<u>Response to second round of reviewer responses for tc-2018-92 "*Snow depth uncertainty and its implications on satellite derived Antarctic sea ice thickness*"</u>

The authors would like to thank the reviewers and the editor for the continuation of their detailed comments on the manuscript. We have addressed these below as responses to Reviewer #1, Reviewer #2 and Editors Comments in bold. There are a few key changes to the manuscript highlighted first.

1. **The principal change to the manuscript is a change to the ERA-Interim dataset after an error in the original code was identified while re-gridding the ERA-I dataset. The ERA-I dataset was too low by an order of magnitude; the ERA-I accumulation was underestimated in the previous versions of the document. The authors apologise for this error in the initial submission. The change to this result makes SnowModel far superior to ERA-I for its eventual snow depths when compared to in situ measurements in McMurdo Sound. All changes to results are highlighted along with relevant changes to the text. The correct dataset has been offered to the editor and is available for the reviewers to view if required. The old and new Figure 2, which best showcase the difference are provided at the end of this response.**
2. **We have changed the title to accommodate the reviewers concerns and agree the initial title was too broad. New title: "*Snow driven uncertainty in CryoSat-2 derived Antarctic sea ice thickness - insights from McMurdo Sound*"**
3. **ERA-Interim in the text has been abbreviated to ERA-I.**

<u>Reviewer #1</u>

Response to author comments for the "Snow depth uncertainty and its implications on satellite derived Antarctic sea ice thickness" paper by Price et al.

I like Figure 4, I'm glad you've included it. However, I still don't buy the decision not to also show the ERA-I grid-cells. I think there could be several grid cells covering your study area and that might be telling to assess its performance. I would guess you could even have one or two grid-cells to represent the three fast ice regions too, making the later analysis a lot more interesting (rather than just showing the ERA-I line as a study region mean).

The reviewer was correct to identify that multiple ERA-I grid cells covered the study region, at the latitude of the study the 0.75º x 0.75º cell size resulted in 14 separate ERA-I cells in the snowmodel domain. The central point of these cells are now displayed in Figure 1. Because of this we have now included a 10 x 10 ERA-I grid as the basis of the analysis which is shown in the results as Figure 4b. The study region is now segmented for fastening date using the ERA-I 10 x 10 grid. However, all changes to the results are principally driven by the major correction to the ERA-I dataset as indicated above.

I'm also still confused about some of the snowmodel choices - can it be run for coarser resolutions? If so, why not do that? What benefit is there for running it at 200 m? My main point really is that the mean precip biases might be more important than capturing the high spatial variability.

In the modeling space when it comes to wind (given that snow distribution was the major objectives) we try to go as high-res as possible. We're looking at the complexity of topography and decide which resolution can capture most of the orographical detail. At the same time, the in situ measurements highlighted the role of topographical complexity in snow distributions. Improving the wind direction and speed is one of the strengths of the snowmodel. Snowmodel cannot achieve this unless it has access to very high-resolution topography.

WRF with 3km resolution could not capture all those detailed topographic complexities in the study region. Snowmodel is able to improve the wind speed and direction coming from the coarser WRF outputs but higher-res topography is critical. 200 m was the most detailed topography data we had access to, we would have done it at 10 m if we had access to that data.

At scales around 200 m we are also providing snow information at similar spatial scales to the satellite footprint. We understand snowmodel hasn't provided snow depths of the desired accuracy but it is attempting to include more complexity. Future developments will likely improve its performance.

We have provided statistics for each of the fastening areas and the entire study area from this higher-res data which addresses the mean precipitation and provides a comparison to the other snow products.

Higher resolution snow depth products are also desirable to capture snow information at the same spatial scales as the satellite altimeter footprint.

"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 think you've missed the point here. ERA-I provides snowfall and total precip as different variables. Why note use the snowfall variable?

Apologies for the miscommunication, we did not use the ERA-I snow product and have just used the total precipitation variable (swe) as no rainfall is expected at this latitude for the study period. We then use the more accurate density measured in situ to convert precipitation to snow depth when required.

"Antarctic fast ice thickness from cryosat-2 using different snow product information" I still think this title needs work! Can you reference more directly your study area as again the title is inferring a wider study than what is presented (it's very local scale). E.g. "Comparison of snow depths in mcmurdo Sound from in-situ data and various snow products and its impact on sea ice thickness altimetry"?

Understood, title amended to:

"Snow driven uncertainty in CryoSat-2 derived Antarctic sea ice thickness - insights from McMurdo Sound"

Extra discussion on satellite data products:

It's still unclear what exact products you are using. Can you provide the links as this may help clarify things (you aren't calculating these data yourself, right?..). E.g. The Envisat description doesn't make this clear. Are you doing this processing or obtaining this information from an existing product?

We have added additional information about the Envisat processing and the source of the AMSR-E data. Enough information is provided about the products for the reader. The Envisat data link is difficult to include in the text as it involves registration online via ESA. This all gets a little complicated in the text and is not required.

Envisat – "*we use a string of C-band Advanced Synthetic Aperture Radar (ASAR) images from Envisat acquired in Wide Swath mode. We process these files using using GAMMA Software to produce ASAR imagery with a spatial resolution of 150 x 150 m*".

AMSR-E – "*The snow depth product provided by NSIDC (https://nsidc.org/data/AE_SI12/versions/3#) is provided at a 12.5 x 12.5 km2 polar stereographic projection and reported as a 5-day running mean, that mean inclusive of that day and the prior 4 days.*".

Comments on initial conditions:

I don't agree with your response to this and your discussion of grid resolutions. You could apply a constant value and just distribute that over the high resolution snowmodel grid if you want, so doing this for a 12 km dataset would be possible also. You just aren't capturing the spatial variability. I still think need to make this potentially missing snow clearer, and hopefully provide some estimate at what potential bias that might introduce.

The authors think this response accurately depicts the situation. The additional snow delivered before sea ice fastening will be negligible. Pack ice in mcmurdo Sound is transported north into the wider Ross Sea region, until it fastens it does not remain in the Sound for long.

An example of this can be visualised over the study region at the link below:

(https://worldview.earthdata.nasa.gov/?P=antarctic&l=VIIRS_SNPP_correctedreflectance_truecolor(hidden),MODIS_Aqua_correctedreflectance_truecolor(hidden),MODIS_Terra_correctedreflectance_truecolor,Coastlines,AMSRE_Sea_Ice_Concentration_12km(hidden),AMSRE_Sea_Ice_Brightness_Temp_89H(hidden)&t=2011-02-20-T00%3A00%3A00Z&z=3&t1=2011-03-20-T00%3A00%3A00Z&v=68147.42217165558,-1504445.119093321,612172.8978546829,-1117069.1665325488&r=-162.064&ab=off&as=2011-03-27T00%3A00%3A00Z&ae=2011-04-03T00%3A00%3A00Z&av=3&al=true)

The fast ice in the Sound fully breaks out during a storm event (21-23 Feb 2011) including sections of the McMurdo Ice Shelf. Sea ice begins and continues to form in the south-western Ross Sea through the first half of March. All this pack ice is forced northward by southerly winds in the wider Ross Sea region. It is not until it fastens that it remains in the model domain and actually accumulates snow. The authors think the fastening date actually provides quite a robust measure of time zero for snow accumulation in this study region. Additionally even if this were not the case, all model snow data sets are biased high and inclusion of this unnecessary factor in this case would increase the discrepancy between model results and in situ measurements.

We have added an additional sentence in section 2.2:

"*In McMurdo Sound during the freeze-up period, pack ice is generally advected north out of the study area unless it fastens.*"

Response to SWE units:

OK but I think it will be illuminating to see what the in-situ density and SnowModel densities are.

Mean in situ density is provided in the text. We have not investigated the additional uncertainty introduced by varying snow density in this study. SnowModel incorporates its varying density through the growth season in the snow depth output. However, we have no information on ERA-I snow density nor AMSR-E and can only reduce to swe via the end of growth season in situ measurements. We choose not to investigate this additional source of uncertainty. To effectively investigate this in situ snow density would need to be collected through the growth season, a significant logistical task. This would allow the correct numbers to be entered monthly with

coincident CS-2 measurements. Better constraining these values is important and a part of our future work.

AMRS-E gridding comment:

Thanks for the information. I think say 'provided at' instead of 'gridded to' as this currently makes it seem like you do the gridding.

This sentence has been amended to:

"*The snow depth product provided by NSIDC (https://nsidc.org/data/AE_SI12/versions/3#) is provided at a 12.5 x 12.5 km2 polar stereographic projection and reported as a 5-day running mean, that mean inclusive of that day and the prior 4 days.*"

Cryosat data link:

Thank you for providing this. Links to data are needed.

Of course. Agreed!

"ρs is the mean of snow pit measurements at 18 of the in situ measurement sites in 2011.": Why only 18 of the sites?

It was only measured at these sites given time constraints during the fieldwork. They have a representative spread across the study area. Sentence amended to "*ρ_s is the mean value taken from 18 of the 39 in situ sites where snow density was measured.*"

"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. ":

The circles are tiny so this hardly distinguishes it from a solid line. This still needs improvement.

This figure has been replotted with different symbols.

