We are grateful to the referee for his/her time dedicated to this manuscript and for the constructive comments, which were all taken into account in the revised manuscript. Below, we answer point-by-point all the comments. The comments are reproduced in blue and the authors' responses (AR) are provided in black. The underlined texts are our corresponding changes in the revised manuscript.

The main changes in the revised manuscript include:

- Continuous melt onset (the first day when snowmelt lasts for at least three consecutive days) was added to investigate the pan-Antarctic snowmelt dynamics.
- The introduction section was revised to describe the motivation clearly and concisely.
- The melt detection methods and the evaluation method were described in more detail.
- The comparison between melt extent on the ice sheet and sea ice was removed.
- Figure 5-13 were redrawn, two figures were added as supplements.
- The manuscript was edited by a native English speaker.

Author Response to Referee #1

The presented paper is addressing the melt season in the Antarctic on the Antarctic ice shelves and the Antarctic sea ice cover. The research uses methods for the melt detection from AMSR-E and AMSR2 which are well established and the correction for ice concentration is promising idea to improve the melt onset detection. However, some of the analysis seems shallow and not well documented. Many information on how the results were obtained are missing.

General Comments:

1. The definition of melt is unclear in the manuscript. What exactly is supposed to be detected and discussed?

AR1: Snowmelt detected by radiometers is actually the presence of snow liquid water (Zheng et al., 2019). We clarified this issue in the revised manuscript:

> Therefore, snowmelt can be detected via microwave radiometry by identifying the sharp changes in microwave brightness temperatures (Tb) caused by the presence of snow liquid water (Serreze et al., 1993; Liu et al., 2005).

Although snow liquid water is produced by surface snowmelt, the presence of liquid water does not always indicate snowmelt. This is because liquid water may remain in snowpack after intense surface snowmelt. However, to be consistent with the previous studies (e.g., Abdalati and Steffen, 1995; Picard and Fily, 2006; Tedesco, 2009; Willmes et al., 2009; Arndt et al., 2016), "snowmelt" is still used in this study. We clarified this issue in Section 5.2 (Uncertainties):

> It should be noted that the presence of snow liquid water detected by AMSR-E/2 does not necessarily mean that the snowpack is melting because it takes time for meltwater to refreeze. In addition, after refreezing of surface snow, subsurface liquid water can still be detected by radiometer due to the penetrating capacity of microwaves (Ashcraft and Long, 2006).

2. Some of the results regarding the melt onset and length are in line with other papers, however the melt onset of sea ice seems quite early in comparison to the cited references and other observations. Thus these early detected

melt onset (July, August) need further physical investigation and should probably not directly interpreted as the real melt onset.

AR2: We thank the referee for this insightful comment.

- Melt onset investigated in this study (the first day that snowmelt is detected) is different from that (the first day when snowmelt lasts for at least three consecutive days) examined in Willmes et al. (2009). In previous studies, the former one was also defined as "early melt onset" (e.g., Semmens et al., 2013; Bliss et al., 2017), while the latter one was regarded as "continuous melt onset" (e.g., Markus et al., 2009) or "persistent melt onset" (e.g., Zheng et al., 2018).
- Early melt onset (EMO) always occurs much later than continuous snowmelt onset (CMO), especially on the first-year sea ice (Fig. R1). Surface melt on the Antarctic sea ice periodically occurs in winter (Massom et al., 2001). In August 2002, early melt events were observed on the first-year sea ice in the Ross Sea, while CMO did not occur until early November (Fig. R1c).

