Spatio-temporal variability and decadal trends of snowmelt processes on Antarctic sea ice observed by satellite scatterometers

Stefanie Arndt[1], Christian Haas[1]

[1]Alfred-Wegener-Institut Helmholtz-Zentrum für Polar- und Meeresforschung, 27570 Bremerhaven, Germany

Correspondence to: Stefanie Arndt (stefanie.arndt@awi.de)

Abstract. The timing and intensity of snowmelt processes on sea ice are key drivers determining the seasonal sea-ice energy and mass budgets. In the Arctic, satellite passive microwave and radar observations have revealed a trend towards an earlier snowmelt onset during the last decades, which is an important aspect of Arctic amplification and sea ice decline. Around Antarctica, snowmelt on perennial ice is weak and very different than in the Arctic, with most snow surviving the summer. Here we compile time series of snowmelt-onset dates on seasonal and perennial Antarctic sea ice from 1992 to 2014/15 using active microwave observations from European Remote Sensing Satellite (ERS-1/2), Quick Scatterometer (QSCAT) and Advanced Scatterometer (ASCAT) radar scatterometers. We define two snowmelt transition stages: A weak backscatter rise indicating the initial warming and destructive metamorphism of the snowpack (pre-melt), followed by a rapid backscatter rise indicating the onset of thaw-freeze cycles (snowmelt).

Results show large interannual variability with an average pre-melt onset date of 29 November and melt onset of 10 December, respectively, on perennial ice, without any significant trends over the study period, consistent with the small trends of Antarctic sea ice extent. There was a latitudinal gradient from early snowmelt onsets in mid-November in the northern Weddell Sea to late (end-December) or even absent snowmelt conditions in the southern Weddell Sea.

We show that QSCAT Ku-band (13.4 GHz signal frequency) derived pre-melt and snowmelt onset dates are earlier by 20 and 18 days, respectively, than ERS and ASCAT C-band (5.6 GHz) derived dates. This offset has been considered when constructing the time series. Snowmelt onset dates from passive microwave observations (37 GHz) are later by 14 and 6 days than those from the scatterometers, respectively.

Based on these characteristic differences between melt onset dates observed by different microwave wavelengths, we developed a conceptual model which illustrates how the seasonal evolution of snow temperature profiles affects different microwave bands with different penetration depths. These suggest that future multi-frequency active/passive microwave satellite missions could be used to resolve melt processes throughout the vertical snow column of thick Antarctic snow.

1 Introduction

Sea-ice extent in the Southern Ocean has experienced large seasonal and inter-annual variations during the last decades, while ice extent has changed little on decadal time scales (Parkinson and Cavalieri, 2012;Stammerjohn et al., 2012;Turner et al., 2015). In addition, there are strong regional differences, with ice extent increases of about 3.9% per decade in the Ross Sea, and decreases of 3.4% in the Bellingshausen and Amundsen Seas (Turner et al., 2015). This is in strong contrast to the Arctic, where sea ice extent has decreased strongly everywhere in all seasons (e.g. Meier et al., 2014). The strong seasonal variability of Antarctic sea ice impacts processes and interactions between atmosphere, sea ice and ocean, and is a key component driving the polar marine ecosystem (Massom et al., 2001). The presence of snow on the ice dramatically alters these interactions through its impact on ice thermodynamics, mass balance, and light transmission.

The role of snow on Antarctic sea ice is exacerbated by the fact that the ice remains snow-covered in most regions throughout the summer (Massom et al., 2001). However, during spring and summer the entire snow column experiences substantial seasonal changes in its physical properties associated with variations in snow temperature profiles, liquid water content, grain size distribution, and stratification (e.g. Haas et al., 2001;Massom et al., 2001;Nicolaus et al., 2009). Detecting these variations in the snowpack on Antarctic sea ice is highly relevant as they modify the energy and mass budgets of sea ice, and strongly influence the retrieval of sea-ice parameters from satellite remote sensing algorithms (e.g. Willmes et al., 2014).

In contrast to sea ice in the Southern Ocean, snow and sea ice properties in the Arctic undergo strong changes during the seasonal cycle (Sturm and Massom, 2017). Due to different radiation and turbulent flux regimes of the Arctic atmosphere during the spring-summer transition (e.g. Andreas and Ackley, 1982;Nicolaus et al., 2006) liquid water forms usually rapidly within in the snow. The subsequent albedo-feedback processes accelerate seasonal snowmelt and the disappearance of snow, and lead to widespread formation of surface melt ponds resulting in substantial alterations of dielectric properties of the ice and snow surface associated with increasing microwave emissivity and decreasing radar backscatter. This distinct seasonal cycle of surface properties and related microwave signatures of Arctic sea ice has been utilized to identify different snow and sea-ice melt stages and the time of melt onset from passive [e.g. *Markus et al.*, 2009] and active satellite microwave remote sensing observations (e.g. Markus et al., 2009). Those satellite retrievals of melt onset in the Arctic have shown that melt onset occurred earlier by 1 to more than 10 days decade^{-1} since 1979 when routine satellite observation commenced, consistent with warmer air temperatures and accelerated ice retreat in the Arctic during the recent past decades.

However, on Antarctic sea ice, the retrieval of snowmelt onset is more challenging because thawing and melting are weaker and more sporadic than in the Arctic. There is widespread occurrence of diurnal thaw-freeze cycles (Haas et al., 2001;Nicolaus et al., 2006;Nicolaus et al., 2009), or the snow may only thaw during the passage of warm marine cyclones, with the snow refreezing shortly after (Willmes et al., 2006). These thaw-refreeze events cause strong, destructive snow metamorphism with icy snow and ice layers. Under more intensive melting conditions, snow changes from the pendular to the funicular regime (e.g. Denoth, 1980) where the liquid snow melt water percolates through the snowpack to lower, colder layers or to the ice surface where it eventually refreezes to form superimposed ice (Tison et al., 2008;Haas et al., 2008;Haas et al., 2001;Nicolaus et al., 2009;Willmes et al., 2009).

These different predominant snow processes and the absence of melt ponding result in different sea ice microwave signatures in the Antarctic than in the Arctic. The absence of longer periods with large amounts of liquid water within the snow mean that strong, persistent decreases of backscatter or increases of emissivity typical for Arctic sea ice during the melt season do not frequently occur in the Antarctic. In contrast, strong snow metamorphism leads to large-grained, polygonal granular textured and salt-free (snow) grains and melt clusters (Colbeck, 1997), increasing radar volume- and surface scattering (Colbeck, 1997;Abdalati and Steffen, 1995;Onstott and Shuchman, 2004), and decreasing microwave emissivity (Willmes et al., 2006).

The presence of frequent diurnal thaw-freeze cycles has been utilized by Willmes et al. (2009) and Arndt et al. (2016) to develop algorithms to observe melt processes and to retrieve snowmelt onset dates from passive microwave radiometers, such as the Special Sensor Microwave/Imager (SSM/I). Their algorithms are based on analyses of the magnitude of diurnal 37 GHz, vertical polarized Brightness Temperature changes observed from ascending and descending morning and afternoon satellite passes approximately 12 hours apart. Both studies found large interannual snowmelt onset variability but no pronounced trends.

So far, there have only been few studies of Antarctic sea ice melt onset using active microwave sensors, i.e. radars. Drinkwater and Liu (2000) applied an Arctic-like algorithm searching for rapid drops in radar backscatter. However, such drops are only occasionally observed on seasonal sea ice near the ice edge, or on the Larsen Ice Shelves (Bevan et al., 2018). On sea ice, drops in radar backscatter can also result from flooding events (Lytle and Ackley, 2001), potentially close to the time of complete deterioration of the ice. Drinkwater and Liu (2000) stated that such backscatter drop events are sparse and short lived. Therefore, their algorithm may not be easily applicable to most regions of Antarctic sea ice.

In contrast, Haas (2001) used C-band ERS scatterometer data from 1992 to 1999 to show that increasing radar backscatter from winter to summer is typical of Antarctic perennial ice, and is consistent with the theoretical considerations of backscatter from metamorphic snow and superimposed ice discussed above. On average, backscatter increased by 5.6 dB during 96 days, commencing on 15 November.

In this study, we update and extend the work by Haas (2001) with new satellite scatterometer data to study if any long-term changes in Antarctic melt onset on sea ice emerged since 1992-99. For this purpose, we compile time series of European Remote Sensing (ERS)-1/2, QuikSCAT (QSCAT), and Advanced Scatterometer (ASCAT) scatterometer data from 1992 to 2015. A similar time series has been compiled and analyzed with QSCAT and ASCAT data for the Arctic (Mortin et al., 2014). We apply the melt-onset algorithm of Haas (2001) to both perennial and seasonal ice regimes (Figure 1), and revise it to include early melt season effects on backscatter, defined as pre-melt phase. In addition, we use twice daily QSCAT observations between 1999 and 2009 to retrieve the magnitude of diurnal backscatter changes similar to earlier work with passive microwave observations discussed above (Arndt et al. (2016);Willmes et al. (2009); Figures 2 and 3).

Three are two short overlap periods of ERS-2 and QSCAT in 1999/2000 and of QSCAT and ASCAT in 2008/9. During those we note clear differences in backscatter behavior and melt onset timing observed by QSCAT and the other scatterometers, which we attribute to the different radar frequencies employed by ERS and ASCAT (C-band; 5.6 GHz), and QSCAT respectively (Ku-band; 13.4 GHz), and their different penetration depths (e.g. Ulaby et al., 1986). The time differences between melt onset detected by the C-band and Ku-band sensors were adjusted to construct the long time series from 1992 to 2015. Finally, we compare results with previously published melt onset dates retrieved from satellite passive microwave sensors using frequencies of 37 GHz (Arndt et al., 2016). The time differences between those retrievals and the radar results are again discussed in the context of temporal snow evolution, penetration depth, and the sensitivity of 37 GHz signals primarily to the uppermost snow layers. The results obtained here demonstrate the potential to observe snow processes at different depths from space, opening new avenues for multi-sensor studies of energy and mass budgets of snow on sea ice in the Southern Ocean.

We would like to point out that with perennial ice we describe sea ice that survives at least one summer melt season. It is important to note that this includes ice that is initially first-year ice, but experiences the melt season to become perennial ice. Antarctic first-year ice is known to be relatively thin and can possess negative freeboard due to its relatively thick snow cover (Massom et al., 2001). Typically, negative freeboard leads to flooding and slush at the snow/ice interface which can refreeze to form snow-ice (e.g. Eicken et al., 1994; Jeffries et al., 1997; Haas et al., 2001; Nicolaus et al., 2009). Due to the presence of salty slush even cold snow on first year ice can be quite saline and damp in winter, which contributes to its low radar backscatter in the end of winter (Lytle and Ackley, 1996). However, it is important to note that brine in snow percolates downwards as soon as the snow warms, and that during summer Antarctic sea ice snow salinity is normally negligible (Massom et al., 2001; Haas et al.; 2001; Nicolaus et al.; 2009). In addition, snow ice and superimposed ice formation lead to zero or positive freeboard, and therefore flooding and saline snow are uncommon on perennial ice in summer (e.g. Massom et al., 2001; Haas et al., 2001; Nicolaus et al., 2009), supporting the increases of backscatter during melt onset utilized here.

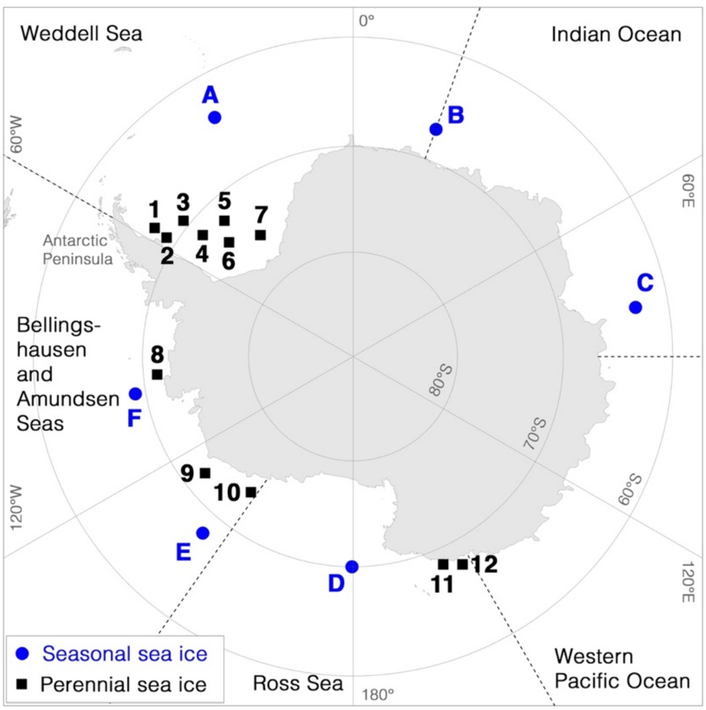

Figure 1. Map of Antarctica showing the 12 study locations in the perennial sea-ice zone (black/squares, locations 1-12, same as used by Haas (2001)) and 6 study locations on seasonal sea ice (blue/circles, regions A-F).