New Figure 5 (was Figure 4): I don't understand the use of linear fits here. Does it look too noisy if you use the actual values? How about bar charts for the different months?

We have used these here to give the reader a better impression of the growth rates through the season. Yes, it is difficult to interpret with the monthly sea ice thickness means as stand-alone data points. The linear fits clarify this and also let the reader compare the CS-2 data to the in situ measured thicknesses points and line (red) also in the figure. We don't agree bar charts would represent the growth through the season well.

Comments on accuracy of the results:

How do you judge this to be an accurate spatial distribution? The map gets the broad spatial distribution pattern correct? If so you could be more explicit. Unsure what you mean by 'correct'. Again, I really think that despite the coarseness of ERA-I you're domain is big enough to get a few grid-cells that could provide some assessment of a regional distribution (albeit only with one or two grid cells per region).

We have made this clearer in the text with:

"*This broad spatial distribution produced by SnowModel 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).*"

We have amended the ERA-I analysis with the 10x10 grid to improve the resolution.

I think you should drop the 0.02 mean bias as this is just because you have compensating errors in your regional differences. The 0.05 cm differences are ~30-50% off, right? So still pretty big!

The authors think it is appropriate to use the study area mean as it gives an idea of the tot al swe delivered to the study region compared to that measured in situ. Yes there are regional differences, these are reported along with the developments required to improve the model.

If you just compared the ERA-I mean with the in-situ values in November I think you would get similar errors to the snowmodel values, correct? This would imply snowmodel isn't doing any better than ERA-I. See earlier comments about ERA-I.

With the revised ERA-I data set SnowModel and ERA-I results are now significantly different, SnowModel far outperforms ERA-I. This is all appropriately addressed in the text.

Reviewer #2

The authors have done a good job in addressing my concerns regarding the initial manuscript submission. I do however have a couple of small remaining issues that should be considered before publication.

1.) Related to the second significant concern of my first review (that the comparison of the various CS-2 sea ice thickness results with in situ data), I appreciate the author's clarifications and expansions. I understand the author's stance that this is in fact an evaluation of the product (and they do not claim it is a detailed validation). However, I would expect a little further comment within the manuscript on the spatial limitations of this comparison.

We feel this is communicated in the manuscript now especially with the amended title. We have also added "*in McMurdo Sound.*" in the abstract.

2.) L196: Quantify "incremental". Could the authors also justify why they plotted the increments they did in Figures 4 and 5, considering Pd = 0.07 gives the best agreements between CS-2 and in situ thickness?

Sentence amended to:

"*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 varying Pd values into the snow pack (0.02 m, 0.05 m, 0.10 m, 0.15 m, 0.30 m and 0.50 m - or to the snow-ice interface, whichever criteria is met first) represents the retracking point.*"

The 0.07 m is representative of the in situ interpolated snow data, for the other data sets we chose to display a range of possibilities through the 0.02, 0.05, 0.10, 0.15, 0.30 and 0.50 range. So in other words when the snow information has the least error 0.07 m is the most accurate *Pd*, given the range in snow provided by the other datasets it is necessary to show a larger range. 0.07 m would not produce the best results with the other products.

Editor's Comments:

The author's should consider each of the reviewers' comments when preparing their revised manuscript. However, to help expedite final acceptance, I note the following key points made by the reviewer that should be addressed. I have also added a couple of my own comments on a some points that I think could be made more clear. These additional comments are not meant as reviewer comments, but are easily addressed and would help improve the paper.

Both referees commented on the limited spatial range of the comparison, and very limited comparisons that can be made (only one point for ERA-I, and a few for AMSR-E). I agree with the reviewers that more discussion/qualification of the results with respect to the very limited comparison and atypical conditions for sea ice needs to be included.

The title has been amended, and McMurdo Sound has been specifically referred to in the abstract for a second time. We have also added to the conclusion and amended some text:

"*Sea ice in McMurdo Sound is atypical of Antarctic pack ice, so improved understanding of the CS-2 freeboard measurement over varying snow and sea ice conditions in open water areas will be critical to accurately provide sea ice thickness estimates for the Southern Ocean.*"

Title: Agree with reviewer #1, this is a specific region, and so the title should reflect that and not generalize.

Title has been amended to: "*Snow driven uncertainty in CryoSat-2 derived Antarctic sea ice thickness - insights from McMurdo Sound*"

The following sentence has also been added to the introduction:

"*The uncertainty associated with these two factors* [points 1 and 2 in the introduction] *has not been directly investigated using satellite altimeter information over Antarctic sea ice. This work provides insights from a case study region, McMurdo Sound Antarctica.*"

Initial conditions – As pointed out, the fastening date is not necessarily the onset of snow accumulation. The method used here could lead to some underestimation if snow had already accumulated – can you estimate how much it might have influenced results (though, snowmodel is biased high)?

Please see response to reviewer 1's comment above. The authors still support that the fastening date is a good measure to begin accumulation given the routine advection of pack ice north, at least in 2011. As the editor points out even if it were worth including additional snow accumulation days prior to fastening, it would cause a larger deviation of model datasets from in situ information.

I agree with the reviewer here wrt lines 454-456. While snowmodel as set up may require 200m resolution, you are not comparing at that resolution except with the in situ data in figure 4. At least based on your results, ERA-I does arguably better for CS-2 ice thickness, as reviewer #1 states (error range is lower in Figure 6). So the value demonstrated by snowmodel here appears to be in matching the spatial pattern of snow distribution, and as you discuss based on physical reasons one would expect snowmodel to be better. But in the manuscript at least, there isn't evidence that snowmodel improves CS-2 thickness estimates (see also comment below on Polar-WRF). You should be clear in your discussion what your results demonstrate, and what they do not.

This discussion point has changed given the correction to the ERA-I dataset, SnowModel is far superior to ERA-I. We are also using the higher resolution advantage of SnowModel to directly extract snow depth values with the 200 m grid cells for each 380 x 1560 m CS-2 altimeter retrieval. This should be the goal for future missions and modelling efforts to tie together the discrepancies in spatial scales between required data products. The best that is currently achieved by the other snow products in the study is 12 km.

Figure 2 – agree with reviewer #1, the dots are hard to see.

This figure has been replotted with different symbols.

Accuracy of results –I agree that the qualitative comparison between SnowModel and Figure 4 could be more informative if made quantitatively.

The aim of Figure 4 is to help the reader visualize the snow distribution as suggested by the reviewers in the previous revision. The authors agree this is important. Figure 3 displays quantitatively the difference between the in situ sites and Snow Model values.

Additional comments:

Line 412-414 –It is worth clarifying that the difference in Pd here is because of thickness, then you get a Pd that is the sum of the true Pd and a correction (Pde) that results from an error in your snow depth estimate (Tse):

$Pde = (pw-ps)/pw*(Tse) = 0.625Tse$.

So, if you have overestimated your snow depth, your apparent penetration depth is corresponding larger than the true one, and vice versa.

We have clarified this by adding "*This range in inferred thickness is driven by the amount of snow produced by the models as Eq. 1 and Eq. 2 subtract and add the product of this value in their second terms respectively. As the snow depth increases, in some cases to higher values than the measured freeboard the Pd simply provides a correcting factor for this discrepancy.*"

Pd = 0.5 m seems too high, given Figure 2 shows a mean snow depth of ~0.1m swe (i.e. ~0.3m actual). How can you have Pd=0.5m in this case? You do say you cut off Pd at the snow depth, but I don't see any evidence that 0.5m is correct for any of your products or in situ data. The correction above would imply you'd need to be off by 0.8 m in Ts, which seems implausible.

Figure 2 shows the mean swe for each fastening area, not the maximum values. Maximum values, especially in the east are far higher (see Figure 4a). Maximum values for swe for SnowModel are in the order of 20-30 cm swe and for ERA-I they are nearly 30 cm swe. This justifies plotting a 0.5 m (snow depth) *Pd*. *Pd* is cut off at the snow depth so is only applied when appropriate.

I think it is important you clarify what is going on here, and be clear that these Pd values you calculate are not necessarily indicative of what is actually happening with the radar reflection. Your conclusions do properly reflect this and rightly only give the value based on the in situ comparison.

Added in abstract:

"*Because of this ambiguity we vary the proportion of ice and snow that represents freeboard – a mathematical alteration of the radar penetration into the snow cover and assess this uncertainty in McMurdo Sound.*"

Added in section 2.4

"*We explore this possible range by changing the amount of snow and ice assumed to represent the freeboard measurement in the thickness equation. There is no physical change to the actual radar penetration, the inferred thickness is simply altered mathematically using a varying penetration depth (Pd) into the snow pack.*"

To summarise, we are taking the available snow products and producing one of our own. We combine these with altimetry and are then left with the further uncertainty associated with the mean scattering horizon. The reason for the *Pd* assessment is to explore the range of uncertainty

associated with this. There is no other way to show these results until the ambiguity is the CS-2 fb is better constrained. From the available data we can only say sea ice thickness is between x and y, and the range is very large.

One thing you did not point out is that snowmodel takes as its input precipitation from Polar-WRF, which will be different from ERA-I. So the comparison between ERA-I and snowmodel and in situ (at least for the CS-2 comparison) mostly just shows that the retrieval is sensitive to errors in snow depth, and not which method is necessarily better (snowmodel would presumably be better where, as you note, snow redistribution matters, but you have not shown that this is a factor here).

