

Comment [DP62]: Additional sentence added.

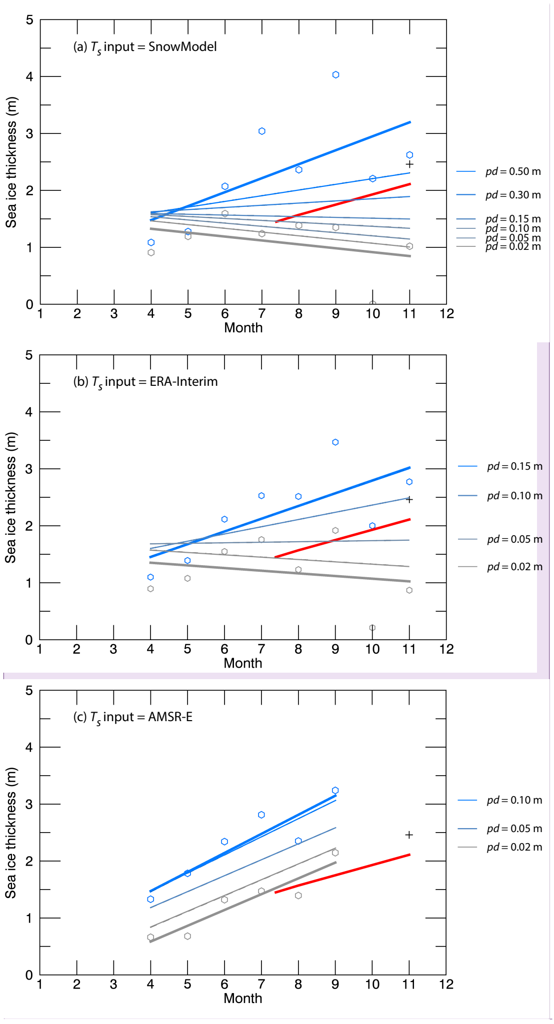


Figure 5. Sea ice thickness trends derived by CS-2 freeboard measurements with snow data provided by (a) SnowModel, (b) ERA-Interim and (c) AMSR-E. Grey dots and bold linear fit are sea ice thickness calculated using equation 1, blue dots and bold linear fit using equation 2 and thin lines between them equation 3 with varying penetration factors (*Pd*). The red line shows sea ice thickness from *in situ* measurements of consolidated sea ice thickness with a tape measure taken in July and November in one location in the south of McMurdo Sound joined assuming a constant growth rate. The black plus sign is the mean 'mass-equivalent thickness' from all *in situ* measurements in November. This is slightly thicker than the end of season thickness indicated by the red line given it takes account of the influence of the sub-ice platelet layer. This is what CS-2 thickness should be compared to (see text).

Comment [DP63]: Pd legend added and moved off the plot for clarity.

Comment [DP64]: Caption amended to reflect changes in the figure.

Comment [DP65]: More detail on red line provided.

Comment [DP66]: Reader is directed to compare equivalent thicknesses.