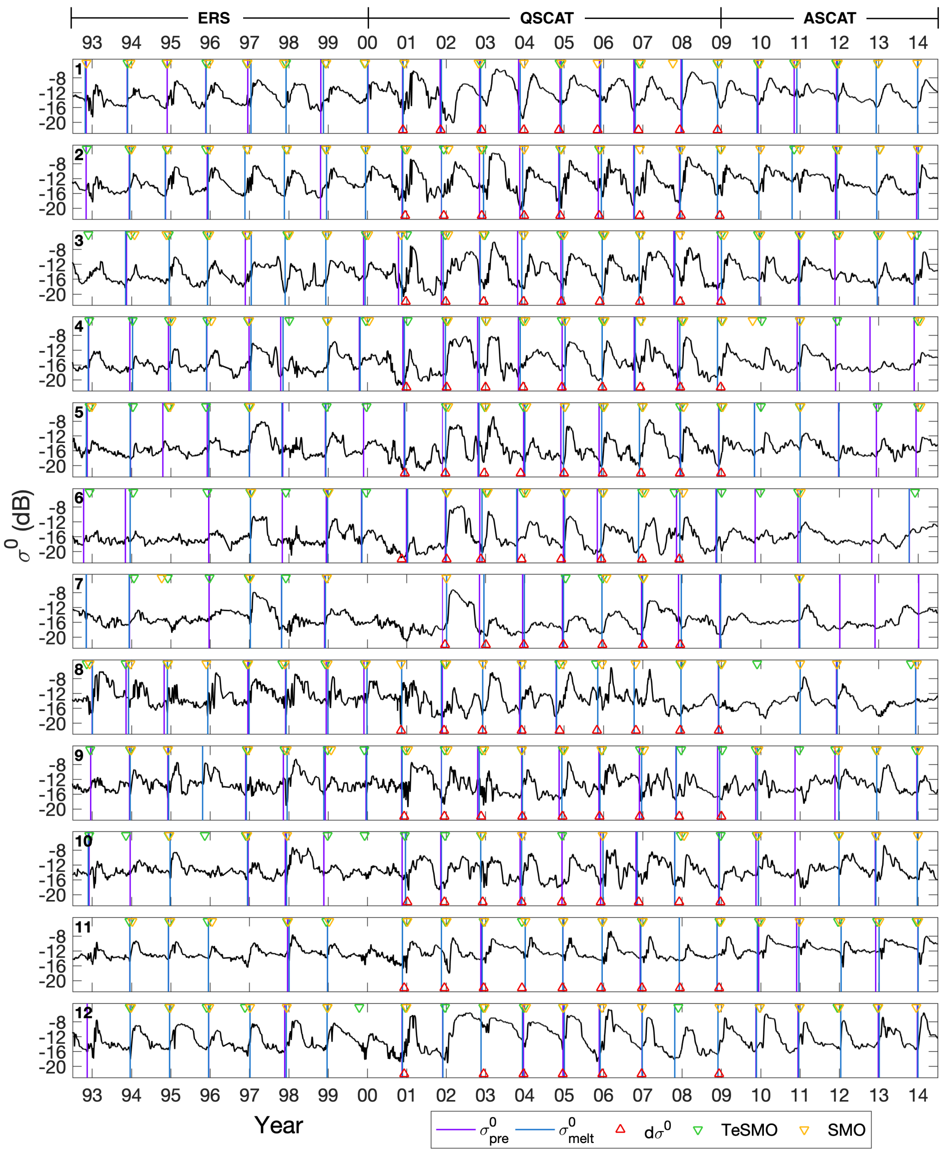

Figure 2. Time series of 6-day mean backscatter coefficients (σ^0) from 1992/1993 to 2014/2015 averaged over the respective 9 nearest-neighbor pixels for the study locations on perennial sea ice (Figure 1, 1-12). Purple and blue lines show the scatterometer-derived snow pre-melt (σ^0_{pre}) and melt (σ^0_{melt}) onset dates when the algorithm criteria were met (Section 2.2.1). Red triangles indicate the snowmelt onset retrieved from diurnal backscatter variations ($d\sigma^0$) of QSCAT data. Green and yellow triangles show the Temporary Snowmelt Onset (TeSMO) and Continuous Snowmelt Onset (SMO) derived from passive microwave observations from Arndt et al. (2016).

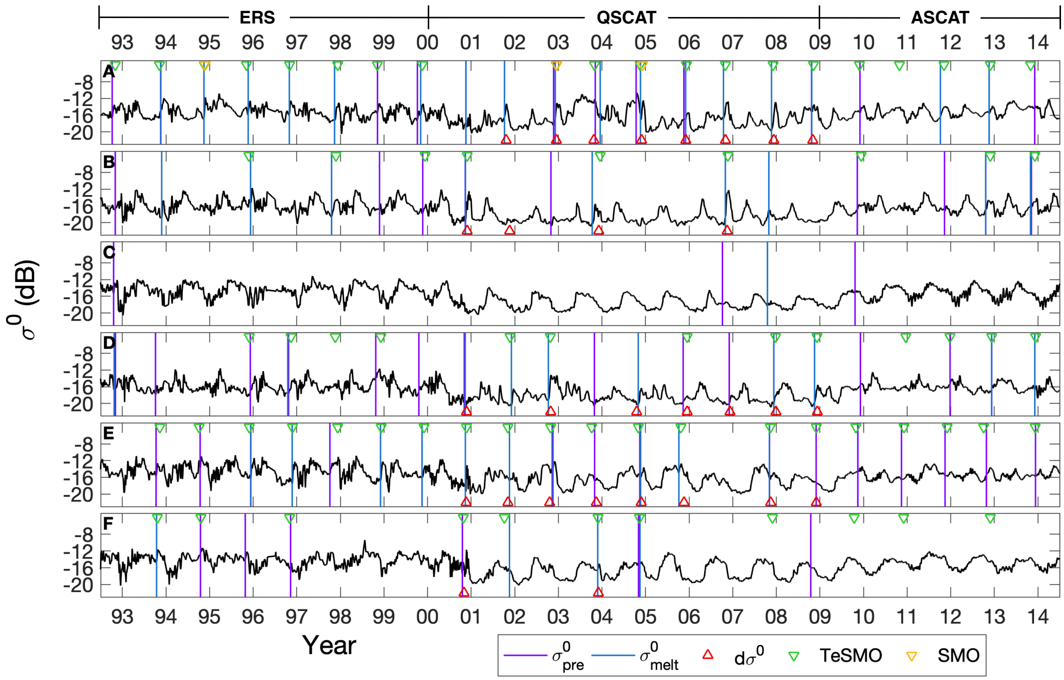

Figure 3. As Figure 2, but for study sites on seasonal sea ice (Figure 1, A-F).

2. Snowmelt retrieval from satellite scatterometer data

2.1 Data set

All presented scatterometer data sets were obtained from the NASA Scatterometer Climate Record Pathfinder (SCP) project, sponsored by NASA (http://www.scp.byu.edu/). For the following analysis, all data are interpolated to a 25x25 km^2 SSM/I polar stereographic grid, using nearest-neighbor resampling.

The scatterometer data from the European Space Agency's (ESA) European Remote Sensing (ERS) 1 and 2 missions are provided as 6-day averages of vertical co-polarized C-band (5.3 GHz, wavelength of 5.7 cm) backscatter. This low temporal resolution was chosen in order to cover the polar oceans and maintain a reasonable stability of successive backscatter maps from this early mission (Ezraty and Cavanié, 1999). Backscatter σ^0 is obtained over a 500 km wide swath and normalized to an incident angle of 40°. ERS-1 was operational from 1991 to 1996, while ERS-2 continued observations until 2001.
The NASA QuikSCAT (QSCAT) mission acquired measurements from 1999 to 2009, i.e. overlapping with both the ERS and ASCAT observations by 2 years, respectively (see below). In contrast to the ERS scatterometer, QSCAT operated at Ku-band, i.e. 13.4 GHz, equivalent to shorter wavelengths (2.2 cm). In this study, we used the QSCAT Scatterometer Image Reconstruction (SIR; Long et al. (1993)) backscatter product in both polarizations (vertically and horizontally co-polarized)

normalized to a 40° incident angle. The SIR algorithm enhances the spatial resolution of the daily data product to 4.45 km. Data are available twice daily, with a morning pass between 04:00 and 12:00 and afternoon pass between 12:00 and 20:00 local time. This allows observations of diurnal backscatter variations caused by colder conditions in the morning and warmer conditions in the afternoon.

Finally, the ESA Advanced Scatterometer (ASCAT) was launched in 2006 on the MetOp-A and MetOp-B satellites. The scatterometer is an upgraded successor of the scatterometers onboard the ERS-1/2 platforms mentioned above, operating in C-band at 5.6 GHz in vertical co-polarization (VV). In this study, we also used the SIR product, similar to the QSCAT product, with a spatial resolution of 4.45 km. Due to a lower spatial coverage of ASCAT, the data are provided as 2-day averages.

To avoid biases of sea ice and snow signatures due to signals from larger amounts of open water in each pixel (e.g. Drinkwater and Liu, 2000), sea-ice concentration (SIC) data from Nimbus-7 SMMR and DMSP SSM/I-SSMIS Passive Microwave Data derived with the bootstrap algorithm were used (Comiso, 2000). The data are available daily since 1978 on a 25 km SSM/I polar stereographic grid. During our study period, starting in 1992, ice concentration data of three different SSM/I sensors were used (F11 from January 1992 to 1995, F13 from May 1995 to December 2008, and F17 from December 2006 onwards).

2.2 Methods

We restrict our analysis of melt onset dates to 18 individual small study regions of 3x3 pixels of scatterometer data carefully chosen to represent typical ice conditions in seasonal and perennial ice regimes (Figure 1, Haas (2001)). This approach was chosen over more regional analyses to avoid blurring of backscatter signatures due to the large spatial and temporal variability of sea ice properties and drift. To account for small scale variability and ensure stable results, we computed melt onset dates for each pixel and then averaged the melt onset dates. Backscatter time series of individual, neighboring pixels were highly correlated and the results of our algorithm varied by only a few days from pixel to pixel. Like the studies of Markus et al. (2009), Mortin et al. (2014), Willmes et al. (2009), and Arndt et al. (2016) our approach is also Eulerian, i.e. not taking into account ice drift and advection for which there is little accurate data. However, as most Antarctic sea ice is first-year ice at the beginning of the melt season, Eulerian and Lagrangian approaches show similar temporal behavior of melt signals (Fig. 3 in Haas (2001)).

We applied two melt detection algorithms based on two different scatterometer observables: First we analyze daily mean backscatter σ^0 which is available from all satellites Second, we analyze the magnitude of diurnal backscatter variations $d\sigma^0$, defined as the absolute difference between morning and evening satellite overpasses only available from QSCAT (Section 2.1).

Analyses for both algorithms were only carried out for locations where sea-ice concentration remained above 70% for at least three weeks into the melting season. This avoided contamination of results by wind-roughened water (Drinkwater and Liu, 2000), and effectively eliminated regions of deteriorating, thin ice where surface flooding and break up into small floes and brash ice may occur, e.g. in the marginal ice zone, with competing effects on backscatter evolution.

2.2.1 Melt onset retrieval from time series of daily mean backscatter

The seasonal cycle of surface properties of Antarctic perennial sea ice is evident in its backscatter time series with higher backscatter in summer than in winter (Haas, 2001). These are well visible in Figure 2 which show the complete time series compiled for 12 perennial sea-ice regions: While location 1-7 are chosen from north to south in the Weddell Sea, all other locations are distributed throughout the perennial sea-ice regime around Antarctica (Figure 1). As expected before, all perennial sea-ice regions show a distinct seasonal cycle with a sharp increase during spring and a subsequent slow backscatter decrease towards autumn/winter (Figure 4 a). In contrast, the backscatter time series at 6 locations with seasonal sea-ice distributed around Antarctica (Figure 1) are much less systematic and show a much weaker seasonal cycle than those of perennial sea ice (Figures 3 and 4 b). However, Drinkwater and Liu (2000) defined the Antarctic-wide snowmelt onset by a sudden drop in the radar backscatter signal during spring. Their algorithm indicated widely missing onset dates on perennial sea ice, especially in the southwestern Weddell Sea, since radar backscatter behaves differently there than expected by their algorithm.