It is stated in the manuscript (L244-248 second version, L251-255 latest version) that hourly atmospheric forcing were generated by version 3.5 of the polar-optimized version of the Advanced Research Weather Research and Forecasting Model. The revised ERA-I dataset also now show that ERA-I is not suitable for retrieving sea ice thickness in this region at least.

476-478 - Note that while shot separation for icesat-2 is 0.7m, you won't get a sufficient number of photons to get a reliable elevation until you sample something like 100 shots. It is unlikely you will be able to resolve meter-scale features. Might be better here to say that you might want to resolve a statistical distribution of features to capture snow accumulation rates in the presence of blowing snow. (not essential, but you might pick a more recent reference for icesat-2 here, e.g. Markus et al., 2017).

Removed specific reference "*with an expected 0.7 m along-track sampling rate*" and added Markus et al., 2017 reference.

Also note that different retrackers pick different interface positions. This introduces an error in addition to Pd and snow depth estimation error that could be mentioned.

Noted, only one retracker is being used here so this error source is absent. I have specifically made comparison between retracking techniques in Price et al. (2015).

For figure 5, you match in part based on the slopes. But I believe the thought behind incomplete penetration into the snowpack is due to some physical scattering horizon, either an icy layer or perhaps wicked brine. Then could it be that Pd is at different depths at different times?

This is true and this was discussed in the previous response. The snow pack is particularly homogenous in this region so such physical influences on the scattering horizon should be at a minimum. It is also beyond the scope of this study to start trying to improve interpretation of the radar waveform, we are taking an elevation product from the ESA retracker and inferring thickness from those estimates.

Minor/technical points:

Line 61 – icesat-2 has successfully launched now, so this statement should be updated.

Corrected and changed to "*and NASA's laser altimeter mission ICESat-2*".

Section 2.3 – as pointed out by the reviewer, it isn't clear if you have calculated snow depth yourself or used an existing product. If the latter, the dataset used should be referenced.

Sentence amended to:

"*The snow depth product provided by NSIDC (https://nsidc.org/data/AE_SI12/versions/3#) is provided at a 12.5 x 12.5 km2 polar stereographic projection and reported as a 5-day running mean, that mean inclusive of that day and the prior 4 days.*"

Line 158 – should be "in coastal Antarctic" I think.

Sentence amended to "*The instrument has three modes and over the coastal Antarctic operates its interferometric (SIN) mode.*"

Line 180 – "but precisely how it is dependent"

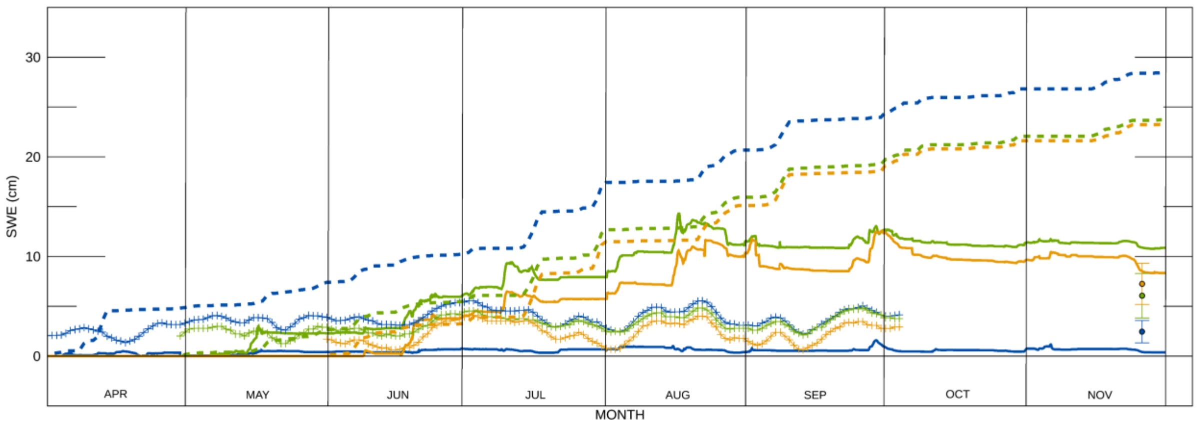
Commas added so this sentence is read correctly.

Line 269 – should be "see Hines et al., (2015)"

Amended.

Figure 4 – you might consider narrowing the scale here, your in situ measurements go up to ~15 cm, but your snowmodel scale goes to 180! It would be more clear if these scales were similar.

Scale amended.



Commented [DP1]: Old Figure 2 with underestimated ERA-I data as single dotted line for entire study area.

Commented [DP2]: New Figure 2 with correct ERA-I data with much higher accumulation rates. The ERA-I dataset was also interpolated into a 10 x 10 (12 km res) grid over the study region and also split up into three lines for each fastening area.

Manuscript mark-up

Snow driven uncertainty in CryoSat-2 derived Antarctic sea ice thickness - insights from McMurdo Sound

Daniel Price[1], Iman Soltanzadeh[2] & Wolfgang Rack[1], Ethan Dale[3]

[1]Gateway Antarctica, University of Canterbury, Private Bag 4800, Christchurch, New Zealand
[2]Met Service, 30 Salamanca Road, Kelburn, Wellington, 6012, New Zealand
[3]Department of Physics and Astronomy, University of Canterbury, Christchurch, New Zealand

Correspondence to: Daniel Price (daniel.price@canterbury.ac.nz)

Commented [DP3]: New title

Commented [DP4]: New author added

Commented [DP5]: Additional affiliation added for new author

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 captures the spatial snow distribution gradient in McMurdo Sound and falls within 2 cm snow water equivalent (swe) of *in situ* measurements across the entire study area. However, it 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, produces a very high mean swe value 20 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. Because of this ambiguity we vary the proportion of ice and snow that represents freeboard – a mathematical alteration of the radar penetration into the snow cover and assess this uncertainty in McMurdo Sound. The range in sea ice thickness uncertainty within these bounds, as means of the entire growth season are 1.08 m, 4.94 m and 1.03 m for SnowModel, ERA-Interim and AMSR-E respectively. Using an interpolated *in situ* snow dataset we find the best agreement between CS-2 derived and *in situ* thickness when this interface is assumed to be 0.07 m below the snow surface.

Commented [DP6]: Main results changed to mean annual range between Pd extremes to better express the uncertainty.

Commented [DP7]: Reworded

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 our ability to better understand the Antarctic sea ice system ~~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~~ large uncertainty 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 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.

The uncertainty associated with these two factors has not been directly investigated using satellite altimeter information over Antarctic sea ice. This work provides insights from a case study region, McMurdo Sound Antarctica. Snow on 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 via passive microwave sensors (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 laser altimeter mission ICESat-2. 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

Commented [DP8]: New sentence frames paper in regional context and provides scope.

other independent datasets, the first ERA-Interim (ERA-I) 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 ~~,~~ by varying the proportion of ice and snow that represents freeboard. ~~and~~ We compare the inferred CS-2 thicknesses with *in situ* information.

Commented [DP9]: Abbreviation added and used throughout.

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~~Additional *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.

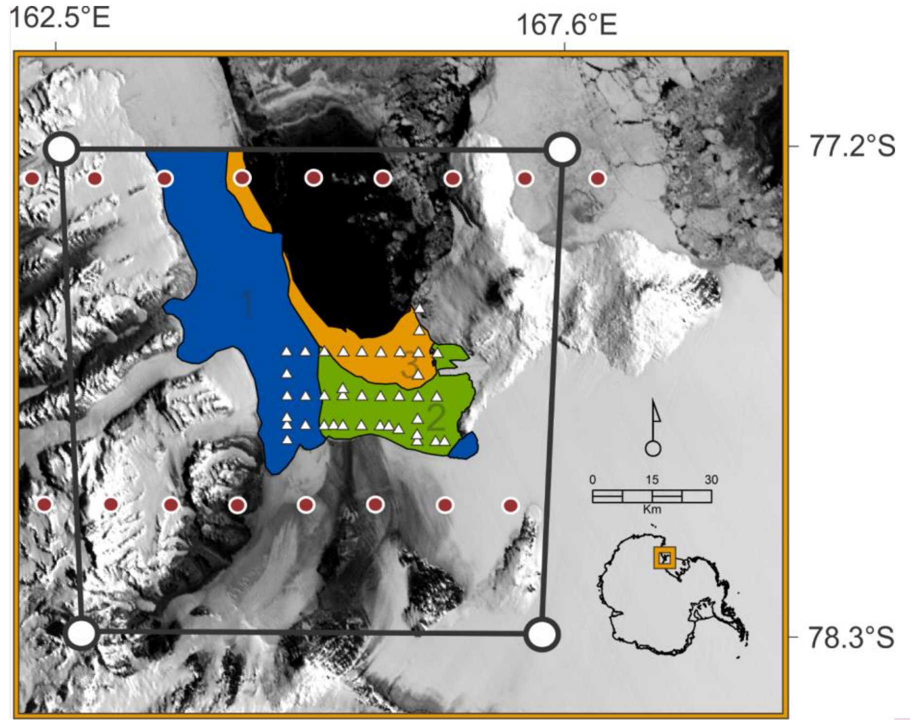


Figure 1. McMurdo Sound study area with each fastening area as identified by Envisat radar imagery: area 1 – 01/04/2011 (Blue), area 2 – 29/04/2011 (Green), area 3 – 01/06/2011 (Orange) and SnowModel domain bounded by the black box. Fastening areas are superimposed on a MODIS image acquired on 15 November 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 centre points of each ERA-I 0.75° x 0.75° grid cell in the vicinity of the study area are displayed as red circles.