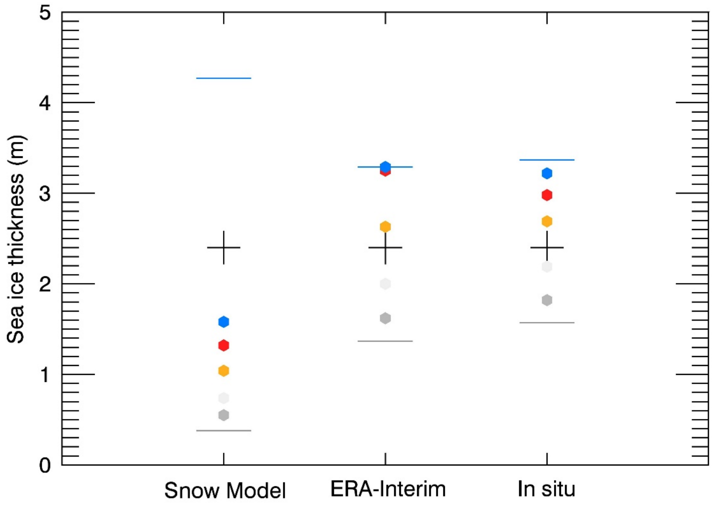


Figure 6. The range in CS-2 derived sea ice thickness in November using snow inputs from SnowModel and ERA-Interim compared to snow input from *in situ* interpolated snow depths. Thickness derived from equations 1 and 2 are shown with the grey and blue lines respectively and for equation 3 the dots are colour coded for different penetration depths (*Pd*); dark grey = 0.02 m, light grey = 0.05 m, orange = 0.10 m, red = 0.15 m and blue = 0.20 m. Black plus signs show *in situ* 'mass-equivalent thickness'. This comparison is produced from all CS-2 data height retrievals available over the *in situ* measurement area in November (n = 279).

6 Discussion

In this section, the performance of the snow depth retrieval methods and CS-2 thickness uncertainty is evaluated. We briefly discuss their future applicability to larger Antarctic sea ice areas.

Comment [DP67]: CS-2 analysis referenced also.

Any method attempting to accumulate snow on sea ice requires the establishment of a starting date from which a sea ice surface is present. This approach used Envisat ASAR imagery and motion between scenes to identify when the sea ice fastened. Freezing may have started prior to the fastening-date but the authors are unaware of any other method to monitor freeze-up at the required spatial resolution for SnowModel. Sea ice could have begun to form slightly before this date, which, assuming a net gain in snow would result in an improvement in SnowModel's performance in area 1, but increased separation between *in situ* validation and SnowModel in areas 2 and 3. In larger open water areas, passive microwave sea ice concentration information could be used to establish the freeze up date. Detail would be lost via this method given the high (200 m) resolution of SnowModel against the coarser resolution passive microwave data. Early snow fall on more dynamic pack ice will also be subject to flooding, sea spray (both likely to result in snow-ice formation) and loss to leads. These uncertainties must all be considered in future work.

Comment [DP68]: Additional sentences added about additional uncertainties in freeze up assessment.

Modelled snow depths have been evaluated in a previous work over Antarctic sea ice (Maksym and Markus, 2008), but the study produced precipitation data while this assessment takes the next step by using a model that accounts for surface transportation, a significant redistribution mechanism in the Antarctic. Leonard and Maksym (2011) report that over half of precipitation over the Southern Ocean could be lost to leads and the application of any model to construct snow depth on sea ice in open sea areas will need to account for this. In coastal regions, local topography will also play a key role, such is the case in McMurdo Sound where Ross Island acts to encourage snow accumulation on the eastern portion of the sea ice cover. This was well replicated in SnowModel although the overestimation of snow was driven by unrealistic values in this area, the model likely accumulating too much snow due to this topographic barrier. Smaller scale snow features such as snow drifts and snow dunes should also be accounted for in future work, as applied in a recent study by Liston et al. (2018). These meter-scale features will be important to capture, especially to support compatibility with smaller satellite altimeter footprints, in particularly ICESat-2 with an expected 0.7 m along-track sampling rate (Abdalati et al., 2010). This work used fast ice to reduce the uncertainty associated with pack ice and use available *in situ* data to validate the snow products. To build on this approach, and make its application valuable in the Southern Ocean, sea ice motion within the SnowModel domain must be incorporated.

Comment [DP69]: More detail provided on ICESat-2 footprint.

We find ERA-Interim mean swe to be 1 cm lower than mean *in situ* swe in McMurdo Sound. This is an encouraging result, but we caution this result is only representative of a single year in a small area, which is not representative of the data void, open ocean regions. The performance of ECMWF reanalysis products over the satellite period is good when compared to Antarctic coastal stations (Bromwich and Fogt, 2004), but there is limited data available to assess the accuracy of these data over Antarctic sea ice. ERA-Interim ranked best among five assessed models for its depiction of interannual variability and overall change in precipitation, evaporation and total precipitable water over the Southern Ocean (Nicolas and Bromwich, 2011). Maksym & Markus (2008) used ERA-40 reanalysis for a snow assessment of the Antarctic sea ice pack but had difficulties in evaluating its accuracy. The improved reanalysis product ERA-5 has over twice the spatial resolution of ERA-Interim and given the promising results here, it should be considered for evaluation as a snow product on sea ice. The principal issue to overcome will be that reanalysis data lack any redistribution mechanism (including snow loss to leads) but parameterisations for this could be built from wind vectors provided by the same reanalysis data.