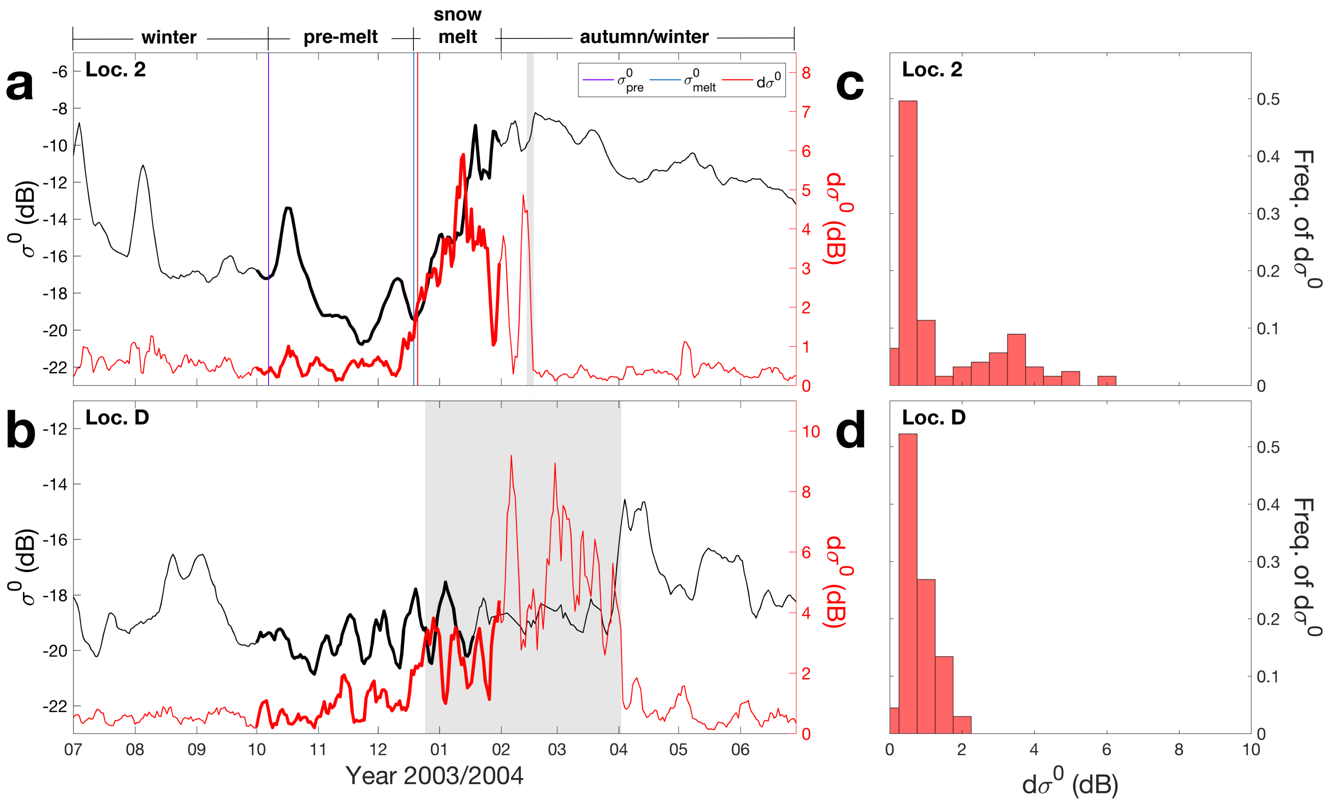

Figure 4. Typical annual time series of mean daily QSCAT radar backscatter (σ^0, black) and its diurnal variations ($d\sigma^0$, red) for location 2 on perennial (a) and location D on seasonal sea ice (b) in 2003/2004. Colored vertical lines illustrate snow pre-melt (σ^0_{pre}, magenta), and melt (σ^0_{melt}, blue) onset derived from backscatter time series only, and snowmelt onset derived from

QSCAT diurnal backscatter variations ($d\sigma^0$, red). Grey shaded areas indicate the time period with sea-ice concentration less than 70%, when the algorithm developed here cannot be applied. Bold lines denote the time period for the spring/summer transition retrieval analysis (01 October to 31 January). Histograms in c and d show frequency of occurrence of the magnitude of diurnal backscatter variations $d\sigma^0$.

In the following analysis of the seasonal cycles in the backscatter time series, we distinguish between two major snowmelt stages. Firstly, sporadic, temporal backscatter rises are defined as pre-melt, preceding the larger backscatter rises at melt onset. We interpret these subtle radar backscatter rises to be caused by changing physical properties associated with the spring warming of upper ice layers and with increases in brine volume (e.g. Nandan et al., 2017), or the appearance of liquid water in the pendular regime in the middle or lower snowpack. Secondly, the most distinct, largest rise in backscatter during spring or summer is defined as melt onset. At this time, the high intensity of thawing of the snowpack transitions the snow to the funicular regime when liquid water percolates to cause strong snow metamorphism and superimposed ice formation, as observed during various field studies (Haas et al., 2001;Willmes et al., 2009;Nicolaus et al., 2009).. Thaw-refreeze cycles may occur diurnally or with periods of several days. However, on Antarctic sea ice their intensity is usually insufficient to initiate the positive albedo feedback with accelerated, irreversible snow melt and melt pond formation (Andreas and Ackley, 1982;Haas et al., 2001;Nicolaus et al., 2009). Thawing can also be interrupted by periods of cooler conditions for periods of hours, days or weeks.

In order to retrieve every summer's pre-melt and melt onset, we split the time series into annual sections extending from the beginning of July of one year to end of June in the following year, with the spring and summer season approximately centered (Figure 4 a, b). Here, the time prior to pre-melt onset is referred to as winter, between pre-melt and snowmelt onset as pre-melt stage, after snowmelt onset as snowmelt stage, and after 31 January as autumn/winter again, as noted in Figure 4 a. Following the approach by Haas (2001), and to be consistent with their analysis of ERS data which are only available as 6-day averages (approximately one week), we first down-sampled the QSCAT and ASCAT data by averaging over 6-day intervals. Then, we analyze local backscatter maxima and their preceding local minima from three-point running means of each σ^0-time series. We define the first instance after 1 October when the difference between a local maximum and the preceding minimum is larger than 2 dB as pre-melt onset (σ^0_{pre}, Figure 4 a, purple line). From there, we search for the instance when the difference between a local maximum and the preceding local minimum is larger than 3 dB. We define that instance as snowmelt onset (σ^0_{melt}, Figure 4 a, blue line). Note that the algorithm only responds to substantial, long-lived changes of snow microwave properties due to the 3-point smoothing of the 6-day averaged data. The thresholds are based on the average rise of the backscatter values during the spring/summer transition.

We apply this pre-melt and melt onset detection algorithm to both, perennial and seasonal sea ice. If no backscatter rises of the required magnitude are found during summer, no pre-melt or melt dates are assigned. This may occur in cooler years, on perennial ice located far south where melt can be small or absent, on seasonal ice when snowmelt is superimposed on other processes like flooding, or where the ice completely disintegrates shortly after snow melt commenced. For example, no melt onset was found at location D in 2003/2004 as shown in Figure 4 b. Overall, pre-melt and melt onset dates were retrievable for 79% and 64% of all analyzed pixels. For the seasonal sea-ice regime, pre-melt and melt onsets were obtained for 46% and 26% of the analyzed pixels.

2.2.2 Melt onset retrieval from diurnal backscatter variations observed by QSCAT

Willmes et al. (2009) described the onset of snow surface melt on Antarctic sea ice as the appearance of dominant diurnal thaw-freeze cycles in the surface layer. Analyzing the time series of the absolute difference between two daily brightness temperature values from ascending and descending satellite passes (dT_B, 37GHz, vertically polarized), they found an increase in dT_B once temporary thawing commences in summer.

Since QSCAT data are also available twice a day from ascending and descending passes, the backscatter time series can be utilized to derive diurnal variations at the chosen locations. Therefore, we use the regionally adaptive approach by Arndt et al. (2016) to identify the snowmelt onset during austral spring: After applying a 5-day running mean to each $d\sigma^0$ time series between 1 October and 31 January, a histogram of $d\sigma^0$ values with a bin width of 0.5 dB is computed for each location. All histograms only contain data from 1 October until 31 January or until the sea-ice concentration drops below 70% (see Section 2.2). For example, Figures 4 c and d show typical histograms for the respective perennial and seasonal ice study locations. Generally, we found two kinds of histograms: unimodal and bimodal $d\sigma^0$ distributions. A mode is defined as a local maximum bounded by at least one lower bin on each side. Multimodal distributions of $d\sigma^0$ (Figure 4 c) indicate the presence of distinctly different diurnal backscatter values, which we interpret as different melt stages including differences in the strength of diurnal thaw-freeze cycles. Normally, at least two modes of the $d\sigma^0$ distributions can be observed in those cases. A histogram is considered to be unimodal if a single mode exceeds a fraction of more than 90% of all included data (Figure 4 d). Locations with unimodal distributions are not further considered in the following analysis, as they do not reveal the characteristic diurnal snow backscatter variations. For example, only few occurrences of strong diurnal backscatter variations were found at the seasonal ice locations, and therefore in most years a reliable melt onset from diurnal variations could not be observed there (Figure 4 b). In contrast, bimodal $d\sigma^0$-distributions are widely detected on perennial sea ice (Figure 4 c). In a next step, an iterative threshold selection algorithm (Ridler and Calvard, 1978) is applied to the respective $d\sigma^0$ time series of each analyzed pixel with a multimodal distribution to derive individual $d\sigma^0$-thresholds delineating winter from summer conditions. Finally, snowmelt onset is defined as the first time when $d\sigma^0$ exceeds the respective local threshold for at least 3 consecutive days (Figure 4 a).

3. Results

3.1 Perennial sea ice

Table 1: Mean snowmelt onset dates indicated in Figure 2 for the 12 study locations on perennial sea ice shown in Figure 1 (mean ± 1 standard deviation).

	From scatterometer data			**From passive microwave data**	
Region	**Pre-melt Onset**	**Snowmelt Onset**	**Diurnal thawing-refreezing Onset (2000/01-2008/09 only)**	**Temporary Snowmelt Onset (TeSMO)**	**Continuous Snowmelt Onset (SMO)**
Northwestern Weddell Sea (region 1-4)	23 November ± 21 days	04 December ± 21 days	09 December ± 15 days	12 December ± 16 days	18 December ± 23 days
Southeastern Weddell Sea (region 5-7)	28 November ± 24 days	09 December ± 25 days	16 December ± 14 days	22 December ± 15 days	05 January ± 19 days
Bellingshausen Sea (region 8)	28 November ± 23 days	05 December ± 23 days	23 November ± 18 days	28 November ± 20 days	12 December ± 18 days
Amundsen Sea (region 9-10)	26 November ± 17 days	05 December ± 19 days	09 December ± 12 days	11 December ± 14 days	23 December ± 16 days
Ross Sea (region 11-12)	10 December ± 18 days	14 December ± 18 days	14 December ± 6 days	14 December ± 13 days	29 December ± 9 days
All regions	28 November ± 22 days	07 December ± 21 days	10 December ± 15 days	13 December ± 16 days	23 December ± 20 days

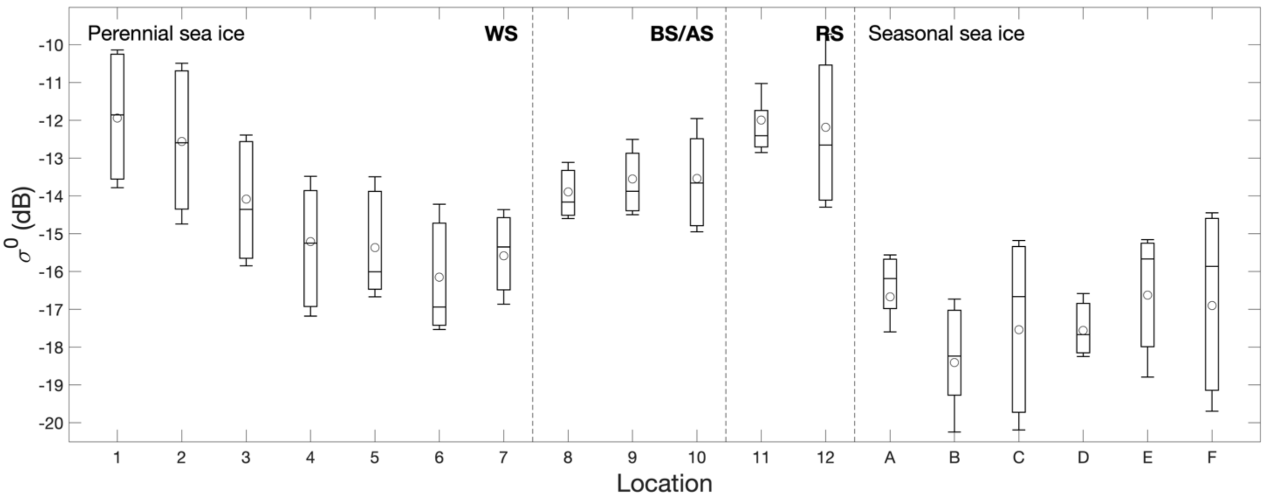

Figure 5. Summary of mean radar backscatter σ^0 (Ku- and C-band) and range of seasonal variability for all study locations during the complete 23-year study period (cf. Figures 2 and 3). Boxes are the first and third quartiles. Whiskers display the 20- and 80-percentiles. Circles indicate mean, horizontal lines median values. Abbreviations according to Figure 1: WS: Weddell Sea, BS/AS: Bellingshausen and Amundsen Seas, RS: Ross Sea.

As expected (Section 1), all backscatter time series show strongly increasing backscatter during the summer, although with some interannual variability (Figure 2). Mean backscatter and the range of seasonal variations are summarized in Figure 5. Mean perennial ice backscatter ranges between -12.0 and -16.2 dB, i.e. is variable between regions and consistently higher than on seasonal ice. Superimposed on mean backscatter are seasonal variations ranging between 1.5 dB at location 8 in the Bellingshausen Sea up to 4.4 dB in the northwestern Weddell Sea and western Ross Sea (locations 1-3 and 12; range between 20 and 80 percentiles in Figure 5). Separating for the different sensor classes indicates that, averaging all 12 study locations on perennial sea ice, the mean amplitude between seasonal minimum and maximum is 8.03dB for the QSCAT time period, while it is only 5.80 and 5.10dB for ERS and ASCAT, respectively (Figure 2).

Figure 2 also includes the pre-melt and melt onset dates between 1992/93 and 2014/15 retrieved with the algorithms described. Average pre-melt and melt onset dates in the different regions are summarized in Table 1. Note that in some years melt events could not be observed because the temporal behavior of backscatter changes did not possess the characteristic rises expected by our algorithms. On average, the initial pre-melt onset is on 28 November, 9 days prior to the actual melt onset on 07 December retrieved from rapidly rising daily backscatter and its diurnal variations. In the Weddell Sea, there are strong latitudinal differences with earlier snowmelt onset in the northwest and increasingly later snowmelt onset in the southeast: On average, the earliest pre-melt onsets are observed in mid-November in the northwestern Weddell Sea (locations 2 und 6), and in the Amundsen Sea (location 9), while the latest pre-melt onsets are found in mid-December in the Ross (locations 11 and 12) and southeastern Weddell Seas (location 7). Regions in the northwestern Weddell Sea (locations 2 and 3) and

Bellingshausen and Amundsen Seas (locations 8 and 9) had the earliest actual snowmelt dates, at the end of November, while again the southeasternmost region in the Weddell Sea (location 7) had the latest onset dates, in the end of December. Regions in the southeastern Weddell Sea (locations 5-7) and western Amundsen Sea (location 10) frequently do not reveal any distinct pre-melt or melt phases (Figure 2).