Commented [DP10]: Amended Figure 1 to include ERA-I cell locations

Commented [DP11]: New sentence in reference to added ERA-I grid cells.

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. In McMurdo Sound during the freeze-up period, pack ice is generally advected north out of the study area unless it fastens. ~~Also,~~ In addition to floe movement, ~~snowfall,~~ before fastening occurs, snowfall 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. We process these files using ~~using~~ GAMMA Software to produce ASAR imagery with a spatial resolution of 150 x 150 m. By comparing motion and patterns between

Commented [DP12]: Added sentence.

Commented [DP13]: Sentence amended to include more detail on product processing.

sequential images we are able to identify three areas that fastened 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 found 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.

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 provided by NSIDC (https://nsidc.org/data/AE_SI12/versions/3#) is provided at 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.

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 over the coastal Antarctic operates its interferometric (SIN) mode. 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 5, to assess the usefulness of the evaluated snow products, we infer sea ice thickness from CS-2 freeboard measurements.

Commented [DP14]: Sentence amended to this.

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 fastening 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 undefined 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 changing the amount of snow and ice assumed to represent the freeboard measurement in the thickness equation. There is no physical change to the actual radar penetration, the inferred thickness is simply altered mathematically using a varying penetration depth (*Pd*) into the snow pack. 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 varying *Pd* values into the snow pack (0.02 m, 0.05 m, 0.10 m, 0.15 m, 0.30 m and 0.50 m - or to the snow-ice interface, whichever criteria is met first) represents the retracking point. 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;

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

Commented [DP15]: Removed '1' typo from before 'undefined'

Commented [DP16]: Comma added.

Commented [DP17]: Comma added.

Commented [DP18]: Rewritten to provide clarity on the Pd method.

Commented [DP19]: Sentence amended to this

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

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

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.~~ ρ_S is the mean value taken from 18 of the 39 *in situ* sites where snow density was measured.

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.

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.

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)].

Commented [DP20]: Corrected

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). Model outputs 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.

3.2 Low resolution model

ERA-I 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. Using splines we interpolate the coarse resolution ERA-I grid and provide a 10 x 10 grid over the study area with a cell resolution of 12 km. The reanalysis does not account for snow transport but with the interpolated grid we are able to segment the model for sea ice fastening dates and begin snow accumulation at the correct time. We average the three hourly outputs, the reported ERA-I data are daily averages for each fastening area.

~~ERA-I 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-I 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-I grid.~~

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-I 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 each snow product segmented by each fastening area, ~~1-3,~~ and this time series is the mean snow depth for each product within each area (Fig. 2). ~~ERA-I 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 and ERA-I distributions ~~is~~ are plotted as ~~a~~ maps at the end of the model run for spatial comparison ~~to the in situ dataset~~ (Fig. 4). The SwowModel ~~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.

Commented [DP21]: Rewritten

Formatted: Font: Italic

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 broad spatial distribution produced by SnowModel 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 fastening 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 coincident pixels are directly compared to *in situ* data 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~~ visible in Figure 4a. Values in the eastern most section of the sea ice cover in McMurdo Sound, adjacent to Ross Island are in the

Commented [DP22]: Amended.

order of 20 to 35 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. 4a). The western region of sea ice in fastening area 1 has far less measured snow. The model produces this well but values are too low. The extremes, where there is a lot of snow and where there is very little snow both seem to be exaggerated by the model.

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. ERA-I also produces a different snow distribution to SnowModel and *in situ* data (Fig. 4b) with an area of lower swe values in the central area of the fast ice and higher swe values over the western and eastern areas. The mean deviation over the entire study area from *in situ* measurements is 20 cm swe. ERA-I swe values are over double that of SnowModel for areas 2 and 3 and an order of magnitude higher for area 1 (Fig. 2). The ERA-I temporal snowfall pattern is the same between all areas and is similar to that produced by Snow Model in areas 2 and 3.

ERA-I 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-I 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-I shows better agreement with AMSR-E during this time period.

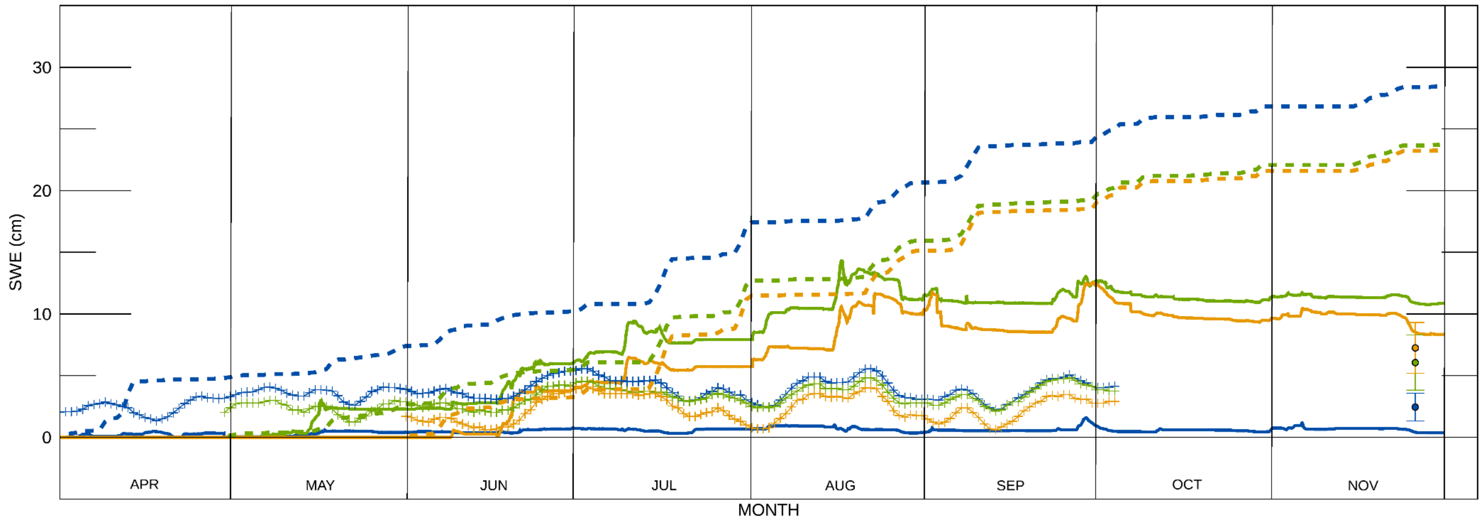


Figure 2. SnowModel hourly (solid lines), ERA-I daily (hashed lines) snow water equivalent (swe) accumulation and AMSR-E daily snow depth (crosses) converted to swe for freeze-up areas 1 (blue), 2 (green) and 3 (orange). The mean *in situ* swe and standard deviations for each area are displayed as circles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

Commented [DP23]: Amended Figure 2 including ERA-I dataset segmented for freeze-up areas.

Commented [DP24]: Amended figure caption.