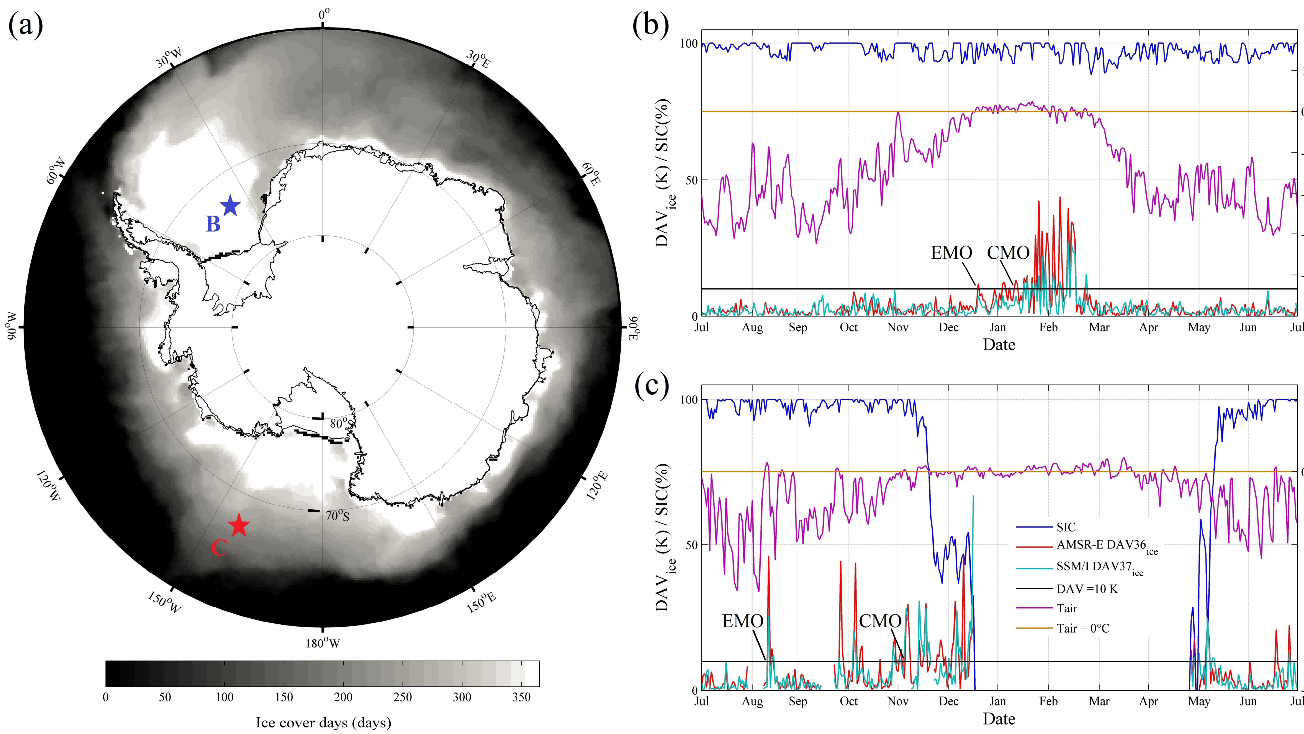


Fig. R1. Surface snowmelt detection on the Antarctic sea ice. (a) Pan-Antarctic ice cover days in 2002-2003, Point B and C show the locations of the pixels examined in (b) and (c). (b) and (c) show the comparisons of sea ice concentration (SIC), ERA-Interim Tair and satellite observations for a multi-year sea ice pixel (Point B) and a first-year sea ice pixel (Point C). $DAV37_{ice}$ and $DAV36_{ice}$ denote diurnal amplitude variations (DAV) of vertically polarized SSM/I 37 GHz Tb and AMSR-E 36.5 GHz Tb contributed by the ice portion, respectively.

- To compare with the results from Willmes et al. (2009) (hereafter W09), CMO was also included in the revised manuscript. Two different kinds of "melt onset" were investigated in this study:

  Considering the existence of both transient and persistent snowmelt in the pan-Antarctic, early melt onset (EMO, the first day when snowmelt is detected) and continuous melt onset (CMO, the first day when snowmelt lasts for at least three consecutive days) were investigated in this study.

  On average, CMO was about 53 days later than EMO. CMO derived from AMSR-E and W09 agreed well with each other at high latitudes during 2002-2008. However, AMSR-E found an earlier CMO on the marginal sea ice compared with the results from W09 (Fig. 10). The reasons for their differences were explained:

First, W09 only studied surface snowmelt on sea ice after 1 October, while the melt season begins on 1 July in this study. Second, the $DAV36_{ice}$ algorithm can amplify snowmelt signals by reducing the effect of open water, so that more melt events can be recognized (Fig. 3). Third, compared with SSM/I, AMSR-E operated in a stable orbit and observed the pan-Antarctic with more appropriate local acquisition time, and hence had more opportunities to identify melt events (Supplement Fig. 2).

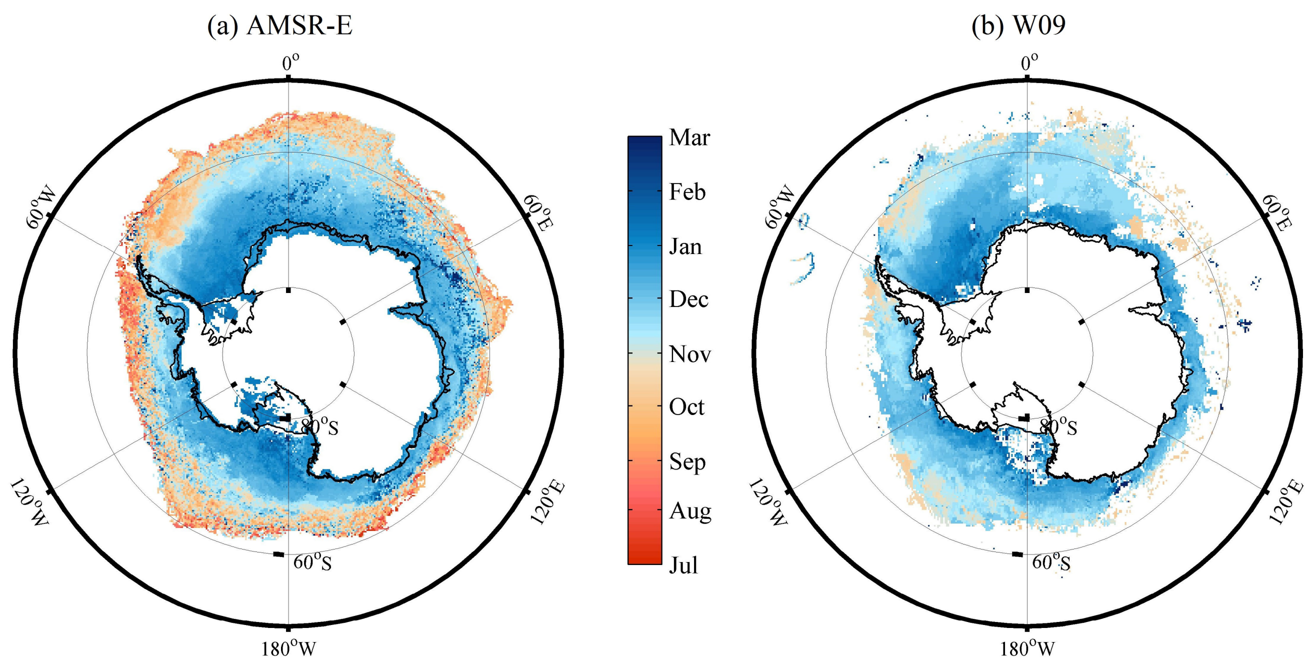


Figure 10. Annual mean CMO derived from (a) AMSR-E and (b) W09 from 2002 to 2008.

3. The optimal local acquisition time of AMSR-E compared to SSM/I repeatedly stated by the authors needs further explanation or investigation. It should be critically discussed whether other influences (maybe sun influences or instrument temperature) can alter the results (lead to too early snowmelt detection)

AR3: The comparison between SSM/I and AMSR-E Tb observations over dry snow zone suggest the effect of other influences is very limited.

- Dai and Che (2010) have compared the SSM/I and AMSR-E Tb observations, and concluded that the differences between AMSR-E vertically polarized 36.5 GHz Tb (Tb_{V36}) and SSM/I vertically polarized 37 GHz Tb (Tb_{V37}) were small.
- To further examine the interferences from cross-platform, we compared AMSR-E Tb_{V36} and SSM/I Tb_{V37} south of 85° S where surface snow is stable and never melts. R-square between AMSR-E Tb_{V36} and SSM/I Tb_{V37} were both 0.96 for ascending and descending passes during 2002-2003. Bias between the two measurements was only about 1 K. Bias between AMSR-E DAV36V and SSM/I DAV37V were less than 0.4 K. The effect of slight Tb offsets between different sensors should not affect the melt detection based on temporal Tb variability (Markus et al., 2009).