Snowmelt onset dates based on diurnal variations in the radar backscatter can only be derived with QSCAT data from 2000/01 to 2008/09. Here, on average, snowmelt onset occurred on 10 December, in an interval from 27 November (northwestern Weddell Sea, location 1) to 21 December (central/northwestern Weddell Sea and Ross Sea, locations 4, 5 and 12).

For comparison, Figure 2 and Table 1 also include Temporary SnowMelt Onset (TeSMO) and subsequent continuous SnowMelt Onset (SMO) retrieved from 37 GHz passive microwave brightness temperature observations [Arndt et al., 2016]. On average, TeSMO occurs on 13 December, i.e. 3 days later than snow melt observed by scatterometers. The average date of SMO occurs another 13 days later on 23 December. On average, the earliest TeSMO starts in mid-November in the Bellingshausen Sea (location 8), while the latest temporal snowmelt onsets are observed in the end of December in the southeastern Weddell Sea (location 6). Again, regions in the northwestern Weddell Sea (locations 1 and 2) showed the earliest SMO in the beginning of December, while the southernmost locations 5 and 6 show the latest SMO in mid-January.

Both, scatterometer and passive microwave observed melt onset parameters consistently show strong gradients towards later snowmelt from north to south as well as the decreasing occurrence of melt events towards the south, in particular in the Weddell Sea. However, we note strong differences in the actual timing of melt events observed by the different sensors which are further discussed in Section 4.4.

3.2 Seasonal sea ice

In addition to the perennial sea ice locations, 6 study locations on seasonal sea ice were chosen, distributed around the Antarctic continent (Figures 1 and 3). Mean backscatter ranges between -16.6 and -18.4 dB, i.e. much lower than on perennial ice (Figure 5). In agreement with previous studies discussed in the introduction, none of the seasonal sea-ice regions show any consistent seasonal backscatter cycle. While the Weddell and Ross Seas (locations A and D) show slight increases in backscatter during the transition from winter to summer, backscatter decreases at locations B and C in the Indian Ocean. Locations E and F in the Bellingshausen and Amundsen Seas reveal very little backscatter variation throughout the spring and summer time. However, most regions show a sharp decrease in the backscatter signal with increasing sea-ice melt, consistent with (Drinkwater and Liu, 2000). As expected from the strongly different seasonal backscatter changes over seasonal sea ice compared to perennial ice, snowmelt onset on seasonal ice is only sporadically detected by our algorithm (Figure 3), demonstrating the spurious nature of backscatter signals on seasonal ice. At location A in the Weddell Sea pre-melt is frequently observed (80% of the respective pixels), with an average date of 4 November. In contrast, hardly any pre-melt has been observed at locations C (7%) and F (13%) in the Indian and Bellingshausen Seas. Overall, subsequent actual melt onset is rarely observed either, but most frequently occurring in the Weddell Sea. During the 23-year study period it was observed in 49% of the analyzed pixels with an average melt onset date of 11 November. Snowmelt onset over seasonal ice could hardly be derived from passive microwave observations either (43%, Arndt et al. (2016)). However, the years and regions when and where it was possible were similar to the ones when also the scatterometer data yielded results. On average, melt onset was observed on 18 November with the passive microwave data (Figure 3).

3.3 Compilation of snowmelt onset time series and analysis of long-term trends

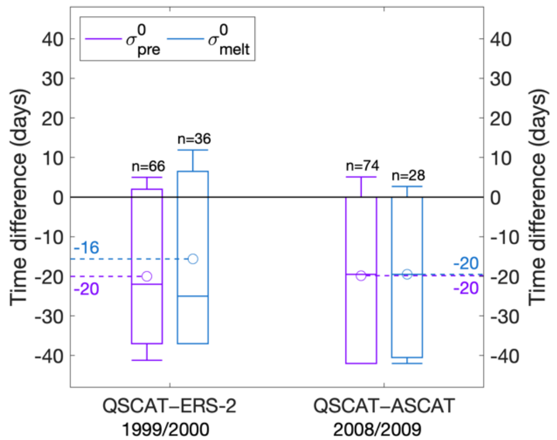

Figure 6. Averaged time differences between pre-melt and snowmelt onset dates retrieved from QSCAT and ERS/ASCAT at the different study locations on perennial sea ice for the overlap periods 1999/2000 and 2008/2009, respectively. Negative (positive) differences indicate an earlier (later) transition detected from Ku-band. Boxes are the first and third quartiles. Whiskers display the 20- and 80-percentiles. Circles indicate mean, lines median values.

Similar to the work of Markus et al. (2009);Mortin et al. (2014);and Stroeve et al. (2014) in the Arctic, here we used the backscatter time series of ERS-1/2, QSCAT and ASCAT to study the inter-annual variability and trends of the previously described scatterometer-derived pre-melt and snowmelt onset dates. However, as ERS/ASCAT and QSCAT use different radar bands with different penetrations depths, and have been shown to retrieve different average melt onset dates, we first quantified the differences between retrieved melt onset dates during the overlap periods of ERS-2 and QSCAT in 1999/2000 and of QSCAT and ASCAT in 2008/2009. Figure 6 shows the average time differences between Ku-band and C-band retrievals for the 12 study locations on perennial sea ice (Figure 1), for both overlap periods, respectively. On average, Ku-band QSCAT data detected pre-melt and melt onset earlier by 20 and 16 days, respectively, then the C-band ERS-2 data. Similarly, QSCAT detected earlier pre-melt and melt onset dates than ASCAT. Both, pre-melt and melt onset were observed 20 days earlier. On average, that adds up to derived pre-melt and melt onset dates from QSCAT Ku-band earlier by 20 and 18 days, respectively, than ERS and ASCAT C-band derived onset dates.

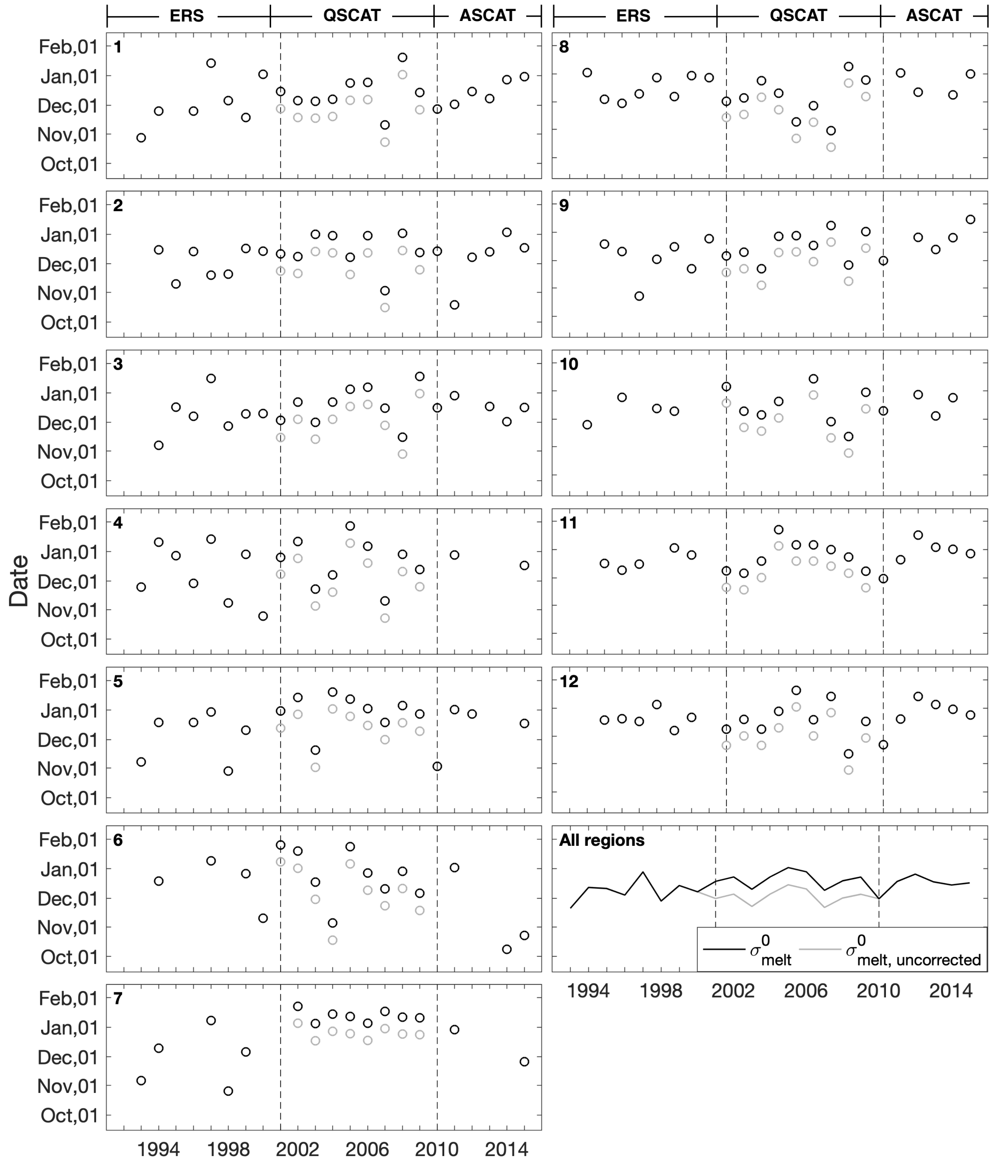

Figure 7. Time series of snowmelt onset dates in the perennial sea-ice zone for individual regions 1-12 (Figure 1), and all regions averaged (bottom right, upper panel). Grey circles (and grey line in bottom right) show the uncorrected QSCAT melt onset dates, while black symbols show dates corrected 11 days, the difference between Ku- and C-band melt onset dates, respectively.

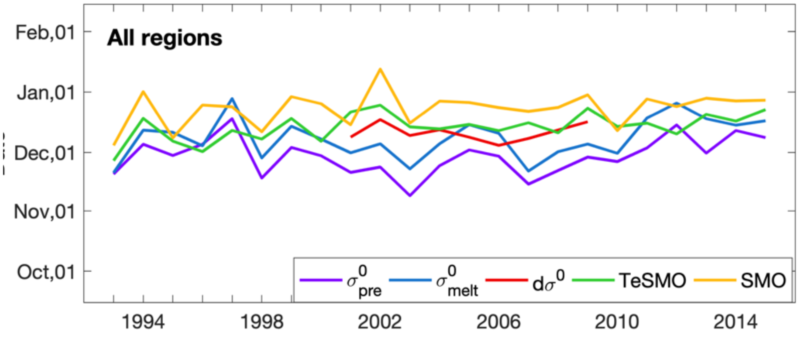

Figure 8. Time series of snowmelt onset dates averaged for all regions derived from backscatter time series (σ^0_{melt}, see Figure 7), diurnal backscatter variations ($d\sigma^0$), as well as the Temporary Snowmelt Onset (TeSMO) and Continuous Snowmelt Onset (SMO) derived from passive microwave observations.

Based on the results above, we corrected the QSCAT pre-melt and melt onset dates by 20 and 18 days, respectively, to derive a consistent time series of scatterometer-derived pre-melt and melt onset dates from 1992/93 to 2014/15 and to retrieve any potential trends. Figure 7 shows the resulting time series of the snowmelt onset for each study location on perennial sea ice. In addition, Figure 8 summarizes these results and also compares them with all other previously described sea ice snowmelt onset dates from scatterometer and passive microwave observations in Antarctica. Neither single locations nor the regional averages reveal any significant temporal trend in the retrieved snowmelt onset dates. Instead, the respective snowmelt onset dates show strong interannual variations with the tendency towards later onset dates.

Figure 8 and Table 1 also show that passive microwave observed TeSMO and SMO dates occur generally later than those observed by C-band scatterometer. More detail is provided in Figure 9 which summarizes the time differences between all observed pre-melt and melt onset dates for all locations. Results show, on average, that 68 (58) % of the pre-melt (snowmelt) onset dates retrieved from scatterometer observations occur earlier than from passive microwave observations. Particularly large negative differences are observed in the Weddell Sea, where on average about half (a quarter) of the pre-melt (snowmelt) onset differences are larger than 20 days. Overall, the mean pre-melt (snowmelt) onset difference between passive microwave and scatterometer observations is 14 (6) days, while only 36 (40) % of the differences are smaller than 10 days, and 56 (61) % are smaller than 20 days. The smallest differences are most notably in the western Amundsen Sea (location 10), while biggest differences are detected in the southernmost Weddell Sea regions (locations 4 and 6). Again, in the Weddell Sea there is a pronounced gradient of larger differences from northwest to southeast.

Similarly, melt onset from diurnal backscatter variations $d\sigma^0$ during the QSCAT era occurred earlier than passive microwave observed melt onset (Figure 9). However, these differences are much smaller than those from the actual time series above, with a mean (mode) or 4 (1) days.