In general, when compared to SnowModel, AMSR-E underestimates snow depth in areas 2 and 3 (eastern Sound) and overestimates snow depth in area 1 (western Sound). Of most interest is that the clear longitudinal gradient in snow depth as indicated by SnowModel and measured *in situ* (November only) is the opposite in the AMSR-E dataset. Worby et al. (2008b) report that AMSR-E snow depths were significantly lower than *in situ* measurements on sea ice in the East Antarctic and that sea ice roughness is a major source of error using passive microwave retrieval techniques. However, they also conclude that when compared to basin-wide observations from ASPECT large differences of up to + 20 cm in the Weddell Sea and + 5-10 cm in the Ross Sea were noted in the AMSR-E snow depths. It is postulated that *in situ* observations underestimated true mean snow thickness as surveys were limited to level ice areas typically presenting thinner snow covers. More work is required to validate passive microwave snow depth estimates over Antarctic sea ice. No detailed sea ice surface condition survey was completed for this investigation, however from visual observations sea ice had clearly been subjected to dynamics in the west, whereas ice was very level in the east. It is

Comment [DP70]: Added for clarity about timing of in situ measurements.

possible that snow depth was underrepresented here by *in situ* measurements and that rougher sea ice in the west affected the AMSR-E retrieval algorithm. Because of the failure of the instrument, we are unable to compare AMSR-E snow depth directly to *in situ* measurements.

CS-2 has difficulty estimating freeboard over thin ice areas (Price et al., 2015, Ricker et al., 2014, Wingham et al., 2006). Here, at the beginning of the growth season CS-2 generally overestimates sea ice thickness with mean April values inferred using snow data from SnowModel and ERA-Interim of around 1 m (with the exception of AMSR-E assuming the air-snow interface is measured T_i = 0.66 m). Other investigations indicate that sea ice thickness in McMurdo Sound in April is between 0.5-0.8 m (Frazer et al., 2018, Gough et al., 2012, Purdie et al., 2006) . This represents a large obstacle to overcome for the application of CS-2 in the Southern Ocean as the mean thickness of Antarctic sea ice is only 0.87 m as reported from ship-based observations (Worby et al., 2008a). This supports the need for multisensor analysis, perhaps using methods already employed in the Arctic (Ricker et al., 2017, Kaleschke et al., 2012, Kwok et al., 1995). As discussed in section 2.4 assumptions must be made about what surface the freeboard measurement represents. In general, using the two modelled snow products (because trends from AMSR-E are incomplete), the thicknesses derived assuming the air-snow interface is freeboard are too thin and those assuming the snow-ice interface is freeboard are too thick. By using the interpolated *in situ* measured snow depth as the snow thickness input to the thickness calculation we minimised the error. With this, we find CS-2 thickness to correlate best with *in situ* thickness if *Pd* values are between 0.05-0.10 m. This is supported by other work in the study area (Price et al., 2015) who estimated the ESA elevation to be between the air-snow and snow-ice interfaces when sea surface height error was ruled out via a manual sea surface classification. Also recent work in the Arctic suggests that the height that represents radar freeboard provided by the ESA Level 2 product is closer to the air-snow interface than the snow-ice interface (King et al., 2018).

Comment [DP71]: Supporting literature has now been added here.