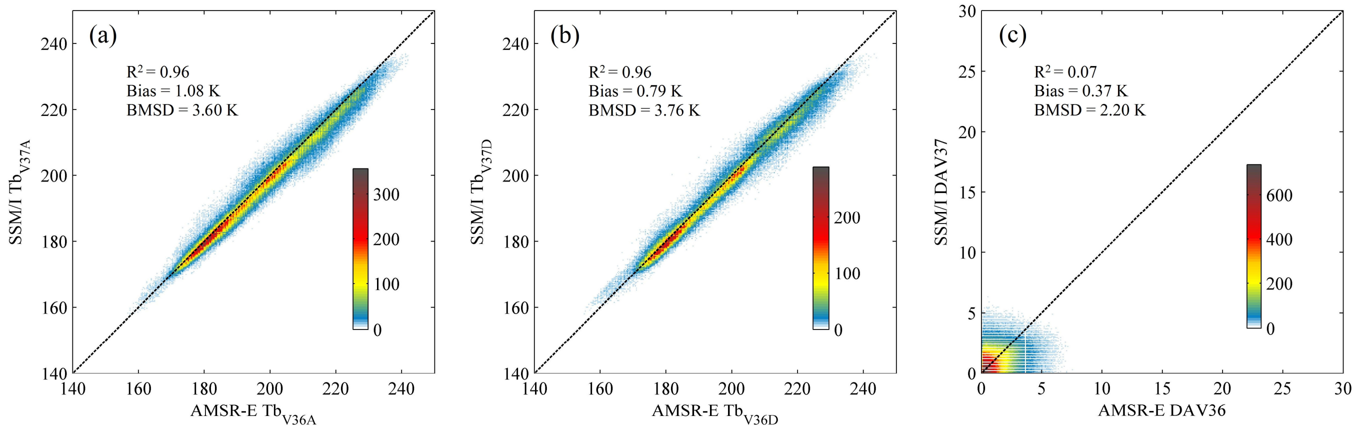


Fig. R2. Comparison between AMSR-E Tb_{V36} and SSM/I Tb_{V37} during 2002-2003. (a), (b) and (c) show the comparisons for ascending passes, descending passes, and the DAV.

- We clarified this issue in the revised manuscript:
  We utilized the same threshold for melt detection based on AMSR-E/2 DAV36 considering the differences between AMSR-E 36 GHz Tb and SSM/I 37 GHz Tb are very small (Dai and Che, 2010). In the region south of 85° S where the surface snow is stable and never melts, the bias between the two measurements was only approximately 1 K during 2002-2003 (Supplement Fig. 1). Slight Tb offsets between different sensors should not affect the results when using temporal Tb variability in melt detection (Markus et al., 2009).

4. I'm surprised to see shelf and sea ice melt in the same way analyzed. They are so different in their nature and also physical properties that I would not even have expected that the same method would work adequately on both. For example there are brine and flooding effects in sea ice which are not present in the shelf ice. It should be more clearly stated in the Manuscript why it is useful or desired to combine the analysis.

AR4: A uniform approach was applied in melt detection on both the sea ice and ice sheet for two reasons:

- First, snowmelt on the ice sheets was found to be correlated with that on the sea ice, but melt detection on sea ice and ice sheet was always conducted separately. This may result in uncertainties in the integrated study.
  Recent studies (e.g., Ballinger et al., 2013; Stroeve et al., 2017) found that ice sheet atmospheric pattern and snowmelt are linked with sea ice melting conditions through atmospheric circulation. Earlier melt onset of the sea ice may have provided an additional source of warm, moist air over the adjacent ice sheet, leading to the earlier arrival of melt onset on the ice sheet. However, snowmelt over sea ice and ice sheet was always separately detected with different approaches. In Stroeve et al. (2017), sea ice melt onset was investigated based on Tb temporal variation and gradient ratio following Markus et al. (2009), while the ice sheet melt onset was determined based on a single-channel method following Mote (2007).
  In the Antarctic, snowmelt on the West Antarctic and Antarctic Peninsula was also found to be linked with adjacent sea ice variations (Scott et al., 2018; Zheng et al., 2019). So it is worthwhile to generate integrated snowmelt over the pan-Antarctic.
- Second, the DAV method has been successfully applied in melt detection on both sea ice (Willmes et al., 2009) and ice sheet (Tedesco, 2007; Zheng et al., 2018). In addition, the thresholds used for melt detection

on the Antarctic sea ice (10 K) and ice sheet (9 K) are very close. A threshold of 10 K works well in melt detection on both sea ice and ice sheet compared with the positive Tair observations (Figure 2&3).

Therefore, this study aims at generating integrated pan-Antarctic surface snowmelt based on the DAV method. We considerably revised the introduction section and clearly clarify the motivations in the last paragraph:

Strong interactions have been found between sea ice and ice sheet surface snowmelt through atmospheric circulation (Stroeve et al., 2017). Surface snowmelt dynamics in the West Antarctic and Antarctic peninsula have been found to be related with the sea ice variations in adjacent seas (Scott et al., 2018; Zheng et al., 2019). Previous studies have separately investigated surface snowmelt on sea ice and ice sheet, which may result in uncertainties in the integrated study. The DAV method has been successfully applied in snowmelt detection on both sea ice (Willmes et al., 2009) and ice sheet (Tedesco, 2007; Zheng et al., 2018). It is worthwhile to estimate snowmelt over the pan-Antarctic based on a uniform approach. The overall objective of this study is to improve the understanding of surface snowmelt over the pan-Antarctic based on the DAV method in three aspects: (1) to detect the pan-Antarctic surface snowmelt at the stable and appropriate local acquisition time based on AMSR-E/2, (2) to improve the performance of the DAV method in the marginal sea ice zone by excluding the effect of open water, and (3) to estimate the pan-Antarctic surface snowmelt as a whole and systematically describe the surface snowmelt patterns and changes from 2002 to 2017.

We acknowledge that brine and seawater flooding could affect the melt detection on sea ice, which was discussed in Section 5.2 (Uncertainties):

Second, although the DAV method used in this study performs well when compared with meteorological observations, the optimal threshold may differ temporally and regionally with varying snow properties. In addition, ice disintegrates, brine and flooding effects may play an important role in seasonal and even diurnal sea ice Tb variations, further complicating the story (Smith, 1998; Willmes et al., 2009).