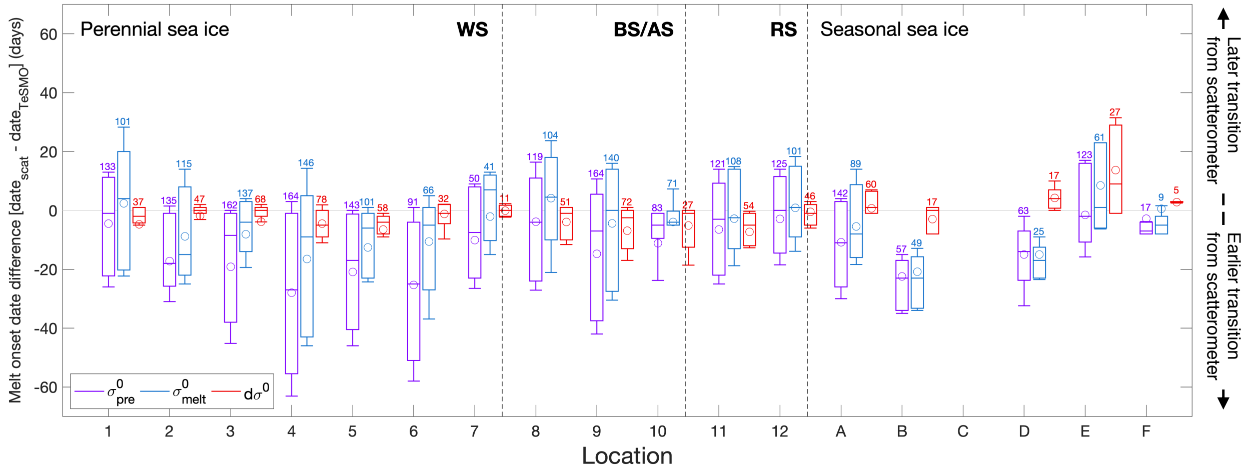

Figure 9. Mean time differences between retrieved snowmelt onset dates from scatterometer observations (σ^0_{pre}, σ^0_{melt}, $d\sigma^0$) and from passive microwave observations (Temporary SnowMelt Onset, according to Arndt et al. (2016)) for all study locations. Snowmelt onset dates from passive microwave observations and backscatter time series are retrieved from 1992 to 2014/15, while the retrieval of diurnal backscatter variations $d\sigma^0$ is only performed with QSCAT from 2000 to 2008. Positive (negative) differences indicate a later (earlier) transition observed by scatterometers. Boxes are the first and third quartiles. Whiskers display the 20- and 80-percentiles. Circles indicate the mean, dashes the median. Numbers above the whiskers indicate the respective sample size. The maximum sample size for derived pre-melt and melt onset dates is 207, while it is 81 only for the melt onset retrieved from diurnal variations. Abbreviations according to Figure 1: WS: Weddell Sea, BS/AS: Bellingshausen and Amundsen Seas, RS: Ross Sea.

4. Discussion

4.1 Regional differences of seasonal backscatter variations

The previously described seasonal cycle of snow processes and the related backscatter signal (Section 1) are typically found on perennial sea ice (Figures 2 and 4 a). The strong summer backscatter rise may be interrupted by few temporary backscatter drops, which can be due to local and temporary flooding or brief, strong melt events with high snow liquid water content associated with the transition towards a funicular snow regime (Figures 2 and 4 a). In the Weddell Sea section, both the magnitude of the seasonal cycle and the actual backscatter values decrease from northwest to southeast (Figure 5), with fewer melt onset dates detected in the South. This is consistent with generally colder and dryer climatic conditions further south, away from the marginal ice zone and close to the Antarctic ice sheet, where also warm air advection from the North is hampered by the Antarctic Circumpolar Trough (e.g. Simmonds and Keay, 2000;Turner et al., 2015). Consequently, both seasonal and diurnal variations in the lower atmosphere and snowpack are weak leading to less snow metamorphism and melt in the southern part of the Antarctic sea-ice regime. The absence of distinct snowmelt processes in the southern Weddell Sea were also observed and described in previous studies on snowmelt detection from passive microwave observations (Arndt et al., 2016).

In contrast, most seasonal sea ice is not showing similarly strong seasonal backscatter cycles. Instead, the younger and thinner seasonal ice is warmer and more salty than perennial ice, and has larger brine volume at the snow/ice interface causing low backscatter through winter (Nicolaus et al., 2009;Yackel et al., 2007). Also, repeated flood-freeze cycles during winter as well as flooding events during spring and summer cause low backscatter in winter and backscatter drops during spring and summer (Drinkwater and Liu, 2000). In addition, the early break-up of seasonal sea ice associated with the formation of leads and thin ice between ice floes contributes to the declining backscatter coefficients. Moreover, due to the a comparatively large ocean heat flux of the Southern Ocean (Martinson and Iannuzzi, 1998), Antarctic sea ice might strongly melt from below and even retreat completely before the pendular-funicular transition in the snowpack have started or even dominant snow melt can develop at its surface in summer. These numerous processes coincide and compete with actual surface snowmelt processes, meltwater percolation, and superimposed ice formation, making it therefore difficult to consistently retrieve snowmelt processes and dates on seasonal sea ice by scatterometer (Section 3.2) and passive microwave algorithms (Arndt et al., 2016). We therefore consider the found snowmelt onset dates on Antarctic seasonal sea ice highly uncertain and potentially not meaningful for further analysis.

4.2 Inter-annual variations in the retrieved snowmelt onset dates

A main achievement of our work is the compilation of a long time series of derived snowmelt onset dates on perennial sea ice from 1992/1993 to 2014/2015, and that no significant trend in the retrieved snowmelt onset dates was found, neither from scatterometer nor from passive microwave observations. Instead we found strong inter-annual variability of all 5 snowmelt onset parameters (Table 1). However, previous studies have shown that during the same time period the duration of the summer open water season, when the ice concentration is below 15% for at least 5 days, shows significant trends in some regions. Stammerjohn et al. (2008) showed that the period of open water was longer by 85±20 days (total change from 1979 to 2004) in the Bellingshausen and Amundsen Seas (and somewhat less in the southern Weddell Sea), whereas in the perennial sea ice regime of the western Ross Sea it decreased by 60±10 days. In general, that study revealed a significant correlation between ice-season duration and sea-ice advance in most regions of the Southern Ocean, while weak correlation was found with the respective sea-ice retreat dates. The absence of similar trends for melt indicates that the timing of snowmelt and snowmelt processes are less important processes for Antarctic sea ice extent variability. Instead, previous studies have shown that seasonal and interannual ice concentration and extent variations rather depend on local oceanic conditions governing ocean heat flux and ice bottom melt, and on large-scale atmospheric circulation patterns, which affect the speed and direction of sea-ice drift and intensity of ice deformation and redistribution (Maksym et al., 2012;Stammerjohn et al., 2008;Turner et al., 2014;Turner et al., 2016).

Our melt onset retrieval algorithms utilize seasonal changes of microwave properties caused by snowpack transitions from the pendular to the funicular snow regime associated with snow metamorphism, ultimately leading to the formation of superimposed ice (Haas, 2001). Changes of these properties also affect other retrieval algorithms, of, e.g., sea-ice concentration (Willmes et al., 2014) and of ice thickness from radar altimetry (e.g. Ricker et al., 2014). For example, increasing snow metamorphism may lead to reduced radar penetration and raising elevations of radar scattering horizons, and therefore to retrievals of apparently increasing ice thicknesses. Combination of altimetric sea-ice thickness data and backscatter changes and melt processes observed by scatterometers may therefore help to improve our understanding of sea-ice surface processes and seasonal mass balance of perennial Antarctic sea ice in the future.

4.3 Sensitivity of different microwave wavelengths to evolving snow temperature and moisture profiles during the melt season

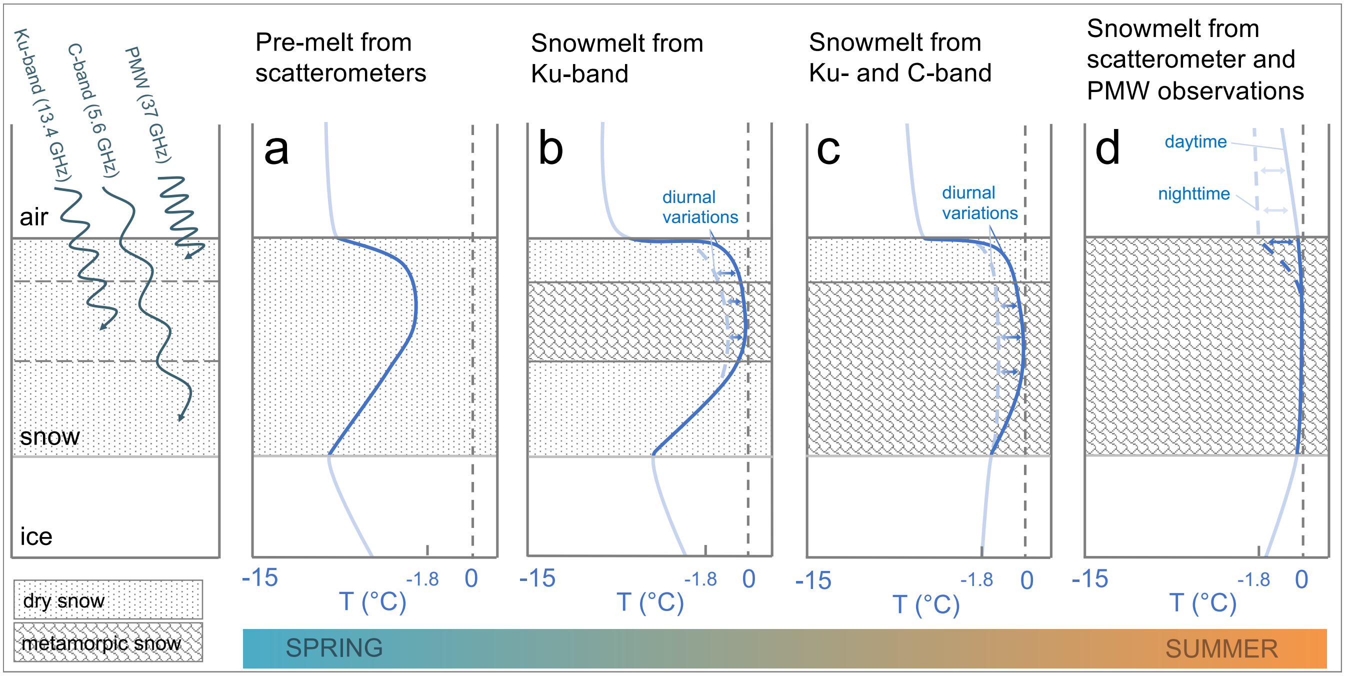

Figure 10. Conceptual model of the evolution of vertical air, snow and sea ice temperature profiles as well as snow metamorphism processes in the Antarctic sea ice regime during spring and summer in four characteristic stages (a-d). Note that snow temperatures close to 0°C lead to the appearance of liquid water and strong snow metamorphism. Diurnal thaw-freeze cycles during the during stage b to d cause significant differences in the snowpack properties and air temperatures between day- and nighttime. Microwaves with different wavelengths are sensitive to changing snow properties at different depths (left panel), and therefore indicate different melt-onset dates in the same region.

An important result of this study is that the retrieved perennial ice snowmelt onset dates from Ku-band (QSCAT), C-band (ERS and ASCAT), and 37 GHz passive microwaves (PMW) were different. On average, melt was detected first with Ku-band, followed by C-band (20 and 18 days later on average), and then PMW (14 and 6 days later on average), see Figures 6, 8, 9, and Table 1). This behavior could be related to the different wavelengths of those three observations with their different penetrations depths, and different sensitivity to increasing Rayleigh scattering due to metamorphic processes with cycles of variable liquid water content, growing snow grains and ice layer formation (e.g. Onstott, 1992;Ulaby et al., 1986). However, the observed behavior indicates that medium wavelength Ku-band signals with their specific wavelength sense these processes first, followed by longer wavelength C-band signals with their deeper penetration, and that short-wavelength PMW signals with the least penetration are affected last.

We therefore propose a conceptional model for the temporal evolution of snow column temperature, moisture, and metamorphism profiles which can qualitatively explain the observed microwave behavior and which suggests that depth-dependent changes of snow properties can be retrieved by multi-frequency satellite microwave observations. The model is illustrated in Figure 10.

During the spring and pre-melt phase, subject to strong diurnal variations, the snow and ice warm from above due to atmospheric turbulent and shortwave radiative heating, with the highest temperatures in the upper, interior snow layers while lower layers remain cooler due to their vicinity to the cold, underlying sea ice with its large heat capacity (Cheng et al., 2003;Haas et al., 2001). During this time, brine which may potentially reside within the snow pack due to brine wicking or sea spray deposition during winter is removed from the snow pack by downward percolation, leading to the fact that snow salinity on sea ice is generally found to be negligible in summer (Massom et al., 2001; Haas et al., 2001; Nicolaus et al., 2009). Note that the presence of brine lowers the melting temperature at snow grain boundaries, and therefore brine remains liquid at temperatures well below 0˚C and can percolate downwards before the time of actual melt onset.

As the snow warms and reaches near melting temperatures internally, at the very snow surface, temperatures can remain lower than in the interior due to longwave radiative cooling of the surface. Therefore, the snow surface can remain cold while there is a sub-surface temperature maximum (Figure 10 a) that can eventually lead to subsurface melt. Similar internal melting is observed in, e.g., blue ice regions on the Antarctic ice sheet (e.g. Brandt and Warren, 1993;Cheng et al., 2003;Liston and Winther, 2005). While the magnitude of the difference between the snow surface temperature and the sub-surface temperature is debated (Brandt and Warren, 1993), the subsurface temperature maximum depends on the snow's extinction coefficient and is larger with denser snow, with larger grains lowering the specific surface area (SSA), and in the presence of ice layers, which are typical for perennial Antarctic sea ice (Nicolaus et al., 2009).