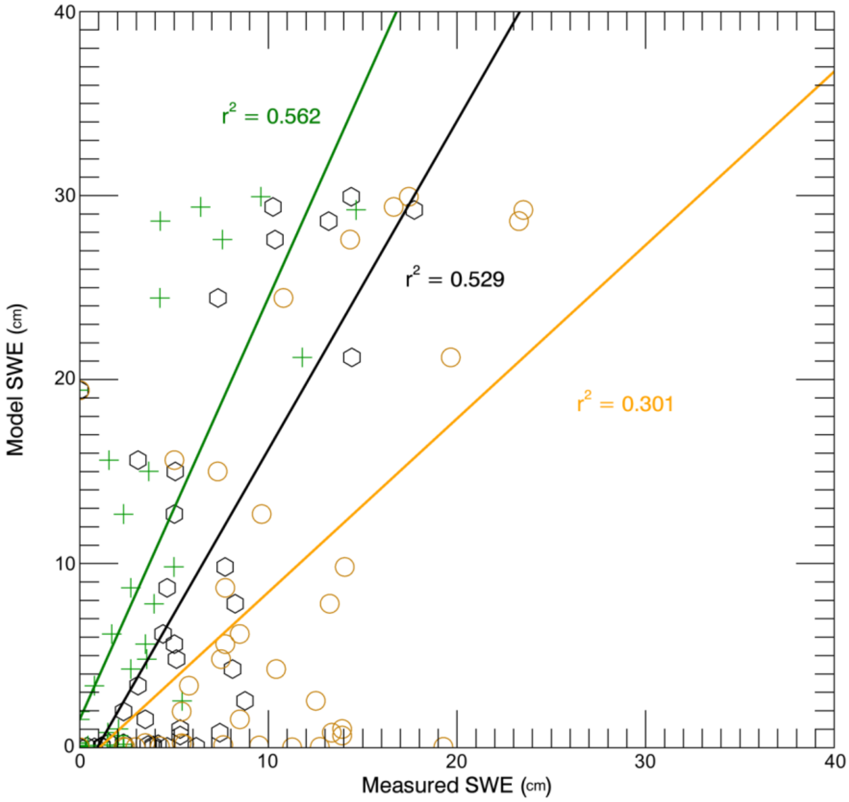
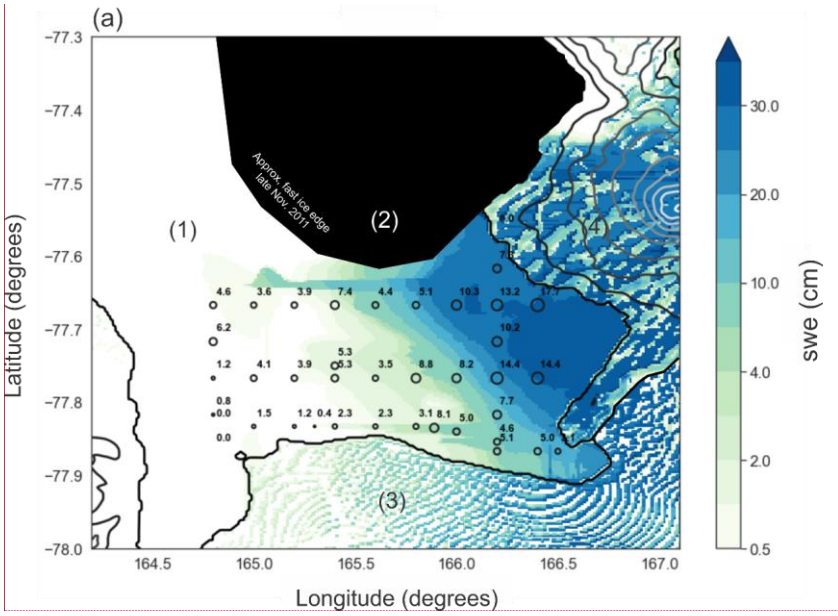
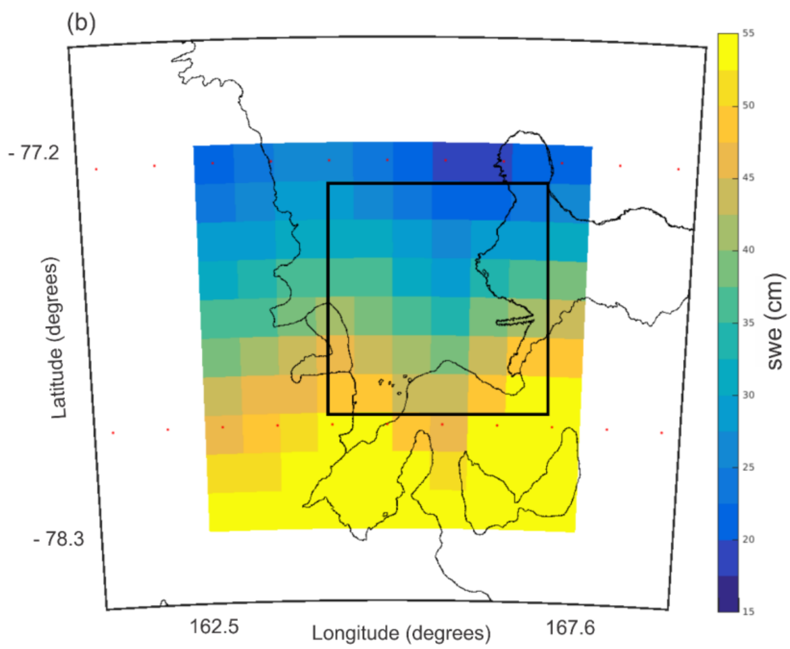


Figure 3. Mean (black), maximum (green) and minimum (orange) *in situ* measured snow water equivalent (swe) for each site against mean SnowModel swe at each coincident model cell for the *in situ* measurement period.



Commented [DP25]: New Figure 4 with amended swe scale



Commented [DP26]: New Figure 4 (b) displaying ERA-I snow accumulation grid.

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 (3,794 m) is the dominant topographic feature on Ross Island to the east of the fast ice. The interpolated 10 x 10 ERA-I grid with 1st December accumulation total, the boundary of the SnowModel inset from (a) is shown as the black box. The ERA-I centre points of the original grid are displayed as red dots.

Commented [DP27]: Addition to Figure 4 caption referring to (b)

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-I 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.

From equations 1-3, sea ice thickness is highly sensitive to the snow-ice ratio ~~for~~ of the measured freeboard. This results in a large range in sea ice thickness for all snow products through the growth season (Fig. 5). This range in inferred thickness is driven by the amount of snow produced by the models as Eq. 1 and Eq. 2 subtract and add the product of this value in their second terms respectively. ~~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 remain relatively stable for the duration of the study. Because of this, the ratio of ice to snow above the waterline remains very similar. In the case of the models, snow depths gradually increase and snow makes up an ever increasing proportion of mass above the waterline. If the air-snow interface (Eq. 1) is taken to represent *Fb* then the trend in sea ice thickness through the growth season is negative for SnowModel and ERA-I derived thicknesses and if the snow-ice interface (Eq. 2) is assumed the trend is too positive. The trends are more extreme for the ERA-I estimates simply because the snow loading is greater. The range in uncertainty between Eq. 1 and Eq. 2 derived thickness as means of available data for the entire growth season are 1.08 m, 4.94 m and 1.03 m for SnowModel, ERA-I and AMSR-E respectively. The mean CS-2 derived thickness values for November using Eq.1 and Eq. 2 are 1.02 m (-2.98 m) for SnowModel (ERA-I) and 2.62 m (6.59 m) for SnowModel (ERA-I) respectively compared to an *in situ* thickness of 2.4 m. The mean CS-2 derived thickness values for November are 2.62 m and 2.77 m for SnowModel and ERA-I 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 the models~~SnowModel~~ to match *in situ* thickness ~~a~~ large *Pd* values of 0.5 m are~~is~~ required given the higher snow depth values.~~,~~ These values are lower for AMSR-E as the snow loading is less.~~while for ERA-I *Pd* values of 0.1 to 0.15 m place CS-2 thickness estimates closer to *in situ* thickness.~~

The differences in the snow depths from each model result make ~~if~~it difficult to constrain what *Pd* value provides CS-2 thicknesses that agree best with measured thickness. To assess the penetration uncertainty further we use~~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 *in 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-I data set is very large at 5.7 m~~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~~ERA-I. The deeper snow creates a larger range of snow-to-ice ratios for freeboard.~~.~~

Commented [DP28]: Rewritten

Formatted: Font: Italic

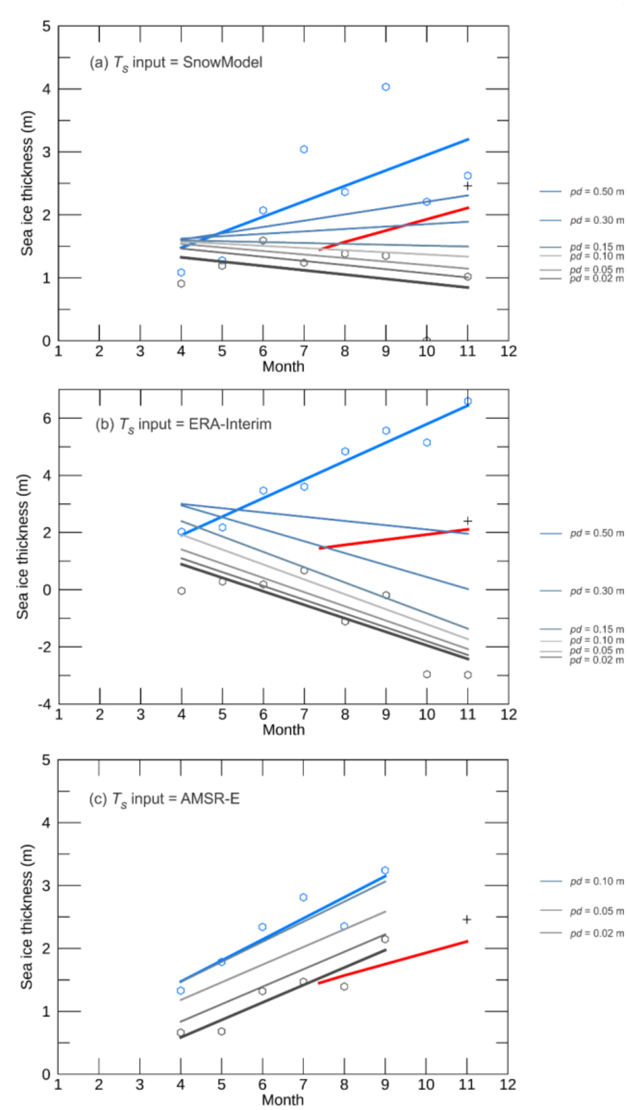


Figure 5. Sea ice thickness trends derived by CS-2 freeboard measurements with snow data provided by (a) SnowModel, (b) ERA-I and (c) AMSR-E. Grey dots and bold linear fit are sea ice thickness calculated using equation 1, blue dots and bold linear fit using equation 2 and thin lines between them equation 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).