5. The vast amount of references makes it very hard to find the the real sources for certain statements. This makes the manuscript appear cluttered and lacking a concrete direction and purpose.

AR5: We thank the referee for pointing out this issue**.** We removed the less relevant references. The introduction was also considerably revised to make the motivations and directions clear.

Some specific Comments:

P1, L16: "DAV" should be directly introduced as TB_v difference of ascending and descending swaths either in the abstract or at the very first occurrence in the text

AR6: DAV was directly introduced in both the abstract:

In this study, the difference between AMSR-E/2 ascending and descending 36.5 GHz Tb in vertical polarization (DAV36) was utilized to map the pan-Antarctic snowmelt because it is unaffected by the snow metamorphism.

and the text:

Ramage and Isacks (2002, 2003) introduced the SSM/I diurnal amplitude variations (DAV, i.e., the Tb difference between ascending and descending passes) in vertically polarized 37 GHz Tb to investigate the snowmelt timing on the Southeast Alaskan Icefields.

P2, L16 & L23: first statement is “passive microwave remote sensing works in all atmospheric conditions” and then “altered by clouds, atmosphere, ….” what do you want to say here?

AR7: Good catch. Although atmospheric effects are generally negligible in melt detection, they could potentially influence the melt signals and introduce errors (Abdalati and Steffen, 1995). Two avoid contradiction between the two statements, we revised the first sentence:

> Microwave radiometers can operate regardless of illumination conditions and are insensitive to atmospheric conditions.

P3, L14: see General point 3.

AR8: The comparisons between SSM/I and AMSR-E Tb observations over dry snow zone suggest the differences between the two measurements are very small. Please see **AR3** for full details.

In addition, AMSR-E/2 can observe the pan-Antarctic snowmelt at more appropriate local acquisition time for two reasons:

- First, AMSR-E and AMSR2 operate in controlled-orbits measurements, and the crossing time for the two sensors are nearly the same. By contrast, crossing time differs between SSM/I sensors and also changes significantly over the years of operation due to orbit degradation (Picard and Fily, 2006) (Fig. R3). AMSR-E/2 measurements with a stable orbit are superior in the analyses of inter-annual snowmelt dynamics.

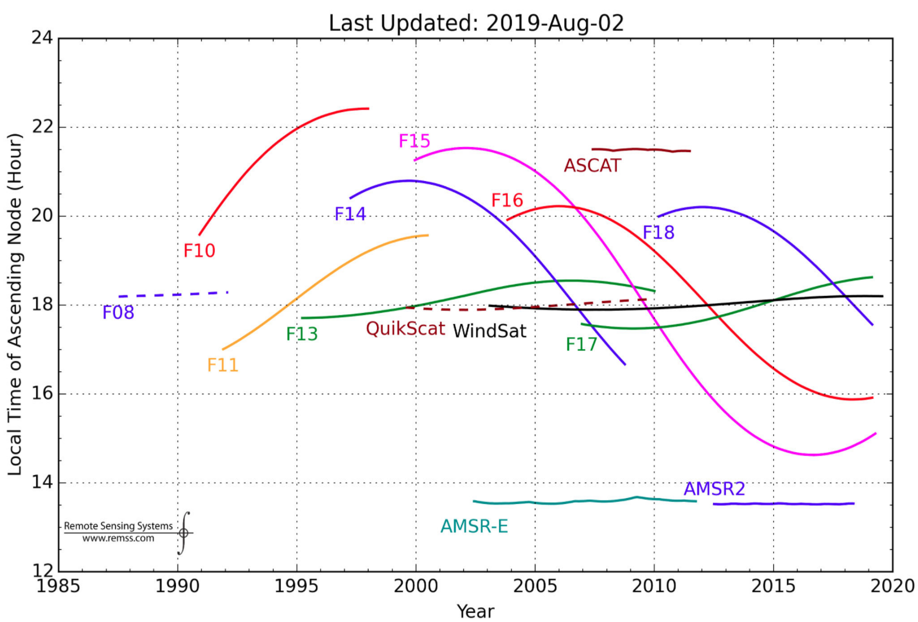


Figure R3. Ascending (solid lines) and descending (dash lines) equatorial crossing times for microwave sensors. The chart is adopted from Remote Sensing Systems (http://www.remss.com/support/crossing-times/).

- Second, the Antarctic diurnal melt area varies approximately as a sinusoid with the peak in the afternoon and the trough in the early morning (Picard and Fily, 2006). It is a great opportunity for us to make full use of the AMSR-E/2 data to detect surface snowmelt because the ascending and descending passes of AMSR-E/2 observed the pan-Antarctic in the afternoon (the warmest period) and at midnight (a cold period).

We rephrased this paragraph to make it clear:

Most of these studies investigated surface snowmelt on sea ice and ice sheets based on SSM/I sensors. However, SSM/I observations show considerable variations in local acquisition time because of orbit degradation (Picard and Fily, 2006). By contrast, the Advanced Microwave Scanning Radiometer for the Earth Observing System (AMSR-E) and the Advanced Microwave Scanning Radiometer 2 (AMSR2) operate in controlled-orbits so that local acquisition time shows little temporal variation (http://www.remss.com/support/crossing-times). AMSR-E/2 measurements with a stable orbit are superior in the analyses of inter-annual snowmelt dynamics. Diurnal melt area in the Antarctic varies approximately as a sinusoid with the peak in the afternoon and the trough in the early morning (Picard and Fily, 2006). AMSR-E/2 can monitor the Antarctic sea ice and ice sheet (referred to as pan-Antarctic) surface snowmelt at the appropriate local acquisition time. Taking 2002-2003 as an example, the local acquisition time of ascending and descending SSM/I Tb products south of 40° S were 19.17±0.44 and 5.45±0.45, respectively, while these values were 14.16±0.20 and 0.88±0.20 for the AMSR-E Tb products. Compared with SSM/I, AMSR-E/2 have more opportunities to detect melt events in the pan-Antarctic due to warmer and colder periods for ascending and descending passes and an expected higher DAV.

P4, L15: SIC>15% was used and only SIC>80% was used in melt detection? Does this mean a pixel never exceeding 80% SIC is never melting? And pixels exceeding80% SIC only later can only melt from this point on? I would expect that this gives you a negative bias in MDF (since it counts as frozen even in melting conditions).