As the snow warming continues and successively affects lower and lower snow layers, first the interior and then lower layers reach near-melting or sporadic melting temperatures (Figure 10 b and c) with increases of liquid water content and diurnal or multi-day transitions into the funicular snow regime, when they are subject to strong, irreversible snow metamorphism and ice lenses or superimposed ice formation (Cheng et al., 2003;Haas et al., 2001). Only at a later stage, during instances of large atmospheric heat fluxes, the very snow surface becomes warm enough to be subjected to strong snow metamorphism as well (Figure 10 d).

The different stages in Figure 10 a-d are frequently interrupted or ending by colder periods which cause the prominent thaw/refreeze cycles. While the appearance of liquid water will generally reduce radar backscatter and increase microwave emissivity, it is the refreezing of the respective snow layers and irreversible snow metamorphism that causes the backscatter increases utilized in this paper.

With their intermediate penetration, it is therefore plausible that Ku-band signals sense initial snow property changes in the interior snow column first (Figure 10 b), while C-band and PMW signals receive their strongest contributions from the unchanged lower and topmost layers and therefore show no response at that time. C-band signals respond next, when the warming and sporadic wetting has reached the lower layers near the snow/ice interface (Figure 10 c). Finally, PMW signals, receiving their main power from the topmost snow layer, are only affected once the very surface is affected by thaw-refreeze cycles as well.

It should be noted that the penetration depth of both Ku- and C band into dry snow is at least more than a meter (Ulaby et al., 1986). However, increased backscatter along the propagation path through the snow at any depth will result in the observed overall backscatter increases. The longer wavelengths of C-band signals may not be sensitive to the initial metamorphism in the interior snow layers which is already sensed by the shorter Ku-band signals (Figure 10 b). Overall, at the 12 study locations on perennial ice the mean amplitude between the seasonal minimum and maximum is 13.35dB for the QSCAT time period, but only 7.66 and 9.35dB for ERS and ASCAT, respectively (Figure 2). This also indicates that Ku-band backscatter could be more strongly affected by a certain degree of snow metamorphism than C-band backscatter.

The mean time differences of 18 days between melt onset detected by Ku-band and C-band, and 6 days between C-band and PMW provides a reference for the time scales of initial warming and snow metamorphism in the Antarctic. Interestingly, in the Arctic Mortin et al. (2014) found hardly any temporal difference between melt onset dates observed by the same sensors. In agreement with our conceptual model above we interpret that behavior by the fact that snow on Arctic sea ice usually warms very rapidly throughout the entire snow column during melt-onset when it is already close to the melting temperature, and therefore all wavelengths respond at approximately the same time. This is consistent with the generally very rapid melt and disappearance of snow on sea ice in the Arctic discussed in the introduction.

5. Summary and conclusions

In this study, we compiled a time series of snowmelt onset dates on Antarctic sea ice from 1992 onwards using different radar scatterometer observations (ERS-1/2, ASCAT: 5.3 GHz; QSCAT: 13.4 GHz), in extension of previous work by Haas (2001). Doing so, we defined two major snowmelt stages: Pre-melt onset associated with the initial warming and increasing appearance of liquid water in the snowpack, followed by snowmelt onset related to diurnal thawing and refreezing of the snowpack.

Results show that the magnitude of seasonal and diurnal backscatter variations is highly dependent on latitude, related to earlier and more frequent snowmelt in the north (mid of November in the northern Weddell Sea). In contrast, regions farther south and closer to the continent reveal weaker seasonal and diurnal backscatter variations, and therefore less snowmelt attributed to the prevalent atmospheric conditions of cold and dry air and the absence of warm air advection events from the North.

For practical reasons we were unable to update this time series to include the 2015/16 to 2018/19 summer seasons, when Antarctic sea ice extent in September had reached record minima (e.g. Schlosser et al., 2018). It would be interesting to see in a follow up study if significantly earlier melt onset dates would be observed during those recent years. However, we believe that they will not, based on the facts that previous changes of ice extent did not strongly affect melt onset dates as mentioned above, that those recent changes may have a strong contribution from oceanic processes (Gordon et al., 2007;Turner et al., 2015), and that most potential surface changes may occur in the seasonal ice zone or closer to the marginal ice zone where our algorithm is not applicable.

Based on the observed successive timing of melt events retrieved from different sensors, i.e. C- and Ku-band radars and 37 GHz passive microwave radiometers, we developed a conceptual model of the temporal evolution of snow temperature and metamorphism and their effect on, and detectability by, different microwave sensors during the spring/summer transition: The model explains qualitatively how snow metamorphism occurs first in interior snow layers and mostly affects Ku-band signals. Once warming has reached the lower snow pack the resulting metamorphism there can be detected by C-band signals. The topmost snow layer remains coldest the longest by radiative cooling. Only when it warms and is affected by thaw/refreeze cycles at last do short wavelength passive microwave signals respond as well.

Based on the results obtained here, we suggest that there is a potential to observe snow processes at different depths from space, opening new avenues for studies of energy and mass budgets of snow on sea ice in the Southern Ocean. In addition, improved observations of snow metamorphism will contribute to better understanding and correction of uncertainties and spatial variability of space-borne retrievals of sea-ice concentration, snow depth and sea-ice thickness. However, improved microwave modeling informed by new in-situ observations of microwave properties and snow melt processes on Antarctic sea ice are required first to inform such activities.

Acknowledgement

Satellite data of radar backscatter were kindly provided by the Scatterometer Climate Record Pathfinder (SCP) project, sponsored by NASA (http://www.scp.byu.edu/), and sea-ice concentration data from the NASA National Snow and Ice Data Center Distributed Active Archive Center, Boulder, Colorado, USA. We acknowledge discussions about microwave emission and scattering behavior with Wolfgang Dierking, Sascha Willmes, and Marcus Huntemann. The work was funded by the Helmholtz Alliance "Remote Sensing and Earth System Dynamics" (HA-310) and the Alfred-Wegener-Institut Helmhotz-Zentrum für Polar- und Meeresforschung, Bremerhaven, Germany.

References

Abdalati, W., and Steffen, K.: Passive Microwave-Derived Snow Melt Regions on the Greenland Ice-Sheet, Geophysical Research Letters, 22, 787-790, Doi 10.1029/95gl00433, 1995.

Andreas, E. L., and Ackley, S. F.: On the differences in ablation seasons of Arctic and Antarctic sea ice, Journal of the Atmospheric Sciences, 39, 440-447, 10.1175/1520-0469, 1982.

Arndt, S., Willmes, S., Dierking, W., and Nicolaus, M.: Timing and regional patterns of snowmelt on Antarctic sea ice from passive microwave satellite observations, Journal of Geophysical Research - Oceans, 121, 5916-5930, 10.1002/2015JC011504, 2016.

Bevan, S. L., Luckman, A. J., Kuipers Munneke, P., Hubbard, B., Kulessa, B., Ashmore, D. W. J. E., and Science, S.: Decline in Surface Melt Duration on Larsen C Ice Shelf Revealed by The Advanced Scatterometer (ASCAT), 5, 578-591, 2018.

Brandt, R. E., and Warren, S. G.: Solar-heating rates and temperature profiles in Antarctic snow and ice, Journal of Glaciology, 39, 99-110, 1993.

Cheng, B., Vihma, T., and Launiainen, J.: Modelling of superimposed ice formation and subsurface melting in the Baltic Sea, Geophysica, 39, 31-50, 2003.

Colbeck, S. C.: A Review of Sintering in Seasonal Snow, CRREL Report, DTIC Document, 1997.

Denoth, A.: The pendular-funicular liquid transition in snow, Journal of Glaciology, 25, 93-98, 1980.

Drinkwater, M. R., and Liu, X.: Seasonal to interannual variability in Antarctic sea-ice surface melt, Ieee Transactions on Geoscience and Remote Sensing, 38, 1827-1842, Doi 10.1109/36.851767, 2000.

Ezraty, R., and Cavanié, A.: Intercomparison of backscatter maps over Arctic sea ice from NSCAT and the ERS scatterometer, Journal of Geophysical Research: Oceans, 104, 11471-11483, 1999.

Gordon, A. L., Visbeck, M., and Comiso, J. C. J. J. o. C.: A possible link between the Weddell Polynya and the Southern Annular Mode, 20, 2558-2571, 2007.

Haas, C.: The seasonal cycle of ERS scatterometer signatures over perennial Antarctic sea ice and associated surface ice properties and processes, Ann Glaciol, 33, 69-73, 10.3189/172756401781818301, 2001.

Haas, C., Thomas, D. N., and Bareiss, J.: Surface properties and processes of perennial Antarctic sea ice in summer, Journal of Glaciology, 47, 613-625, 10.3189/172756501781831864, 2001.

Haas, C., Nicolaus, M., Willmes, S., Worby, A., and Flinspach, D.: Sea ice and snow thickness and physical properties of an ice floe in the western Weddell Sea and their changes during spring warming, Deep-Sea Res Pt Ii, 55, 963-974, 10.1016/J.Dsr2.2007.12.020, 2008.

Liston, G. E., and Winther, J.-G.: Antarctic surface and subsurface snow and ice melt fluxes, Journal of Climate, 18, 1469-1481, 2005.

Long, D. G., Hardin, P. J., and Whiting, P. T.: Resolution Enhancement of Spaceborne Scatterometer Data, Ieee Transactions on Geoscience and Remote Sensing, 31, 700-715, Doi 10.1109/36.225536, 1993.

Lytle, V., and Ackley, S.: Heat flux through sea ice in the western Weddell Sea: Convective and conductive transfer processes, Journal of Geophysical Research: Oceans, 101, 8853-8868, 1996.

Lytle, V. I., and Ackley, S. F.: Snow-ice growth: a fresh-water flux inhibiting deep convection in the Weddell Sea, Antarctica, Ann Glaciol, 33, 45-50, Doi 10.3189/172756401781818752, 2001.

Maksym, T., Stammerjohn, S. E., Ackley, S., and Massom, R.: Antarctic Sea Ice-A Polar Opposite?, Oceanography, 25, 140-151, 10.5670/oceanog.2012.88, 2012.

Markus, T., Stroeve, J. C., and Miller, J. A.: Recent changes in Arctic sea ice melt onset, freezeup, and melt season length, Journal of Geophysical Research, 114, C12024, 10.1029/2009jc005436, 2009.

Martinson, D. G., and Iannuzzi, R. A.: Antarctic Ocean-ice interaction: Implications from ocean bulk property distributions in the Weddell Gyre, Wiley Online Library, 1998.

Massom, R. A., Eicken, H., Haas, C., Jeffries, M. O., Drinkwater, M. R., Sturm, M., Worby, A. P., Wu, X. R., Lytle, V. I., Ushio, S., Morris, K., Reid, P. A., Warren, S. G., and Allison, I.: Snow on Antarctic Sea ice, Rev Geophys, 39, 413-445, 10.1029/2000rg000085, 2001.

Meier, W. N., Hovelsrud, G. K., Oort, B. E., Key, J. R., Kovacs, K. M., Michel, C., Haas, C., Granskog, M. A., Gerland, S., and Perovich, D. K.: Arctic sea ice in transformation: A review of recent observed changes and impacts on biology and human activity, Rev Geophys, 52, 185-217, 2014.

Mortin, J., Howell, S. E. L., Wang, L. B., Derksen, C., Svensson, G., Graversen, R. G., and Schroder, T. M.: Extending the QuikSCAT record of seasonal melt-freeze transitions over Arctic sea ice using ASCAT, Remote Sensing of Environment, 141, 214-230, Doi 10.1016/J.Rse.2013.11.004, 2014.

Nandan, V., Geldsetzer, T., Mahmud, M., Yackel, J., and Ramjan, S.: Ku-, X-and C-Band Microwave Backscatter Indices from Saline Snow Covers on Arctic First-Year Sea Ice, Remote Sensing, 9, 757, 2017.

Nicolaus, M., Haas, C., Bareiss, J., and Willmes, S.: A model study of differences of snow thinning on Arctic and Antarctic first-year sea ice during spring and summer, Annals of Glaciology, 44, 147-153, 2006.

Nicolaus, M., Haas, C., and Willmes, S.: Evolution of first-year and second-year snow properties on sea ice in the Weddell Sea during spring-summer transition, Journal of Geophysical Research, 114, 10.1029/2008JD011227, 2009.

Onstott, R., and Shuchman, R.: SAR measurements of sea ice, Chapter, 3, 81-115, 2004.

Onstott, R. G.: SAR and scatterometer signatures of sea ice, Microwave remote sensing of sea ice, 73-104, 1992.

Parkinson, C. L., and Cavalieri, D. J.: Antarctic sea ice variability and trends, 1979-2010, Cryosphere, 6, 871-880, 10.5194/tc-6-871-2012, 2012.

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, 10.5194/tc-8-1607-2014, 2014.

Ridler, T., and Calvard, S.: Picture thresholding using an iterative selection method, IEEE trans syst Man Cybern, 8, 630-632, 1978.

Schlosser, E., Haumann, F. A., and Raphael, M. N.: Atmospheric influences on the anomalous 2016 Antarctic sea ice decay, Cryosphere, 12, 1103-1119, 10.5194/tc-12-1103-2018, 2018.

Simmonds, I., and Keay, K.: Mean Southern Hemisphere extratropical cyclone behavior in the 40-year NCEP–NCAR reanalysis, Journal of Climate, 13, 873-885, 2000.

Stammerjohn, S., Martinson, D. G., Smith, R. C., Yuan, X. J., and Rind, D.: Trends in Antarctic annual sea ice retreat and advance and their relation to El Niño -Southern Oscillation and Southern Annular Mode variability, Journal of Geophysical Research: Oceans, 113, 2008.

