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Interactive comment on "Interannual Variability of Summer Surface Mass Balance and Surface Melting in the Amundsen Sector, West Antarctica" *by* Marion Donat-Magnin et al.

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We thank Reviewer #1 for this constructive and motivating feedback. We agree with most of the following objections and have considered them in the revised manuscript.

Major Comments : C1 One important consideration that is missing is a description of why summer SMB is critical and how it relates to the annual SMB. December-January-February (DJF) clearly are the relevant months for surface melting, but I think there should be more discussion as to why the paper specific isolated summer SMB. Specifically, melt is the highest in DJF, but snowfall is typically the lowest in DJF (Lenaerts et al., 2012). Please consider evaluation of winter (or other seasons of SMB relevance)

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or add language justifying the importance of summer SMB.

First of all, we would like to remind that annual SMB and surface melt rates (not only summer) are evaluated with respect to observations (Fig.4 and Fig.6). Then, we focus on a single season (summer) to analyze the teleconnections and associated mechanisms because the modes of variability and their teleconnections to the Amundsen Sea region both have strong seasonal characteristics, so that each season needs to be considered separately. We thought that analyzing all seasons separately would make the paper way too long, while showing the similarities and differences between the melt and SMB summer teleconnections was interesting. We agree that summer SMB is weaker than in other seasons, but it still represents 15% of the annual SMB (over the Amundsen Sea drainage basins) which is not negligible (vs 31%, 28% and 25% for MAM, JJA and SON respectively). The seasonal predictability of summer SMB from climate mode such as ENSO can also be of interest for operational prediction and summer field work. We have nonetheless included a supplementary table providing the correlation between SMB, and SAM, ENSO, ASL for other seasons (Table S3). The justification for the summer focus has also been added to the manuscript (section 1, L.130-134).

C2 The relationship between melt and SMB is not investigated. The paper provides background on the importance of the role of melt on hydrofracture of ice shelves and potential rapid disintegration of an ice shelf, but it does not discuss the role of firn pore space. According to Table 2, nearly all of the surface melt refreezes within the firn column, so this mechanism should be introduced as well. The paper also notes that into the future there will be more snowfall and melt, but did not mention that the enhanced snowfall could potentially also provide more pore space for meltwater infiltration and refreezing. Please consider additional discussion of the role of SMB (or snowfall) on providing addition pore space for surface melt.

First, we apologize for a mistake : we omitted to mask nunataks in the basin averages, which slightly modified the values in table 2 (now updated). For all drainage basins the runoff is indeed equal to zero, meaning that the firn is never saturated with melt water (which is a prerequisite to form runoff in our version of MAR). The minimum rate of surface melting + rainfall needed to saturate the annual snow layer (i.e. depleting all the air in the annual snow layer) can be estimated as snowfall*[water/snow]*[1- snow/ice], where snowfall is annual (in water equivalent), and is the density of water snow and ice. Considering a fresh snow density of 300 kg.m-3 and ice density of 920 kg.m-3, this means that the sum of annual melt and rainfall rates would need to exceed 2.25 times the annual snowfall value (all being expressed in water equivalent) to saturate the annual snow layer. This does not occur in any of the drainage basins in any year, indicating that meltwater ponding and complex surface hydrological flows are unlikely to develop over the West Antarctic drainage basins with such amount of precipitation and surface melting. The rate of surface water production (rainfall + melting) would need to increase by nearly two orders of magnitude to saturate present-day annual snow layer and therefore to initiate hydrofracturing. This is possible for strong warming scenarios given the exponential temperature dependence described by Trusel et al. (2015), although snowfall is also expected to increase (Krinner et al. 2008; Agosta et al., 2013; Ligtenberg et al., 2013; Lenaerts et al., 2016; Palerme et al., 2017), requiring even more meltwater to reach saturation. This discussion has been added to section 4, L.634-642 and L.692-697.

C3 There is no discussion on the relatively small proportions of variance explained by the climate indices. For instance, over western WAIS 20-40% of the summer SMB variability can be explained by the ASL longitude; however, it explains <6% of the Abbot, Cosgrove, and Pine Island catchments. None of the indices is significantly correlated with SMB over those catchments. Thus, the impact of ASL longitude is only relevant from Thwaites moving westward. The paper should make this clear and also potentially investigate other drivers of change for the eastern catchments or at least add clarifying statements that the drivers in eastern WAIS are unknown and potentially postulate why. Along similar lines, while ASL central pressure is a clear control on all catchments, the explained variance range from 12-21%, suggesting that there are additional factors at

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play when it comes to surface melt. Would investigation of multiple regression with the different indices help clarify how they interplay (for example, perhaps the combination of some movement and strengthening or weakening of the ASL is more strongly related). Please consider adding more multivariate relationships and discuss other potential influences on meltwater production since only a small portion is explained.