AR9: We mean that the pixels with SIC above 80% for less than 5 days (i.e., very short-lived sea ice) were not included in the analyses. That is to say, these pixels were marked as being ice-free (Markus et al., 2009).

- Sea ice pixels and the occurrences of sea ice were first determined, and the melt detection methods were applied henceforth. We employed the same preconditions for melt detection on sea ice based on AMSR-E/2 and ERA. This may not result in the difference in MDF retrieved from the two methods.
- This sentence was rephrased to clarify:
  Pixels with SIC greater than 80% for less than 5 days were marked as being ice-free (Markus et al., 2009). For a sea ice pixel, SIC above 15% indicates the presence of sea ice (Meier and Stroeve, 2008).

P4, L20: please state the exact field of the ERA interim dataset used including timestep, are you using "Air temperature at 2m height" from the surface analysis? Also: in how far was the data used to "assist" with the AMSR-E/2 melt detection? Is this is described somewhere else in the text?

AR10: We revised this sentence to clarify:

The 6-hourly air temperature (Tair) from the gridded ERA-Interim reanalysis at 2 m height was used to...

Yes, in Section 3.2 (Melt detection methods), we clearly described how the ERA-Interim Tair was used.

- First, ERA-Interim Tair was used to assist with melt detection based on AMSR-E/2:
  Further, melt detection was constrained to the days with compatible thermal regimes following Belchansky et al. (2004). The days with ERA-Interim Tair > -5°C were first determined, and the DAV36 algorithm was applied henceforth.
- Second, ERA-Interim Tair was also used to determine snowmelt directly:
  To evaluate the performance of the DAV method on a larger scale, snowmelt over the pan-Antarctic was also determined by ERA-interim reanalysis when the daily maximum Tair exceeded -1°C.

P4, L29-P5: It is unclear what the MEMLS simulation is for. In Kang et al. (2014), which you are citing four times in this paragraph, this is discussed in very detail. The variation of snow grain size is barely discussed in this paragraph and from what I got, never really picked up again in the manuscript. I would probably just remove the Fig. 1.

AR11: We recalled the work from Kang et al. (2014) to show that the DAV method is superior to single-channel methods in snowmelt detection. In Willmes et al. (2009), the DAV method was only applied in the detection of snowmelt onset on sea ice. The analysis with varying snow grain size was added to explain that the DAV method can be used to detect snowmelt throughout the melt season with snow metamorphism:

- In early melt season, Tb_{V36} of the fine-grained snowpack increases rapidly in energy saturation phase with a slight amount of liquid water. Daily Tb variations are large because of the contrasting freeze/thaw state. DAV method can recognize these sharp changes.
- During the melt seasons, snow grain size can increase to 2 mm when meltwater refreezes in the pore space (Winebrenner et al., 1994). Tb_{V36} from a melting snowpack may be even lower than the winter mean due to the enhanced volume scattering, and single-channel methods may fail to work (Zheng et al., 2018). By contrast, significant daily Tb_{V36} variations still exist in the transition from dry to wet snow regime in the coarse-grained snowpack, and the DAV method still works.

Fig. 1 illustrates the advantage and principle of DAV method in melt detection. We revised this section to clarify the necessity of this figure:

> Tb_{V36} of the fine-grained snowpack increases rapidly in the energy saturation phase with a slight amount of liquid water, and daily Tb variations are large because of the contrasting freeze/thaw state. Therefore, both single-channel and DAV methods can recognize these sharp changes in the early melt season. During the melt seasons, snow grain size can increase to 2 mm when meltwater refreezes in the pore space (Winebrenner et al., 1994). As a result, Tb_{V36} of the coarse-grained snowpack is much lower than that of the fine-grained snowpack due to enhanced volume scattering. Single-channel methods may fail to work when the Tb_{V36} of a melting snowpack is even lower than the winter mean in the late melt season (Zheng et al., 2018). By contrast, significant daily Tb_{V36} variations still exist in the transition from a dry to wet snow regime during the heavy melt season, even when day-time Tb_{V36} is in the energy dampening phase (Fig. 1). Diurnal freeze-thaw cycles are prevalent in polar regions (Hall et al., 2009; Willmes et al., 2009; van den Broeke et al., 2010b). The simulations suggest that the DAV method can detect melt signals for both the melt onset (e.g., Willmes et al., 2009) and the entire melt season when diurnal freeze/thaw transition occurs (e.g., Zheng et al., 2018). Moreover, the optimum acquisition time of AMSR-E/2 enables us to take full advantage of the DAV method in melt detection.

P5, L5-6: specify the interface you are talking about, probably the snow-air-interface

AR12: Done! Yes, we mean the snow-air interface.

P5, L10-15: Since you employ the method, can you show that this signal is consistent characteristic for melt? For a longer constant melt under full sun illumination, there is probably not much difference between day and night wetness in the snow. Also in Fig. 3, under constant positive air temperatures, there is not constant DAV>10 which indicates that the melt indicator from DAV and the positive temperatures are not strictly connected.

AR13: Yes, positive Tair can only provide evaluation rather than validation of the melt detection methods. Considering the absence of in-situ snow wetness measurements in polar regions, positive Tair was always used to evaluate satellite-derived snowmelt because the occurrence of surface melt corresponds to the spatial pattern of Tair (Tedesco, 2009; Liang et al., 2013). However, melt signals (i.e., the presence of snow liquid water) detected by AMSR-E/2 do not always strictly connect with positive Tair for the following reasons:

- First, positive Tair was derived from the hourly Tair measurements from AWS, while AMSR-E/2 only provide twice-daily observations, which may miss the time when melt occurs.
- Second, passive microwave sensors detect liquid water rather than snowmelt. It takes time for meltwater to refreeze after intense melt events. Subsurface liquid water may remain after the refreezing of the surface, and can still be detected by the satellites due to the penetrating ability of microwave (Zheng et al., 2019).
- Third, owing to the penetration and absorption of solar radiation within the snowpack, snowmelt may occur when Tair is below the freezing point (Koh and Jordan, 1995).
- Last, the DAV method may fail to detect snowmelt when liquid water does not refreeze or snowpack is still melting in warm nights (Willmes et al., 2009).