Stammerjohn, S., Massom, R., Rind, D., and Martinson, D.: Regions of rapid sea ice change: An inter-hemispheric seasonal comparison, Geophysical Research Letters, 39, 10.1029/2012gl050874, 2012.

Stroeve, J. C., Markus, T., Boisvert, L., Miller, J., and Barrett, A.: Changes in Arctic melt season and implications for sea ice loss, Geophysical Research Letters, 41, 1216-1225, Doi 10.1002/2013gl058951, 2014.

Sturm, M., and Massom, R. A.: Snow & Sea Ice, in: Sea Ice. 3rd Edition, edited by: Thomas, D., Wiley-Blackwell, New York (UAS) & Oxford (UK), 65-109, 2017.

Tison, J.-L., Worby, A., Delille, B., Brabant, F., Papadimitriou, S., Thomas, D., De Jong, J., Lannuzel, D., and Haas, C. J. D. S. R. P. I. T. S. i. O.: Temporal evolution of decaying summer first-year sea ice in the Western Weddell Sea, Antarctica, 55, 975-987, 2008.

Turner, J., Barrand, N. E., Bracegirdle, T. J., Convey, P., Hodgson, D. A., Jarvis, M., Jenkins, A., Marshall, G., Meredith, M. P., Roscoe, H., Shanklin, J., French, J., Goosse, H., Guglielmin, M., Gutt, J., Jacobs, S., Kennicutt, M. C., Masson-Delmotte, V., Mayewski, P., Navarro, F., Robinson, S., Scambos, T., Sparrow, M., Summerhayes, C., Speer, K., and Klepikov, A.: Antarctic climate change and the environment: an update, Polar Rec, 50, 237-259, 10.1017/S0032247413000296, 2014.

Turner, J., Hosking, J. S., Bracegirdle, T. J., Marshall, G. J., and Phillips, T.: Recent changes in Antarctic sea ice, Philosophical Transactions of the Royal Society of London A: Mathematical, Physical and Engineering Sciences, 373, 20140163, 2015.

Turner, J., Hosking, J. S., Marshall, G. J., Phillips, T., and Bracegirdle, T. J.: Antarctic sea ice increase consistent with intrinsic variability of the Amundsen Sea Low, Climate Dynamics, 46, 2391-2402, 10.1007/s00382-015-2708-9, 2016.

Ulaby, F. T., Moore, R. K., and Fung, A. K.: Microwave Remote Sensing. Active and Passive. Vol. 3. From Theory to Applications., Addison Wesley Pub., London, U.K., 1065–2162 pp., 1986.

Willmes, S., Bareiss, J., Haas, C., and Nicolaus, M.: The importance of diurnal processes for the seasonal cycle of sea-ice microwave brightness temperatures during early summer in the Weddell Sea, Antarctica, Annals of Glaciology, 44, 297-302, 2006.

Willmes, S., Haas, C., Nicolaus, M., and Bareiss, J.: Satellite microwave observations of the interannual variability of snowmelt on sea ice in the Southern Ocean, Journal of Geophysical Research-Oceans, 114, 10.1029/2008jc004919, 2009.

Willmes, S., Nicolaus, M., and Haas, C.: The microwave emissivity variability of snow covered first-year sea ice from late winter to early summer: a model study, The Cryosphere, 8, 891-904, 2014.

Yackel, J. J., Barber, D. G., Papakyriakou, T. N., and Breneman, C.: First-year sea ice spring melt transitions in the Canadian Arctic Archipelago from time-series synthetic aperture radar data, 1992-2002, Hydrological Processes, 21, 253-265, Doi 10.1002/Hyp.6240, 2007.

Copernicus Publications
The Innovative Open Access Publisher

Figure 1: The logo of Copernicus Publications.

Anonymous Referee #1

Received and published: 10 March 2019

The manuscript builds on the study of Haas et al. (2001) on the analysis of spaceborne scatterometer data for investigating snow melt. The work compiles a time-series of melt onset information from ERS-1/2, QuikSCAT, and ASCAT for the 1992 to 2015 period. The retrieved dates are then compared to those derived from passive microwave data. The analysis presents new and relevant information about snow on Antarctic sea ice and the capability to remotely sense snow conditions on Antarctic sea ice. There are several aspects of the analysis that require clarification, more details and revised interpretation based on previous studies. Please find detailed comments below.

We highly appreciate the great work that the reviewer put into revising our manuscript. This work is really excellent and we realize that he / she is really familiar with this field of research and has a great expertise to make most useful comments and suggestions. We thank the reviewer for the very critical questioning regarding the described relevant and dominant processes causing seasonal changes in the properties of the Antarctic snowpack. To overcome these missunderstandings, we added more explanations in the respective sections as pointed out in the following explicite responses.

Page 1, line 13. Metamorphism is an umbrella term for several types of metamorphic processes of snow. What exactly do the authors mean by metamorphism? The use of it in the manuscript is ambiguous at times. I recommend adding “melt” or “freeze- melt” before “metamorphism” throughout the manuscript to differentiate it from other metamorphic processes.
We have added “destructive” to describe what kind of metamorphism we refer to. Other than that we believe that it is clear from the context that this is what is meant, and don’t feel that it needs to be repeated frequently.

Page 1, lines 23-26. I suggest rewriting this section since it’s an over-extension of the results. The conceptual model hypothesizes that the evolution of seasonal snow temperature profiles could affect different microwave bands. It’s also important to define the environmental conditions that the conceptual model is limited to. From what’s been described, it seems like the conceptual model would be applicable to a snowpack with low density, no damp/saline basal layer, no internal icy layers or lenses, somewhat uniform vertical grain structure, and over perennial ice where high-frequency diurnal temperature fluctuations occur simultaneously with a slow, steady increase in mean temperature.
We have added “on thick Antarctic snow” to the abstract to indicate that our model may not be applicable to all sea ice regions worldwide. Other than that we don’t feel that much more information should be given in the abstract., although we have added more specific information later in the text.

Page 2, line 10 and throughout the manuscript. Please specify which Haas et al. 2001 paper that you refer to.
Throughout the manuscript as well as in the reference list we carefully distinguish between Haas et al, 2001 and Haas, 2001.

Page 2, line 10. How do variations in snow properties affect the mass budget of the ocean?
We agree that the given sentence is misleading and therefore adapted it towards the “mass budget of sea ice”.

Page 2+ Snowmelt onset in the Antarctic is described as more subtle than the Arctic. What is meant by subtle? Previous studies describe warm, marine cyclones that bring dramatic temperature swings and/or rainfall throughout the year, and with increasing frequency going into summer. The induced melt from these events is not subtle and typically results in a more structurally-complex snowpack. Similarly, the manuscript overly generalizes Arctic snowmelt, as on page 21 line 9-10, “...warms very rapidly throughout the entire snow column during melt onset...” What observations support these statements? Snowmelt is often not as rapid and continuous in the Arctic as de- scribed in the manuscript. Peng et al. 2018 is an insightful example with their definitions of melt onset periods. Studies have shown numerous snowfall and freeze events during spring and summer, which highlights the discontinuous nature of melt (and freeze) that seems to occur in all snow environments.
Which studies does the reviewer refer to? Our statements are meant in general and address the fact that no melt ponds are observed in the Antarctic, in contrast to the Arctic. It is clear that there are instances when melt in the Arctic is retarded by new snow events or cold spells. However, this does not change the general recognition that snow melt in the Antarctic is much more subtle/slow/sporadic than in the Arctic. A more detailed deicussion of differences between Arctic and Antarctic snow processes is beyond the scope of that paper. We have clarified the text:

However, on Antarctic sea ice, the retrieval of snowmelt onset is more challenging because thawing and melting are weaker and more sporadic than in the Arctic. There is widespread occurrence of diurnal thaw-freeze cycles (Haas et al., 2001;Nicolaus et al., 2006;Nicolaus et al., 2009), or the snow may only thaw during the passage of warm marine cyclones, with the snow refreezing shortly after (Willmes et al.,xxx). These thaw-refreeze events cause strong, destructive snow metamorphism. Under more intensive melting conditions, snow changes from the pendular to the funicular regime (e.g. Denoth, 1980) where the liquid snow melt water percolates through the snowpack to lower, colder layers or to the ice surface where it refreezes to form superimposed ice (Tison et al., 2008;Haas et al., 2008;Haas et al., 2001;Nicolaus et al., 2009;Willmes et al., 2009).

Page 2, line 31. In contrast to what?
'In contrast" was meant to distinguish between dominant processes in winter (snow-ice formation) and spring/summer (superimposed ice). However, to reduce the confusion, we removed the discussion of flooding and snow ice from this section and have included it in our later discussion of winter processes preceding the transformation of first-year ice to perennial ice during melt onset.

Page 2+. Salinity affects radar backscatter. Previous observations not only show brine wicking up to 15-20 cm into the Antarctic snowpack from its base, but that as a whole the Antarctic snow cover is saline. I encourage the authors to consider the effects of salinity on the retrieved dates and adding in a discussion on this topic in the manuscript.
We are well aware of the saline nature of some snow on first year ice, and that there can be widespread flooding. These properties are also responsible for the ice's low backscatter in winter. However, once the snow warms the brine typically drains and snow salinity measurements in summer show negligible salinity throughout. The text has been rewritten significantly to clarify these points.

Page 3, line 2. Arndt et al. 2016 seems like the wrong reference here.
We agree and deleted it.

Page 3, lines 17-18. If flooding is indeed an important mechanism for Antarctic snow and sea ice as described in Massom et al. (2001), I recommend adding more discussion on what the potential effects of flooding are on the results. Here and elsewhere in the manuscript, flooding is swept "under the rug" so to speak by suggesting that it only occurs right before the sea ice cover disintegrates or is limited to the edge of the sea ice pack.
See above, we have consolidated the text to better separate between winter and summer properties and processes, and have described that salty snow and flooding are responsible for low backscatter during winter. We have then clarified that the snow desalinates during spring and that negative freeboard is uncommon on perennial ice.

Page 3, line 23. Superimposed ice. Do we know that this it is a wide-spread phenomenon during snow melt onset? My understanding is that a substantial amount of snowmelt is required before the meltwater can fully percolate down to the ice surface. I suspect superimposed ice would occur after snow melt onset for this reason. The observations in Haas et al. 2001 were ~2 months after the snow melt onset dates shown here, so it's not clear if the presence of superimposed ice can be used to interpret the backscatter for identifying melt onset. There may be comparable situations in the Antarctic where superimposed ice does not form at all, see Polashenski et al. 2017 for an Arctic example. Based on the literature, rainfall may also be important to consider in Antarctic snow.
We agree with the reviewer that superimposed ice is not responsible for the initial backscatter rises. However, together with icy snow and ice layers it contributes to maintaining high radar backscatter by the end of the summer. We have clarified this in the text by restructuring and adding a few words. We added a few words about passage of warm cyclones to include cases of rain fall. Again, these events are mostly sporadic and typically lead not to strong, accelerated melt nor the formation of melt ponds.

Page 4, line 3. "Adjusted" would be a more appropriate word that "corrected" here and elsewhere in the manuscript.
We agree and adapted it.

Page 7. The sample size is limited to a pixel for each location to reduce the variability associated with different ice conditions. How sensitive are the results to one pixel vs. a multi-pixel average? I would suspect that variability is larger for a single pixel due to the advection of ice with differing properties. An eight-neighbor mean may be more stable.
We had actually conducted our analysis for individual pixels and groups of 3x3 pixels. We agree that a larger region of 3x3 pixels will provide more representative results for the respective areas. Therefore, we are now reporting the results of the analysis of the 3x3 pixel regions. However, this has no effect on the presented results in the manuscript but the given dates shifted slightly by 1-2 days back or forward.

Page 7, line 10. It would be helpful to clarify that the sea ice concentrations are from the Bootstrap algorithm.
We agree and added that information.

Page 5, lines 15-16. What information was used to determine which areas were pre- dominantly seasonal and perennial ice? Is there the possibility that some years had a mixture of ice types at the designated sites?
The given locations were chosen to agree with those of Haas (2001) in order to ensure both a proper comparison between both studies and a reasonable continuation of the given time series. However, it can not be ruled out that single

points are not in all given years covered by a MYI regime. In such years there may not be any results because our algorithm does not work for thin, deteriorating FYI. We have stated the percentage of successful retrievals on page xxx: Overall, pre-melt and melt onset dates were retrievable for 79% and 64% of all analyzed pixels. For the seasonal sea-ice regime, pre-melt and melt onsets were obtained for 46% and 26% of the analyzed pixels.

Page 5, lines 18. Anderson, Bliss, Peng appear to be under-referenced with regard to melt onset detection from passive microwave data.
Thank you for these suggestions but we prefer to limit our citations to a few, most relevant and recent publications.

Page 7, lines 26-29. How would a 70% sea ice concentration threshold remove flooded ice from your sampling? How are ice concentration and flooded sea ice related?
Clarified: This avoided contamination of results by wind-roughened water (Drinkwater and Liu, 2000), and effectively eliminated regions of deteriorating, thin ice where surface flooding and break up into small floes and brash ice may occur, e.g. in the marginal ice zone, with competing effects on backscatter evolution.

Page 8, figure 4. It would be helpful to show the sea ice concentration here and either as additional figures or in supplementary information for figures 2 and 3 given its influence on backscatter. How were the start and end points of the bolded solid lines determined?
For Figure 4 the grey shaded area indicates the part of the time series with sea-ice concentration less than 70%. As given in the figure caption, the bold lines indicate the time period included in the transition retrieval (01 Oct to 31 January). However, we added these dates in order to make this clearer.