Commented [DP29]: New Figure 5 including revised ERA-I data

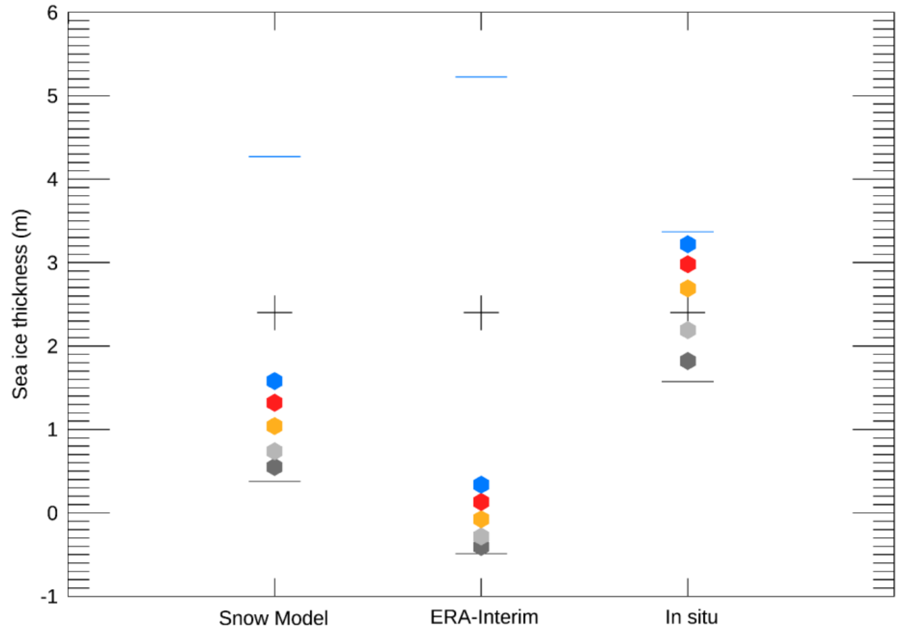


Figure 6. The range in CS-2 derived sea ice thickness in November using snow inputs from SnowModel and ERA-I compared to snow input from *in situ* interpolated snow depths. Thickness derived from equations 1 and 2 are shown with the grey and blue lines respectively and for equation 3 the dots are colour 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).

Commented [DP30]: New Figure 6 including revised ERA-I data

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.

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. ERA-I performance would be worse in all cases, AMSR-E would not be impacted as it is a real-time snow depth measurement. 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.

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 (Markus et al., 2017). 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.

Commented [DP31]: Specific reference to 0.7 m removed and more recent reference added.

We find the ERA-I mean swe to be 20 cm higher than mean *in situ* swe in McMurdo Sound. In area 1 ERA-I swe is an order of magnitude higher than *in situ* swe, while in areas 2 and 3 it is over double the value. These create very high, unrealistic snow depths which causes a large range in CS-2 derived thickness using Eqs. 1-3. This is a very poor result and the product is inadequate to infer sea ice thickness when combined with altimetry data. Of further interest is that the clear longitudinal gradient in snow depth as indicated by SnowModel and measured *in situ* (November only) is not produced by ERA-I, swe values are lower in the central fast ice area and higher in the western and eastern areas. The performance of ECMWF reanalysis products over the satellite period has been reported as 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-I 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-I 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.~~ A first step to improve reanalysis results will be to incorporate snow redistribution (including snow loss to leads) and parameterisations for this could be built from wind vectors provided by the same reanalysis data.

Commented [DP32]: Rewritten for updated ERA-I results.

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.~~ The decreasing snow distribution gradient from east to west is again, like ERA-I, reversed 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 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-I 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, a simple consequence of the density dependent hydrostatic equilibrium assumption.. By using the interpolated *in situ* measured snow depth as the snow thickness input to the thickness calculation, ~~we minimised~~ the error is minimised. 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).

~~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-I) 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.~~ Having confidence in the results assumes that the sea surface height has been accurately identified for each CS-2 track. 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 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. A changing ρ_s through the growth season was not applied to the CS-2 thickness analysis but this source or uncertainty must also be considered in larger scale assessments.

Commented [DP33]: Removed, doesn't add a huge amount and is confusing to the reader.

7 Conclusions

This work has evaluated the ability of three independent techniques to provide snow depth on fast ice in the coastal Antarctic. SnowModel accurately captures the *in situ* measured snow distribution 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-I swe is 20 cm higher than *in situ* measurements and the gradient of the snow distribution produced by the analysis does not match~~is opposite to~~ that measured *in situ*. A positive bias in accumulation should be expected from ERA-I as no snow redistribution mechanism is included. Any future work making use of precipitation reanalysis over Antarctic sea ice must include snow redistribution by wind, shown here by SnowModel to improve results. 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~~ two 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. The range in sea ice thickness uncertainty from the assumption that the snow surface or ice surface represents freeboard, as means of the entire growth season are 1.08 m, 4.94 m and 1.03 m for SnowModel, ERA-Interim and AMSR-E respectively. Using interpolated *in situ* snow information, ~~Here,~~ we find CS-2 freeboard measurements provided by the ESA retracker agree best with *in situ* measured thickness if ~~are most likely representative~~

Commented [DP34]: Rewritten

~~of~~ a ~~mean~~ dominant scattering horizon 0.07 m beneath the air-snow interface is assumed, 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. This work demonstrates the need to reduce the uncertainty associated with the ambiguity of the altimeter radar freeboard measurement over Antarctic sea ice. Sea ice in McMurdo Sound is atypical of Antarctic pack ice, so improved understanding of the CS-2 freeboard measurement over varying snow and sea ice conditions in open water areas will be critical to accurately provide sea ice thickness estimates for the Southern Ocean.

Commented [DP35]: New sentence added.

Commented [DP36]: Added text and amended final sentence of paragraph.

Here, we show that modelled snow information has the potential to produce a time series of snow depth on Antarctic sea ice. However, major developments in modelling capability are required before their snow products can provide useful information for use in combination with altimetry data to provide sea ice thickness. ~~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, especially where snow depth is high and passive microwave techniques are non-informative.

Commented [DP37]: Added.

8 Acknowledgments

Gratitude is shown for the support of Antarctica New Zealand and Scott Base staff during the 2011/12 Antarctic field season permitting the collection of *in situ* snow and sea ice measurements, and the members of field team K053. ~~We thank Ethan Dale for compiling and providing ERA-I data.~~ Thanks is given to Oliver Marsh and Christian Wild for productive discussions about the topic. This work was partially supported by NIWA subcontract C01X1226 (Ross Sea Climate and Ecosystem) and the Marsden Fund Council from Government funding, managed by Royal Society Te Apārangi. We are grateful to Victoria Landgraf, Troy Beaumont, and Grant Cottle from Antarctica New Zealand's Scott Base 2011 winter-over team for making the July sea ice thickness measurements as part of the winter support of a University of Otago Research Grant funded project (PI: Pat Langhorne, AI: Inga Smith). We thank Peter Green and Inga Smith for their insights into the 2011 sea ice growth rates, which were supported by the fieldwork and analytical efforts of Greg Leonard, Alex Gough, Tim Haskell, Pat Langhorne, Jonothan Everts, and by the technical advice of Joe Trodahl and Daniel Pringle, and the technical support of Myles Thayer, Peter Stroud and Richard Sparrow. A final thanks is given to Eamon Frazer and Pat Langhorne for the time given to discussions about and analysis of seawater density in the study region. This research was completed at Gateway Antarctica, University of Canterbury, Christchurch, New Zealand.

9 References

Commented [DP38]: Abdalati reference removed.

Agustsson, H., and Olafsson, H.: Simulating a severe windstorm in complex terrain. Meteorol Atmos Phys., 103, 173–185, doi: 10.1007/s00703-008-0347-y, 2007.

Armitage, T. W. K., and Davidson, M. W. J.: Using the Interferometric Capabilities of the ESA CryoSat-2 Mission to Improve the Accuracy of Sea Ice Freeboard Retrievals, in IEEE Transactions on Geoscience and Remote Sensing., vol. 52, no. 1, pp. 529-536, doi: 10.1109/TGRS.2013.2242082, 2014.

Beaven, S. G., Lockhart, G. L., Gogineni, S. P., Hossetnmostafa, A. R., Jezek, K., Gow, A. J., Perovich, D. K., Fung, A. K., and Tjuatja, S.: Laboratory measurements of radar backscatter from bare and snow-covered saline ice sheets. International Journal of Remote Sensing, 16, 851-876, 1995.

Bouffard, J.: CryoSat-2 Level 2 product evolutions and quality improvements in Baseline C. Available at: https://earth.esa.int/documents/10174/1773005/C2-Evolution-BaselineC-Level2-V3. 2015

Bromwich, D.H., Hines K.M., and Bai, L.S.: Development and testing of Polar WRF: 2. Arctic Ocean, J. Geophys. Res., 114, D08122, doi: 10.1029/2008JD010300, 2009.