The mean radar freeboard in November (not corrected for radar wave speed in the snowpack) is 0.18 m. *In situ* ice freeboard was 0.22 m and *in situ* snow freeboard was measured as 0.33 m. When corrected for radar wave speed CS-2 freeboard varies between 0.18-0.21 m (0.19-0.22 m) for SnowModel (ERA-Interim) through the full range of *Pd* assumptions (i.e. *Pd* = 0.02 m-ice freeboard detected). Again, this result is supportive of penetration into the snowpack but it should be cautioned that it is dependent on the established sea surface height. If the established sea surface height here has been biased high, the freeboard measurements would actually be more representative of the snow freeboard. Freeboard errors from automated sea surface height identification were in the order of 0.05 m when compared to supervised procedures in the study area (Price et al., 2015). To eliminate this uncertainty throughout the study period the sea surface would need to be manually identified for each individual CS-2 track. This is not practical for basin-scale assessments and confidence needs to be built in the sea surface height identification algorithm. The modification of the sea surface height will apply a systematic increase or decrease in freeboard making each thickness from each assumption thicker or thinner. The freeboard measurements exhibit an unexpected decrease in October and November and it is impossible to discern whether this is forced by a sea surface height that is too high, or a change in the sea ice surface conditions that causes a decrease in the freeboard measurement, an additional uncertainty. More detailed *in situ* investigations, with surface roughness and snow characteristic statistics at the scale of the altimeter footprint are required before a seasonally varying *Pd* can be applied with any confidence. As this analysis

Comment [DP72]: Sentence added about requirement for in situ information representative of the actual satellite footprint.

was focused on the combination of independent snow products and CS-2 altimeter data, the range in sea ice density has not been taken into account. We have confidence in the middle ground *ρi* value used from previous work in McMurdo Sound (Price et al., 2014) but this is another source of uncertainty for regional and basin-scale assessments.

Comment [DP73]: Sentence added about focus on snow products in this study.

7 Conclusions

This work has evaluated the ability of three independent techniques to provide snow depth on fast ice in the coastal Antarctic. The snow distribution from SnowModel accurately captures the relative distribution measured in November 2011 and produces a swe mean value that is 0.02 m above the mean of *in situ* validation, but when sea ice is segmented by fastening date large deviations of up to 5 cm are present in the east where the model has overestimated snow depth. This accurately captures the mechanism of snowfall and transport driven by the topography of Ross Island, but the rates are higher than in reality. ERA-Interim swe is 1 cm lower than *in situ* measurements but its coarse resolution prevented the adjustment of precipitation to sea ice fastening dates. AMSR-E snow depth information suffers from problems already documented in the literature, and we find that its performance may have again been influenced by rough sea ice. The snow distribution produced by AMSR-E was opposite to that provided by SnowModel and measured *in situ* at the end of the growth season. We were unable to validate the instrument due to its failure 2 months before the *in situ* data was collected. The uncertainty in the snow depth estimates manifest themselves in the sea ice thickness estimates from CS-2. A large range in estimated thickness of over 2 m exists if the range in freeboard used is between the air-snow and snow-ice interfaces. Here, we find CS-2 freeboard measurements provided by the ESA retracker are most likely representative of a mean scattering horizon 0.07 m beneath the air-snow interface, in agreement with recent literature. It is impossible to confidentially constrain this number without reducing uncertainty in the established sea surface height from which the freeboard is estimated. An improved understanding of the CS-2 freeboard measurement will be critical to accurately provide sea ice thickness estimates over varying snow and sea ice conditions in the Southern Ocean.

Comment [DP74]: Number more specific (0.05-0.10 m previously). This is not a change in the analysis we have simply used a more specific number instead of a range.

Here, we show that modelled snow information has the potential to produce a time series of snow depth on Antarctic sea ice, that could be used with altimetry data to infer sea ice thickness if the reference surface of the altimeter can be accurately defined. With improvements to redistribution mechanisms and adequate representation of the effect of topographic features, atmospheric models could be used as an alternative to contemporary passive microwave algorithms. Future work should begin to assess the usefulness of SnowModel products over the larger pack ice areas, and critically develop a method to (1) incorporate sea ice drift through the atmospheric model domains, and (2) account for snow loss to leads. If these two influences can be adequately incorporated, SnowModel could provide a valuable resource for snow and sea ice thickness investigations over the wider Antarctic sea ice area.

Comment [DP75]: Sentence added about importance of a defined reference surface.

Comment [DP76]: Sentence changed from 'at least as reliable as contemporary passive microwave algorithms.' This wording was too strong especially considering untested model application over open ocean.

Comment [DP77]: Concluding sentence on application of SnowModel to wider Antarctic sea ice area has been added.

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