In the revised manuscript, we explained the reasons why satellite-derived melt signals and the positive Tair are not strictly connected:

> Melt signals derived from the DAV method and the positive Tair from AWS were not always strictly connected (Figs. 3&4). Their differences may be attributed to inconsistent temporal resolutions because snowmelt and refreezing can occur at any time of the day. The daily maximum Tair was derived from hourly Tair records, while only two daily satellite observations were used in the DAV method. In addition, snowmelt may occur when Tair is below the freezing point because of the penetration and absorption of solar radiation within the snowpack (Koh and Jordan, 1995).

The limitations of the DAV method were also clarified:

> There are several uncertainties in the pan-Antarctic snowmelt derived from AMSR-E/2 data. First, the DAV method may fail to work when liquid water does not refreeze or snowpack is still melting in warm nights (Willmes et al., 2009). The regions with snowmelt that became more prevalent would presumably show a decrease in melting days based on the DAV method. Fortunately, unlike the Arctic, surface snowmelt on the Antarctic sea ice is always patchy and relatively short-lived (Drinkwater and Liu, 2000). Second, although the DAV method used in this study performs well when compared with meteorological observations, the optimal threshold may differ temporally and regionally with varying snow properties. In addition, ice disintegrates, brine and flooding effects may play an important role in seasonal and even diurnal sea ice Tb variations, further complicating the story (Smith, 1998; Willmes et al., 2009).

P5, L15: see General point 3.

AR14: The differences between AMSR-E Tb_{V36} and SSM/I Tb_{V37} are small (Dai and Che, 2010). The comparisons between SSM/I and AMSR-E Tb observations in the dry snow zone suggest the effect of other influences is very limited (Fig. R2). AMSR-E/2 DAV36 is superior to SSM/I DAV37 in melt detection because of the more stable orbit and more appropriate acquisition time. Please see **AR3** and **AR8** for full details.

P5, L21: see General point 3.

AR15: The differences between AMSR-E Tb_{V36} and SSM/I Tb_{V37} are small (Dai and Che, 2010). The comparisons between SSM/I and AMSR-E Tb observations in the dry snow zone suggest the effect of other influences is very limited (Fig. R2). AMSR-E/2 DAV36 is superior to SSM/I DAV37 in melt detection because of the more stable orbit and more appropriate acquisition time. Please see **AR3** and **AR8** for full details.

P5. L31: I cannot see this in Figure 2. There are at least 3 years (2005, 2007,2009) where there is day in mid-winter with positive air temperature where DAV does not exceed the threshold nor shows any signal.

AR16: Positive Tair and snowmelt are short-lived in winter. Positive Tair was derived from the hourly Tair measurements from AWS, while AMSR-E/2 only provide twice-daily observations, which may miss the short-lived melt events because refreezing can be quasi-instantaneous in the Antarctic (van den Broeke et al., 2010a). Positive Tair can only provide evaluation rather than validation of the melt detection methods. Considering the absence of in-situ snow wetness measurements in polar regions, positive Tair was always used to evaluate satellite-derived snowmelt because the occurrence of surface melt corresponds to the spatial pattern of Tair (Tedesco, 2009; Liang et al., 2013). However, melt signals (i.e., the presence of snow liquid water) detected by AMSR-E/2 do not always strictly connect with positive Tair. We have explained the reasons for their differences in **AR13**.

P5. L32: Accuracy and Kappa should be defined somewhere.

AR17: The overall accuracy and Kappa coefficient were defined in the revised manuscript:

> The overall accuracy (p_0, the proportion of observed agreement) and Kappa coefficient $k = (p_0 - p_c)/(1-p_c)$ were used to measure the coincidence based on the confusion matrix, where p_c is the proportion in agreement due to chance (Cohen, 1960).

P6. L9 (Eq 4): This is only true under the assumption that SIC did not change within the_12h from ascending to descending overflight. This should be mentioned. The method could be optimized in this regard by using the Tbs to retrieve the ice concentration in ascending and descending separately and then calculate the DAV with the aid of an open water tie point (which does not cancel out in case SICs are different for ascending and descending overflights)

AR18: We thank the referee for pointing out this issue.

Yes, the equation is true under the assumption that SIC is the same for both passes. We revised this part to clarify:

> Regardless of the atmospheric effects, the Tb of sea ice is comprised of the ice portion (Tb_{ice}) and open water portion (Tb_{ow}) (Markus and Cavalieri, 1998):

$$Tb = Tb_{ice}\, SIC + Tb_{ow}\, (1\text{-}SIC) \tag{3}$$

therefore, $DAV36_{ice}$ can be calculated as follows:

$$DAV36_{ice} = \left| \frac{Tb_{V36A} - Tb_{ow}(1-SIC_A)}{SIC_A} - \frac{Tb_{V36D} - Tb_{ow}(1-SIC_D)}{SIC_D} \right| \tag{4}$$

where SIC_A and SIC_D represent the SIC for ascending and descending passes. If we assume that the SIC of the two passes remains unchanged (i.e., $SIC_A = SIC_D$), then we have:

$$DAV36_{ice} = \frac{|Tb_{V36A} - Tb_{V36D}|}{SIC} \tag{5}$$

We acknowledge the $DAV36_{ice}$ algorithm can be further improved with corresponding SIC for each pass. However, producing a twice-daily SIC product is challenging at present. Extensive simultaneous ground- and space-based observations are needed in the validation. This is likely to be difficult to achieve in polar regions and beyond the scope of this paper. We mentioned this issue in Section 5.2 (Uncertainties):

The $DAV36_{ice}$ algorithm for sea ice snowmelt detection assumes that the SIC of the two passes remains unchanged, which may not be true due to quick sea ice drift and disintegration. The algorithm can be further improved if the twice-daily SIC product is available in the future.

P6. L20: accuracy and Kappa definition again

AR19: Done!

P6. L22: Why is a spatial median needed here, what are erroneous microwave signals?

AR20: We explained why a spatial median is needed:

Spurious Tb variations may occasionally be mistaken for melt signals, which can be caused by clouds, atmospheric water vapor, wind-induced surface roughening, and residual calibration errors. To mitigate their impacts on melt detection, a median filter with a 3×3 window was applied to the satellite observations.