Bromwich, D. H., and Fogt, R. L.: Strong Trends in the Skill of the ERA-40 and NCEP–NCAR Reanalyses in the High and Midlatitudes of the Southern Hemisphere, 1958–2001, Journal of Climate., 17, 4603-4619, doi: 10.1175/3241.1, 2004.

Chen, F., and Dudhia, J.: Coupling an Advanced Land Surface–Hydrology Model with the Penn State–NCAR MM5 Modeling System. Part I: Model Implementation and Sensitivity, Monthly Weather Review., 129, 569-585, doi: 10.1175/1520-0493(2001)129<0569:CAALSH>2.0.CO;2, 2001.

Comiso, C., Cavalieri, J. & Markus, T.: Sea Ice Concentration, Ice Temperature, and Snow Depth Using AMSR-E Data, IEEE Transactions on Geoscience and Remote Sensing., 41, 243-252, doi: 10.1109/TGRS.2002.808317, 2003.

Dee, D. P., Uppala, S. M., Simmons, A. J., Berrisford, P., Poli, P., Kobayashi, S., Andrae, U., Balmaseda, M. A., Balsamo, G., Bauer, P., Bechtold, P., Beljaars, A. C. M., van de Berg, L., Bidlot, J., Bormann, N., Delsol, C., Dragani, R., Fuentes, M., Geer, A. J., Haimberger, L., Healy, S. B., Hersbach, H., Hólm, E. V., Isaksen, L., Kållberg, P., Köhler, M., Matricardi, M., Mcnally, A. P., Monge-Sanz, B. M., Morcrette, J. J., Park, B. K., Peubey, C., De Rosnay, P., Tavolato, C., Thépaut, J. N., and Vitart, F.: The ERA-I reanalysis: configuration and performance of the data assimilation system, Quarterly Journal of the Royal Meteorological Society., 137, 553-597, doi: 10.1002/qj.828, 2011.

Drinkwater, M.: 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, 1991.

Dudhia, J.: Numerical study of convection observed during the winter monsoon experiment using a mesoscale two-dimensional model, Journal of Atmospheric Sciences., 46, 3077-3107, doi: 10.1175/1520-0469(1989)046<3077:NSOCOD>2.0.CO;2, 1989.

Fichefet, T., and Maqueda, M. A. M.: Modelling the influence of snow accumulation and snow-ice formation on the seasonal cycle of the Antarctic sea-ice cover, Climate Dynamics., 15, 251-268, doi: 10.1007/s003820050280, 1999.

Frazer, E. K., Langhorne, P. J., Williams, M. J. M., Goetz, K. T., and Costa, D. P.: A method for correcting seal-borne oceanographic data and application to the estimation of regional sea ice thickness, Journal of Marine Systems., doi: 10.1016/j.jmarsys.2018.08.002, 2018.

Giles, K. A., Laxon, S. W., and Worby, A. P.: Antarctic sea ice elevation from satellite radar altimetry, Geophysical Research Letters., 35, L03503, doi: 10.1029/2007GL031572, 2008.

Gough, A. J., Mahoney, A. R., Langhorne, P. J., Williams, M. J. M., and Haskell, T. G.: Sea ice salinity and structure: A winter time series of salinity and its distribution, Journal of Geophysical Research: Oceans., 117, C03008, doi:10.1029/2011JC007527, 2012.

Hallikainen, M., Ulaby, F., and Abdelrazik, M.: Dielectric properties of snow in the 3 to 37 GHz range, IEEE Transactions on Antennas and Propagation., 34, 1329-1340, 1986.

Hendricks, S, Stenseng, L, Helm, V., and Haas, C.: 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, 2010.

Hines, K. M., Bromwich, D. H., Bai, L., Bitz, C. M., Powers, J. G., and Manning, K. W. Sea Ice Enhancements to Polar WRF, Monthly Weather Review., 143, 2363-2385, doi: 10.1175/MWR-D-14-00344.1, 2015.

Hong, S.-Y., and Lim, J.-O. J.: The WRF Single-Moment 6-Class Microphysics Scheme (WSM6), Journal of the Korean Meteorological Society., 42, 129-151, 2006.

Kaleschke, L., Tian-kunze, X., Maaß, N., Mäkynen, M., and Drusch, M.: Sea ice thickness retrieval from SMOS brightness temperatures during the Arctic freeze-up period, Geophysical Research Letters., 39, L05501, doi: 10.1029/2012GL050916, 2012.

Kern, S., and Ozsoy-Çiçek, B.: Satellite Remote Sensing of Snow Depth on Antarctic Sea Ice: An Inter-Comparison of Two Empirical Approaches, Remote Sensing., 8(6), 450, doi: 10.3390/rs8060450, 2016.

Kern, S., Ozsoy-Çiçek, B., Willmes, S., Nicolaus, M., Haas, C. & Ackley, S.: An intercomparison between AMSR-E snow-depth and satellite C- and Ku-band radar backscatter data for Antarctic sea ice, Annals of Glaciology., 52(57), 279-290. doi:10.3189/172756411795931750, 2011.

King, J., Skourup, H., Hvidegaard, S. M., Rosel, A., Gerland, S., Spreen, G., Polashenski, C., Helm, V., and Liston, G. E.: Comparison of freeboard retrieval and ice thickness calculation from ALS, ASIRAS, and CryoSat-2 in the Norwegian Arctic to field measurements made during the N-ICE2015 expedition, Journal of Geophysical Research: Oceans., 123, 1123–1141, doi: 10.1002/ 2017JC013233, 2018.

Kurtz, N. T., Galin, N., and Studinger, M.: An improved CryoSat-2 sea ice freeboard retrieval algorithm through the use of waveform fitting, The Cryosphere., 8, 1217-1237, https://doi.org/10.5194/tc-8-1217-2014, 2014.

Kurtz, N. T., and Markus, T.: Satellite observations of Antarctic sea ice thickness and volume, Journal of Geophysical Research: Oceans., 117, C08025, doi: 10.1029/2012JC008141, 2012.

Kwok, R.: Simulated effects of a snow layer on retrieval of CryoSat-2 sea ice freeboard, Geophysical Research Letters., 41, 5014–5020, doi: 10.1002/2014GL060993, 2014.

Kwok, R., and Cunningham, G. F.: ICESat over Arctic sea ice: Estimation of snow depth and ice thickness, Journal of Geophysical Research: Oceans., 113, C08010, doi: 10.1029/2008JC004753, 2008.

Kwok, R., Nghiem, S. V., Yueh, S. H., and Huynh, D. D.: Retrieval of thin ice thickness from multifrequency polarimetric SAR data, Remote Sensing of Environment., 51, 361-374, doi: 10.1016/0034-4257(94)00017-H, 1995.

Laxon, S., Peacock, N. & Smith, D.: High interannual variability of sea ice thickness in the Arctic region, Nature., 425, 947-950, doi: 10.1038/nature02050, 2003.

Laxon, S. W., Giles, K. A., Ridout, A. L., Wingham, D. J., Willatt, R., Cullen, R., Kwok, R., Schweiger, A., Zhang, J., Haas, C., Hendricks, S., Krishfield, R., Kurtz, N., Farrell, S., and Davidson, M.: CryoSat-2 estimates of Arctic sea ice thickness and volume, Geophysical Research Letters., 40, 732-737, doi: 10.1002/grl.50193, 2013.

Leonard, K. C., and Maksym, T.: The importance of wind-blown snow redistribution to snow accumulation on Bellingshausen Sea ice, Annals of Glaciology., 52, 271-278, doi: 10.3189/172756411795931651, 2011.

Liston, G. E., Polashenski, C. , Rösel, A. , Itkin, P. , King, J. , Merkouriadi, I., and Haapala, J.: A Distributed Snow Evolution Model for Sea Ice Applications (SnowModel), J. Geophys. Res. Oceans., Accepted Author Manuscript, doi:10.1002/2017JC013706, 2018.

Liston, G. E., and Hiemstra, C. A.: Representing Grass– and Shrub–Snow–Atmosphere Interactions in Climate System Models, Journal of Climate., 24, 2061-2079, doi: 10.1175/2010JCLI4028.1, 2011.

Liston, G. E., and Hiemstra, C. A.: A Simple Data Assimilation System for Complex Snow Distributions (SnowAssim), Journal of Hydrometeorology., 9, 989-1004, doi: 10.1175/2008JHM871.1, 2008.

Liston, G. E., Haehnel, R. B., Sturm, M., Hiemstra, C. A., Berezovskaya, S., and Tabler, R. D. Instruments and Methods Simulating complex snow distributions in windy environments using SnowTran-3D, Journal of Glaciology., 53, 241-256, doi: 10.3189/172756507782202865, 2007.

Liston, G. E., and Elder, K.: A Distributed Snow-Evolution Modeling System (SnowModel), Journal of Hydrometeorology., 7, 1259-1276, doi: 10.1175/JHM548.1, 2006a.

Liston, G. E., and Elder, K.: A Meteorological Distribution System for High-Resolution Terrestrial Modeling (MicroMet), Journal of Hydrometeorology., 7, 217-234, doi: 10.1175/JHM486.1, 2006b.

Liston, G. E., and Winther, J.-G.: Antarctic Surface and Subsurface Snow and Ice Melt Fluxes, Journal of Climate., 18, 1469-1481, doi: 10.1175/JCLI3344.1, 2005.