Page 9, lines 1-11. How much of this is speculation? Were coincident in situ observations linked with observed changes in backscatter? Please clarify in the manuscript.
Most of our observations were carried out during the ISPOL drift station in 2004/05. We added more references to that part.

Page 9, line 10-11. Please specify that you mean a positive albedo feedback. The manuscript neglects here and elsewhere the possibility of stopping surface melt due to fresh snowfall.
We agree and clarified that.

Page 9, line 20-22. How was October 1st determined? How were the 2 dB and 3 dB thresholds determined? Are the results sensitive to these choices?
The thresholds are based on the average rise of the backscatter values during the spring/summer transition. This is stated in the last sentence of the paragraph. It is unlikely that melt onset would occur before.

Page 9, lines 26-30. What fraction of the time-series had indeterminable melt dates for perennial and seasonal ice? It would be helpful to put those numbers in the results section.
We agree and added the percentage of the respective successful retrievals: Overall, pre-melt and melt onset dates were retrievable for 79% and 64% of all analyzed pixels. For the seasonal sea-ice regime, pre-melt and melt onsets were obtained for 46% and 26% of the analyzed pixels.

Page 10, line 5. It would be helpful to give more detail on what the “regionally adaptive” approach does.
The working principle of the regionally adoptive approach is described right after the approach is mentioned.

Page 10, lines 18-20. It would be helpful to give more detail here. What is the iterative algorithm converging on exactly? Is a priori information on thresholds needed?
The iterative threshold selection algorithm derives from the given $d\sigma^0$ values per pixel the optimized threshold in order to distinguish between summer and winter conditions. We slightly adjusted that sentence in order to make this clearer.

Page 12, line 14. Is 7.66 dB different from the value found in Haas et al. 2001? If so, why?
Numbers are slightly different from the ones given in Haas (2001) as the amount of analyzed pixels slightly differ between both studies.

Page 13, Section 3.2. Similar to an earlier comment, approximately what fraction of the time-series had detectable melt onset? This can help provide the reader with context on the limitations (and possibilities) of this approach over seasonal ice.
We agree and provided the respective fraction of detectable dates.

Page 17, figure 9. It would be helpful to give the sample size of each mean difference, either in the figure or in a table, so that readers can appropriately interpret the spread.
We agree and added these numbers to the figure.

Page 18, lines 1-3. I suggest rewording this sentence. As it's stated, it sounds like perennial ice has larger brine volume at the surface, which is probably not what you mean.
Reworded: Instead, the younger and thinner seasonal ice is warmer and more salty than perennial ice, and has larger brine volume at the snow/ice interface causing low backscatter through winter

Page 18, lines 7-9. Do you have a reference for this statement?
Yes, we added a respective reference: (Martinson and Iannuzzi, 1998).

Page 18, line 25. "Instead, we suggest. . ." I recommend changing this to: "Instead, other studies have shown. . ." since this analysis does not show results on these topics.
We agree and added that.

Page 19, line 3. ". . .seasonal mass balance of Antarctic sea ice in the future." Based on the results, isn't this approach only appropriate for perennial sea ice? If so, it would be good to make that clarification in this ending paragraph.
We agree and specified that we are referring to perennial sea ice only.

Page 19, Section 4.3. This is an interesting idea, but it misses some fundamental characteristics of snow, the most significant being light penetration in snow vs. blue ice, the existence of a saline, damp layer at the base of the snowpack and icy layers and lenses within the snowpack. The Brandt and Warren (1993) study shows that visible wavelengths are not absorbed at depth in a snowpack, but are scattered back to the surface. Near-infrared wavelengths only get absorbed in the top few millimeters of the snowpack. The study then describes optimal conditions where sub-surface melt could be important. These are low-albedo ice like blue ice and low-density snow, like depth hoar. Both conditions are not typical of snow on Antarctic sea ice. The description on page 20, lines 11-16 must be a misinterpretation of the Brant and Warren analysis and needs revising.
We disagree with the reviewer and are confident that we do not misinterpret the Brant and Warren study. We are clear about the importance of extinction coefficients, and the debate about how strong the sub-surface temperature maximum can be. However, we have added a few words to actually suggest that properties of metamorphic snow on Antarctic sea ice can be comparable to the properties of blue ice (which is essentially clear ice with few air bubbles), in as they have large grains lowering the snow's specific surface area (SSA), and ice layers which are essentially clear ice with few air bubbles.

Changed text: Similar internal melting is observed in, e.g., blue ice regions on the Antarctic ice sheet (e.g. Brandt and Warren, 1993;Cheng et al., 2003;Liston and Winther, 2005). While the magnitude of the difference between the snow surface temperature and the sub-surface temperature is debated (Brandt and Warren, 1993), the subsurface temperature maximum depends on the snow's extinction coefficient and is larger with denser snow, with larger grains lowering the specific surface area (SSA), and in the presence of ice layers, which are typical for perennial Antarctic sea ice (Nicolaus et al., 2009).

Related, several studies have since shown technical issues with radiative heating of sensors, such as in Cheng et al. 2003, making observed sub-surface temperature increases somewhat dubious.
We acknowledge the fact that temperature measurements in warm snow in a radiative environment can be challenging. However, we do not rely on measurements for developing our conceptional, qualitative model, and Cheng's modeling and other considerations suggest that the occurrence of subsurface temperature maxima in the snow are quite possible. This is also demonstrated by the subsurface melting on blue ice, even though albedo and extinction coefficients may not be directly comparable with sea ice as discussed above. As witnessed by the authors on Novo airbase, water pockets under a surface layer of ice are quite common during summer, resulting exactly from the vertical profiles of radiation absorption and emission discussed here.

Secondly, there is a wealth of papers that show the widespread occurrence of icy layers and a damp, saline basal layer in snow on Antarctic sea ice, in contrast to an assumption of dry snow as on page 20, line 33. This damp layer, as well as internal icy layers within the snowpack, greatly modify the electromagnetic signature of snow, its temperature gradient and snow metamorphism. I encourage the authors to give these aspects consideration and incorporate them into the proposed hypothesis. If the hypothesis in Section 4.3 conflicts with typical characteristics of Antarctic snow, then explicitly state that it does and describe specifically which environmental conditions the hypothesis is limited to.
We feel that throughout the text and in our replies above we have argued sufficiently and have changed the text sufficiently to acknowledge the presence of damp, saline snow in winter, but have also convincingly explained that saline snow does not play a role in summer. On the contrary, ice layers, which are mentioned by the reviewer along

with saline snow although they usually do not form concurrently in the same seasons, do contribute to the observed backscatter increases and most likely also play an important role in the development of a subsurface temperature maximum.

Although simple, the schematic in Garrity (1992) is informative and may help with this.
We are well aware of the work of Garrity and have worked with her in the field. However, we find that work little useful for our study as it describes only the short time of snow wetting during short melt events, and does not consider the temporal changes throughout the melting period and refreezing. The reported floes were in the marginal ice zone. We suspect that most of that ice did not survive the summer.

For figure 10, it would be helpful to overlay snow grain symbols so that readers can have a better idea of which melt-induced characteristics you're referring to in the snowpack for each stage. The WMO and Colbeck (1991) would be useful references for this.
Unfortunately, there is not one symbol for metamorphic snow but they are distinguished for different grain types which would be misleading at this stage. We therefore decided to keep the given symbols but added horizontal arrows between the day- and nighttime temperature profile in order to make the thaw-freeze cycle clearer.

Page 21, lines 24-27. Could you provide some references to support these statements? Also, what is meant by "the most potential surface changes?"
We have rephrased the sentence and also added a reference for the role of the ocean in contributing to Antarctic sea ice extent variability: However, we believe that they will not, based on the facts that previous changes of ice extent during our study period did not strongly affect melt onset dates as mentioned above, that those recent changes probably have a strong contribution from oceanic processes (Turner et al., 2015), and that most of the potential surface changes related to ice extent fluctuations may occur in the seasonal ice zone or closer to the marginal ice zone where our algorithm is not applicable.

Page 21-22, lines 30-32/lines 1-2. How do we know this is true? Are there references to support these statements?
We don't understand this comment. The paragraph is a summary of our findings and conceptual model and has been supported by the discussion throughout the text.

Page 22, line 3. It's stated that the results obtained in this study demonstrate the potential to observe snow processes at different depths from space. This is not true. However, the study does hypothesize that this could be possible, which is different from a demonstration. Please correct this for clarity.
Rephrased: Based on the results obtained here, we suggest that there is a potential to observe snow processes at different depths from space, opening new avenues for studies of energy and mass budgets of snow on sea ice in the Southern Ocean.

Anonymous Referee #2

Received and published: 11 March 2019

General Comments:

The authors examined the onset of snow melt over Antarctic sea ice using data sets from scatterometers (ERS-1/2, QSCAT and ASCAT) and passive microwave radiometers. Between 1992 and 2015, they found insignificant changes in onset dates which they claim be consistent with the small trends in Antarctic sea ice extent. Also, they used the differential lag in onset timing between the observing instrument to develop a conceptual model for inferring the evolution of the depth/temperature-dependent snow processes during the onset period, and conclude that multi-wavelength instruments may be able to provide information on the behavior of the snow column on Antarctic sea ice during early melt.

Throughout the paper, the authors contrasted the behavior of the Arctic and Antarctic – I find those discussions to be interesting and useful.
We highly appreciate the great work that the reviewer put into revising our manuscript and we realized that he/she is really familiar with the topic of our manuscript. Therefore, we thank the reviewer, as the constructive comments, improved significantly the quality of our manuscript.

The only comment is that the authors inferred from only a few samples (12) the general behavior of the onset-dates of circumpolar ice cover and their relationship to the observed trend in ice extent. This is less credible without more justification as to why a non-uniform sampling of the ice cover (Fig. 1) is sufficient for this analysis.
We had actually conducted our analysis for individual pixels and groups of 3x3 pixels. We agree that a larger region of 3x3 pixels will provide more representative results for the respective areas. Therefore, we are now reporting the results of the analysis of the 3x3 pixel regions. However, this has no effect on the presented results in the manuscript but the given dates shifted slightly by 1-2 days back or forward. However, we refrain from applying the analysis to the entire Antarctic sea-ice area, as there is, so far, no reliable data set on the respective ice types in the ice-covered Southern Ocean.

I would like the comments below addressed prior to publication.

Detailed Comments:
Page:Line number

1:28 While it is true that the circumpolar ice extent has changed insignificantly over the period of study, the trends are significant in the different sectors (e.g., Ross Sea sector). I think that fact should be noted and there are implications as far as the discussions in the remainder of the text regarding expected trends in the onset dates and ice extent.
We agree that it is worth mentioning the regional differences in the temporal evolution of the sea-ice extent over the past decades. We therefore added this fact in the manuscript.

3:20 This is in contrast to what is expected in the Arctic, where backscatter from perennial ice is expected to decrease during the summer. Perhaps another point to note.
This point is already noted in the beginning of page 3 and is therefore not noted again.

6:19 Need clarification: Is it the daily product that was used or the twice daily product? On p.6, the text indicated only the daily product is used.
The word “daily” was wrong and misleading at that point. As mentioned in the following line, QSCAT is given as a twice-a-day product, which is also used here for the analysis of diurnal variations in the snowpack.

7:10 Please specify which ice concentration product is used here.
We used the Bootstrap sea-ice concentration data product. We added this information.

7:15 Perhaps it’s good to point out how the samples were ‘carefully’ chosen to reflect/represent the large-scale behavior/trends of the Southern Ocean ice cover.
The chose locations were the same as those from Haas (2001) in order to ensure both a proper comparison between both studies and a reasonable continuation of the given time series. To point that out, we added the respective reference.

9:1 I don't think 'extensive' is appropriate here – let the reader decide.
We agree and deleted that word.

Figures 3&4. Shouldn't the seasonal ice in sample D disappear during the summer?
Yes, it does disappear. That's why the time period between end of December and end of March is shaded gray in Figure 4b.

Figure 5. Are the backscatter for both C-band and Ku-band merged here? If so, please indicate so because one would expect differences between the two wavelengths.
Yes, we added that.

18:8 Large oceanic heat flux (I imagine relative to the Arctic) – a reference is appropriate here.
Yes, we added a respective reference: Martinson, D. G., and R. A. Iannuzzi (1998), *Antarctic Ocean-ice interaction: Implications from ocean bulk property distributions in the Weddell Gyre*, Wiley Online Library, doi:10.1029/AR074p0243.

18:13 meaningful for? For indicating the ice extent?
We referred that statement to the overall upcoming analysis and discussion (as e.g. sea-ice season duration). To make this clearer, we added this to the given sentence.

18:24 I think this is what you are referring to above, i.e., 18:13.
See previous comment.

Section 4.2 the suggestion here that snow processes may be secondary in explaining the ice extent is important – perhaps worth noting in the abstract. Your work points to that and it is geophysically important, but saying that it is 'NOT' important may be a bit too strong without more discussion and supporting evidence.
We agree and weakened the given statement in the respective context. However, we do not see the need to add this to the abstract as the main focus should be kept on the seasonal snow processes.

20:14 This conceptual model depends on the initial changes to occur in the subsurface prior to that on the surface such that permittivity changes in the interior, while in the pendular regime, leads the change at the surface. I think this is perhaps too dependent on the temperature argument. Is the temperature profile entirely necessary?
Temperature is tbe key physical indicator for snow metamorphism and variations in liquid water content, and therefore we believe that we can not argue with heavily relying on the snow temperature profile and its diurnal and seasonal variations.