P6. L25: "Melt freeze-up and duration…." - I don't understand what is meant here

AR21: Some studies include the analyses of freeze-up (the last day with surface snowmelt) and duration (the days between melt onset and freeze-up) on sea ice (e.g., Markus et al., 2009). However, sufficient Antarctic sea ice melts quickly in austral summer and does not emerge any more in the melting year. In such cases, the last day with snowmelt is always the day that sea ice disappears, rather than the day that freeze-up begins. We revised this sentence to clarify:

Sufficient Antarctic sea ice melts quickly in austral summer and does not emerge again in the melting year. In such cases, the last day of snowmelt is always the day that sea ice disappears, rather than the day that freeze-up begins. Thus freeze-up and melt duration were not included in this study.

P6. L29: extend -> extent

AR22: Done!

P7. L7: if below -5_C means frozen state (P6. L24) and above -1_C means melting, what state is there in between and how is that classified?

AR23: There is no intermediate state in freeze/thaw cycles. The two conditions were used separately and do not contradict each other:

- The first condition was used to mitigate the effect of spurious Tb variations (see **AR20**) in melt detection based on AMSR-E/2.
- The second condition was used to derive snowmelt directly based on ERA-Interim Tair.

The first condition was not used to determine the freeze/thaw state. To avoid confusion, we rephrased this sentence:

> Further, melt detection was constrained to the days with compatible thermal regimes following Belchansky et al. (2004). The days with ERA-Interim Tair > -5°C were first determined, and the DAV36 algorithm was applied henceforth.

P7. L16: Discussion about Fig. 5, see also General 2.: the mid July melt onset around -60 to -65 latitude is quite surprising and needs discussion. Also the later melt onset in the more outer parts are interesting. Is it because there was no ice at the melt onset of the more southern regions and ice drifted there later so that melt occurs later in these regions? However, than the MDF should be even higher in these regions, probably close to 100%. I would also suggest not using the parula but a diverging colormap for the difference plot.

AR24: We thank the referee for pointing out this issue. Yes, this is because sea ice advance (the first day when SIC > 15%) in these areas is later than July 1 (the first day of melting year). Specifically, sea ice does not occur until early September in some parts of the marginal sea ice zone (Stammerjohn et al., 2008) (Fig. R4).

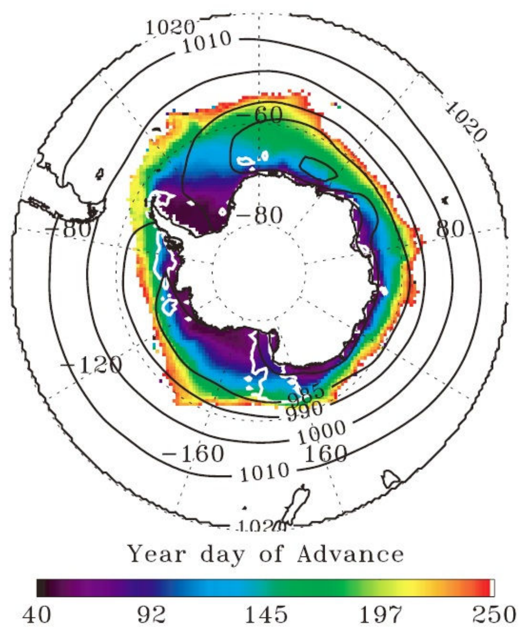


Figure R4. Day of Antarctic sea ice advance over 1979–2004. The figure is adopted from Stammerjohn et al. (2008).

Therefore, early melt onset (EMO) on some marginal sea ice is later than that on the sea ice in lower altitudes where transient melt events can occur before September (e.g., Fig. R1c).

We mentioned this issue in the revised manuscript:

> <u>In some parts of the marginal sea ice zone, EMO was later than that in higher altitudes. This is because sea ice did not occur in these regions until early September (Stammerjohn et al., 2008), while transient surface snowmelt can occur before that in August at lower latitudes (Supplement Fig. 2). However, the earliest CMO was still found in the marginal sea ice zone (Fig. 5b,d).</u>

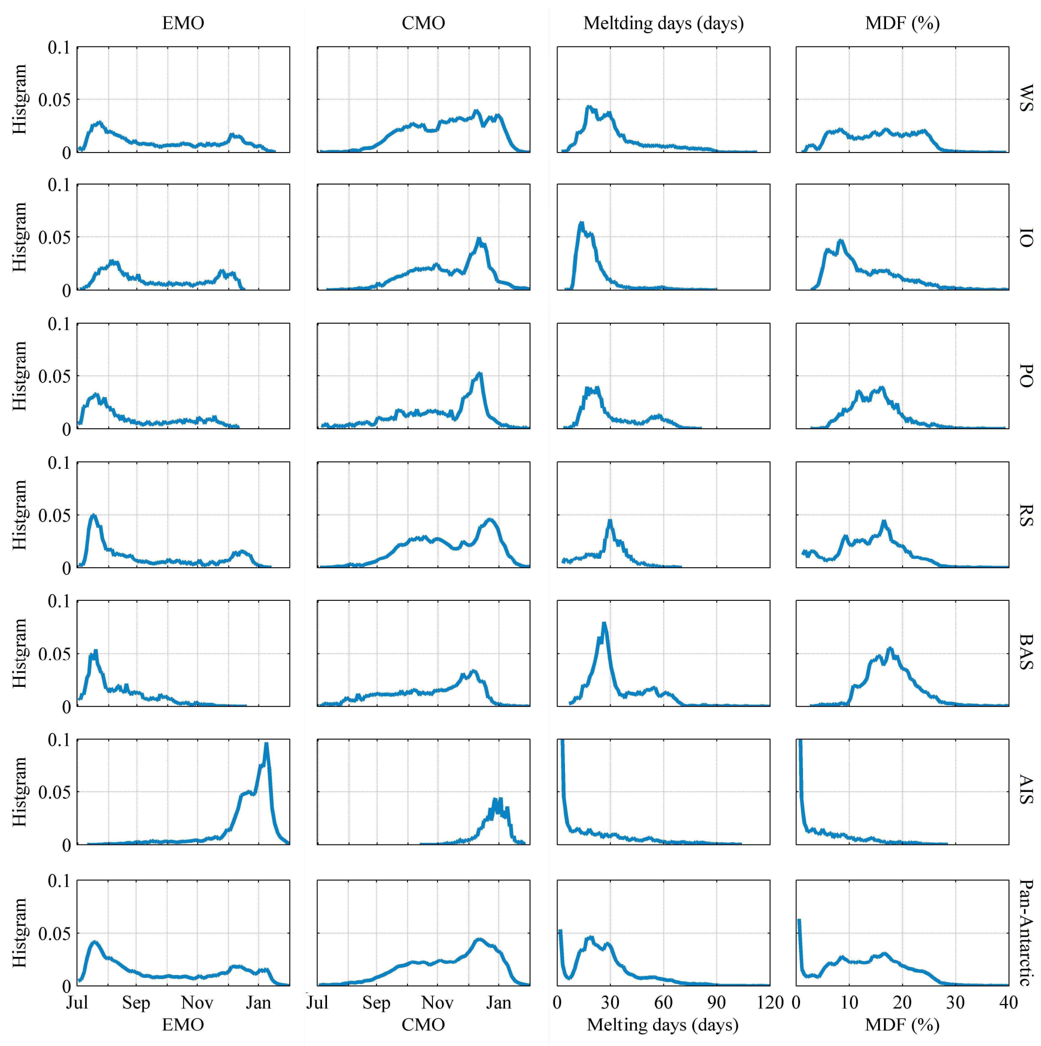
Fig. 5 was also redrawn as suggested.