Liston, G. E., Pielke, R. A., and Greene, E. M.: Improving first-order snow-related deficiencies in a regional climate model, Journal of Geophysical Research: Atmospheres., 104, 19559-19567, doi: 10.1029/1999JD900055, 1999.

Liston, G. E. & Sturm, M.: A snow-transport model for complex terrain, Journal of Glaciology., 44, 498-516, doi: 10.3189/S0022143000002021, 1998.

Maksym, T., and Markus, T.: Antarctic sea ice thickness and snow-to-ice conversion from atmospheric reanalysis and passive microwave snow depth, Journal of Geophysical Research: Oceans., 113, C02S12, doi:10.1029/2006JC004085, 2008.

Markus, T., Neumann, T., Martino, A., Abdalati, W., Brunt, K., Csatho, B., Farrell, S., Fricker, H., Gardner, A., Harding, D., Jasinski, M., Kwok, R., Magruder, L., Lubin, D., Luthcke, S., Morison, J., Nelson, R., Neuenschwander, A., Palm, S., Popescu, S., Shum, C.K., Schutz, B.E. Smith, B., Yang, Y., and Zwally, J.: The Ice, Cloud, and land Elevation Satellite-2 (ICESat-2): Science requirements, concept, and implementation, Remote Sensing of Environment., 190, 260-273, doi: 10.1016/j.rse.2016.12.029, 2017.

Commented [DP39]: Reference added.

Markus, T., and Cavalieri, D. J.: Snow Depth Distribution Over Sea Ice in the Southern Ocean from Satellite Passive Microwave Data. Antarctic Sea Ice: Physical Processes, Interactions and Variability, American Geophysical Union, M. O. Jeffries (Ed.), doi:10.1029/AR074p0019, 1998.

Markus, T., and Cavalieri, D. J.: Interannual and regional variability of Southern Ocean snow on sea ice, Annals of Glaciology., 44, 53-57, doi: 10.3189/172756406781811475, 2006.

Massom, R. A., Eicken, H., Hass, C., Jeffries, M. O., Drinkwater, M. R., Sturm, M., Worby, A. P., Wu, X., Lytle, V. I., Ushio, S., Morris, K., Reid, P. A., Warren, S. G., and Allison, I.: Snow on Antarctic sea ice, Reviews of Geophysics., 39(3), 413–445, doi:10.1029/2000RG000085, 2001.

Maykut, G., and Untersteiner, N.: Some results from a time dependent thermodynamic model of sea ice, J. Geophys. Res., 76, 1550-1575, 1971.

Mernild, S.H., Liston, G.E., Hasholt, B., and Knudsen, N.T.: Snow distribution and melt modeling for Mittivakkat Glacier, Ammassalik Island, southeast Greenland, J. Hydrometeorology., 7, 808-824, doi: 10.1175/JHM522.1, 2006.

Mlawer, E. J., Taubman, S. J., Brown, P. D., Iacono, M. J., and Clough, S. A.: Radiative transfer for inhomogeneous atmospheres: RRTM, a validated correlated-k model for the longwave, Journal of Geophysical Research: Atmospheres., 102, 16663-16682, 1997.

Nakanishi, M.: Improvement of the Mellor-Yamada turbulence closure model based on large-eddy simulation data, Boundary Layer Meteorology., 99, 349-378, doi: 10.1023/A:1018915827400, 2001.

Nakanishi, M., and Niino, H.: An Improved Mellor–Yamada Level-3 Model with Condensation Physics: Its Design and Verification, Boundary-Layer Meteorology., 112, 1-31, doi:10.1023/B:BOUN.0000020164.04146.98, 2004.

Nakanishi, M., and Niino, H.: An Improved Mellor–Yamada Level-3 Model: Its Numerical Stability and Application to a Regional Prediction of Advection Fog, Boundary-Layer Meteorology., 119, 397-407, doi: 10.1007/s10546-005-9030-8, 2006.

Nicolas, J. P., and Bromwich, D. H.: Precipitation Changes in High Southern Latitudes from Global Reanalyses: A Cautionary Tale, Surveys in Geophysics., 32, 475-494, doi: 10.1007/s10712-011-9114-6, 2011.

Olafsson, H., and Agustsson H.: Gravity wave breaking in easterly flow over Greenland and associated low level barrier-and reverse tip-jets, Meteorol. Atmos. Phys., 104, 191-197, doi: 10.1007/s00703-009-0024-9, 2009.

Pope, A., Wagner, P., Johnson, R., Shutler, J. D., Baeseman, J., and Newman, L.: Community review of Southern Ocean satellite data needs, Antarctic Science., 29, 97-138, doi: 10.1017/S0954102016000390, 2016.

Price, D., Beckers, J., Ricker, R., Kurtz, N., Rack, W., Haas, C., Helm, V., Hendricks, S., Leonard, G., and Langhorne, P. J.: Evaluation of CryoSat-2 derived sea-ice freeboard over fast ice in McMurdo Sound, Antarctica, Journal of Glaciology., 61, 285-300, doi: 10.3189/2015JoG14J157, 2015.

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, doi: 10.5194/tc-8-1031-2014, 2014.

Purdie, C. R., Langhorne, P. J., Leonard, G. H., and Haskell, T. G.: Growth of first-year landfast Antarctic sea ice determined from winter temperature measurements, Annals of Glaciology., 44, 170-176, doi: 10.3189/172756406781811853, 2006.

Ricker, R., Hendricks, S., Helm, V., Skourup, H., and Davidson, M.: Sensitivity of CryoSat-2 Arctic sea-ice freeboard and thickness on radar-waveform interpretation, The Cryosphere., 8, 1607-1622, doi: 10.5194/tc-8-1607-2014, 2014.

Ricker, R., Hendricks, S., Kaleschke, L., Tian-Kunze, X., King, J., and Haas, C.: A weekly Arctic sea-ice thickness data record from merged CryoSat-2 and SMOS satellite data, The Cryosphere., 11, 1607-1623, doi: 10.5194/tc-11-1607-2017, 2017.

Schwegmann, S., Rinne, E., Ricker, R., Hendricks, S., and Helm, V.: About the consistency between Envisat and CryoSat-2 radar freeboard retrieval over Antarctic sea ice, The Cryosphere., 10, 1415-1425, doi: 10.5194/tc-10-1415-2016, 2016.

Skamarock, W. C., Klemp, J. B., Dudhia, J., Gill, D. O., Barker, D. M., Duda, M. G., Huang, X.-Y., Wang, W., and Powers, J. G.: A Description of the Advanced Research WRF Version 3, NCAR Technical Note, 2008.

Stroeve, J. C., Markus, T., Maslanik, J. A., Cavalieri, D. J., Gasiewski, A. J., Heinrichs, J. F., Holmgren, J., Perovich, D. K., and Sturm, M.: Impact of Surface Roughness on AMSR-E Sea Ice Products, IEEE Transactions on Geoscience and Remote Sensing., 44, 3103-3117, doi: 10.1109/TGRS.2006.880619, 2006.

Warren, S. G., Rigor, I. G., Untersteiner, N., Radionov, V. F., Bryazgin, N. N., Aleksandrov, Y. I., and Colony, R.: Snow Depth on Arctic Sea Ice, Journal of Climate., 12, 1814-1829, doi: 10.1175/1520-0442(1999)012<1814:SDOASI>2.0.CO;2, 1999.

Willatt, R. C., Giles, K. A., Laxon, S. W., Stone-Drake, L., and Worby, A. P.: Field Investigations of Ku-Band Radar Penetration Into Snow Cover on Antarctic Sea Ice, IEEE Transactions on Geoscience and Remote Sensing., 48, 365-372, doi: 10.1109/TGRS.2009.2028237, 2010.

Wingham, D. J., Francis, C. R., Baker, S., Bouzinac, C., Brockley, D., Cullen, R., De Chateau-Thierry, P., Laxon, S. W., Mallow, U., Mavrocordatos, C., Phalippou, L., Ratier, G., Rey, L., Rostan, F., Viau, P., and Wallis, D. W.: CryoSat: A mission to determine the fluctuations in Earth’s land and marine ice fields, Advances in Space Research., 37, 841-871, doi: 10.1016/j.asr.2005.07.027, 2006.

Worby, A. P., Geiger, C. A., Paget, M. J., Woert, M. L. V., Ackley, S. F., and DeLiberty, T. L.: Thickness distribution of Antarctic sea ice, Journal of Geophysical Research: Oceans., 113, C05S92, doi: 10.1029/2007JC004254, 2008a.

Worby, A. P., Markus, T., Steer, A. D., Lytle, V. I., and Massom, R. A.: Evaluation of AMSR-E snow depth product over East Antarctic sea ice using in situ measurements and aerial photography, Journal of Geophysical Research: Oceans., 113, C05S94, doi: 10.1029/2007JC004181, 2008b.

Wu, X., Budd, W. F., Lytle, V. I., and Massom, R. A.: The effect of snow on Antarctic sea ice simulations in a coupled atmosphere-sea ice model, Climate Dynamics., 15, 127-143, doi: 10.1007/s003820050272, 1999.