P7. L31: "Fig. 5k-o" -> "Fig. 5g-i"

AR25: Done.

P8. Discussion about Fig. 6: I would suggest splitting the histograms to maybe a 7 by 3 plot to be able to discuss the particular regions better. Also bin size in the histograms is too small, i.e., the histograms are to noisy to comfortable read their data.

AR26: Fig. 6 was redrawn as suggested.



P8. L11-12: The comparison of the melt extent of AIS with the sea ice area makes no sense in my opinion. The AIS is a much smaller region. What is the purpose of this comparison? I suggest to remove Figure 7 completely. However, the melt extentis quite small in the early months like July/August on sea ice which actually contradicts the early melt onset in Fig. 6. This also indicates that the early melt onset is probably just a random noise effect since it does not cover a large area apparently.

AR27: We thank the referee for pointing out this issue.

- We agree that the comparison between melt extent and sea ice extent makes little contribution to this work. The comparison and Fig.7a were removed, but we would like to keep Fig. 7b which illustrates the seasonal evolution of surface snowmelt. In addition, melt extent fraction (MEF) will be further discussed in Section 5.3 (Response of the pan-Antarctic surface snowmelt to atmospheric indices).
- The occurrence of early snowmelt onset (EMO) does not result in a significant increase in melt extent because the early melt events are always short-lived. Instead, the histogram of continuous melt onset (CMO) suggests most of the pan-Antarctic continuous snowmelt began between October and January (Fig. 6) when MEF increased quickly (Fig. 7).
- Snowmelt can occur in austral winter on both Antarctic ice sheet (Kuipers Munneke et al., 2018) and the Antarctic sea ice (Massom et al., 2001). In Fig. R1c, winter melt events have been clearly observed based on both AMSR-E and SSM/I measurements, accompanied by positive Tair records.
  Yes, these early melt events are always short-lived, and can be easily regarded as random noises. We have conducted data preprocessing and quality control to mitigate the effect of spurious Tb variations on melt detection:
  Spurious Tb variations may occasionally be mistaken for melt signals, which can be caused by clouds, atmospheric water vapor, wind-induced surface roughening, and residual calibration errors. To mitigate their impacts on melt detection, a median filter with a 3×3 window was applied to the satellite observations. Further, melt detection was constrained to the days with compatible thermal regimes following Belchansky et al. (2004). The days with ERA-Interim Tair > -5°C were first determined, and the DAV36 algorithm was applied henceforth.

P8. L17: with “mean maximum MEF” you mean the “Mean anual Maximum MEF” right? should than be changed in the text.

AR28: We mean the maximum of daily mean MEF, this part was removed as suggested (see **AR27**).

P9. L2: I actually do not understand how the trends are calculated. Fig 9 indicates that you calculate the trends pixel based. One would expect that neighbouring pixel having similar melt onset dates (Fig 9a). If the shown pixel based trends have any significance also the spatial pattern should be coherent.

AR29: Yes, the trends were calculated for each pixel.

- There are a large number of transient melt events during the melt seasons (Fig. 6). Melt onset always shows considerable spatial and temporal variations. A similar phenomenon can be found in the Arctic (Fig. R5) (Stroeve et al., 2014).

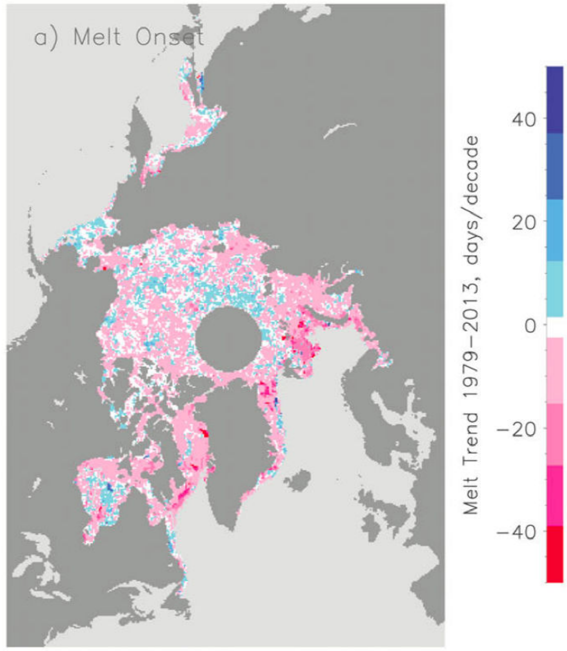


Figure. R5. Trends in Arctic sea ice snowmelt onset from 1979 to 2013. This figure is adopted from Stroeve et al (2014).

- Actually, most of the trends were not statically significant. We redrew Fig.9 with additional significance levels of the trends.

P11. L 18: I suspect the values and discussion to change in case you reconsidered the early snowmelt onset

AR30: We assume the referee would like to see the analyses and discussion of continuous melt onset (CMO), which were included in the revised manuscript.

Other changes in the revised manuscript include:

- We have made mistakes in statistical analyses in the first version, but they do not affect the main conclusion of this study. We corrected these mistakes and checked the manuscript carefully.
- The manuscript was edited by a native English speaker and the grammatical errors were corrected.
- Figure 5-13 was redrawn, two figures were added as supplements.

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