First of all, we have replaced NINO34 with (-SOI) throughout our paper because, as indicated by Holland et al. (2019), SOI gives slightly stronger correlations than NINO34. Following the Reviewer's suggestion, we have investigated multi-linear regression (using a least shrinkage and selection operator (LASSO, Tibshirani 1996)) of summer SMB and melt rates onto the non-dimensionalized climate indices (divided by their standard deviation). The variance explained by individual regression coefficients are very close to the ones obtained by simple correlation, but considering the entire regression clearly shows that we are able to explain a larger portion of the SMB and melt rate variance by including several indices (16-49% for SMB and 21-30% for melting). As anticipated by the Reviewer, this indicates an interplay between the different modes of variability. A column providing the correlation of the multi-linear regression has been added to Tables 3 and 4, with associated description in section 3.2, L.464-468. Even with SOI instead of NINO34 and considering multi-linear relationships, the part of explained variance never exceeds 50% of the summer melt and SMB variance. Possible reasons for this are (i) the modes of variability do not explain all the variance locally; for example, the leading EOF of SST in the Equatorial Pacific (representing ENSO) only accounts for 50 to 70% of the SST variance (e.g. Roundy, JCLI 2015), meaning that the tropical convection thought to influence Antarctica is not completely described by SOI or NINO34; (ii) assuming that a large part of the tropospheric circulation variability is explained by ENSO, SAM and ASL indices, there are reasons why the connection may be weaker for SMB and surface melting because of their non-linear dependence on sea ice and evaporation in coastal regions, the evolution of snow properties, etc; (iii) strong modulation of the southeast Pacific extratropical circulation by Rossby wave train is not only due to the existence of El Niño events but also depends on the exact

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spatial distribution of deep convection in the tropical central Pacific and to the strength of the polar jet (Harangozo et al. 2004) (iv) a part of the variability of SMB and melting may be stochastic, i.e. not necessarily driven by variability with spatio-temporal coherence at large scales. We have added a paragraph in the text (section3.2 L.492-509) to mention these possible reasons for relatively little explained variance.

C4 The postulation of potential lags is not adequately investigated. The hypothesis regarding sea ice reduction and transport from the Ross Sea could be tested as MAR using the sea-ice concentration from ERA-Interim. Thus, please consider adding analysis of sea ice concentrations to support this postulation. Although not as clear cut, intrusion of marine CDW could be evaluated by looking at the effective wind stresses as done by Steig et al. just off the continental shelf and attempt to quantify a six-month lag between strong wind events and surface melt. Also, there is no mention of potential preconditioning of the snowpack/firn for melt. An additional important variable in control of surface melt in the summer is the amount of snow that fell the prior winter, and it should be added to the analysis presented and included in Table 4. This signal might not matter at all, but also could lead to misinterpretation of an ENSO lag. Please consider all potential snowpack preconditioning variables that might explain melt from year-to-year.

In the discussion, we indeed suggested the existence of a delayed response of summer SMB and surface melting to the previous winter's ENSO events. We are not able to show perfectly robust evidence because this would probably require running dedicated experiments using a global ocean/atmosphere model (e.g. pacemaker simulations in Holland et al. 2019). We have nonetheless expanded this part of the discussion based on the literature and on additional diagnostics that indicate that such physical lag is highly probable:

1- Seasonality of ENSO and Rossby wave trains: First of all, the connection between ENSO and the Amundsen sector are thought to occur through Rossby wave trains originating in the equatorial Pacific (e.g. Ding et al. 2011). Numerous observational and modeling papers reported that austral winter and spring conditions were more favorable for Rossby wave trains to be formed and to propagate to high southern latitudes (Harangozo 2004, Lachlan-Cope and Connolley 2006, and references therein). Scott Yiu and Maycock (2019) have recently found that the poleward propagation of tropically sourced Rossby waves in summer is inhibited by the strong polar front jet in the South Pacific sector at that time of the year, which leads to Rossby wave reflection away from the Amundsen Sea region. Steig et al. (2011) also found that changes in wind stress over the Amundsen Sea had non-significant correlations to ENSO indices in austral summer, in contrast to the other seasons showing significant correlations.

2- Snow memory: In the initial draft, we only mentioned that there was no correlation between summer melt rates and snow temperature in the previous months (which could be hypothesized as El Niño events are known to warm West Antarctica in winter; Ding et al. 2011). We agree with Reviewer #1 that snowfall in winter and spring could also be thought to influence summer melt (e.g. because the amount of fresh snow affects albedo feedbacks). However, in all the basins, we find no significant correlations between summer melt rates and snow accumulated over the previous 3 months or 6 months. For example, here are some correlation values (R):

Thwaites:

R (DJF melt / DJF smb) = 0.31(p=0.06) //// R (DJF melt / SON smb) = -0.03(p=0.86) //// R (DJF melt / JJA+SON smb) = -0.01(p=0.94) ////

Pine Island:

R (DJF melt / DJF smb) = 0.48(p=0.02) //// R (DJF melt / SON smb) = -0.21(p=0.19) //// R (DJF melt / JJA+SON smb) = -0.11(p=0.50) ////

Dotson: R (DJF melt / DJF smb) = 0.48(p=0.01) //// R (DJF melt / SON smb) = 0.09(p=0.59) //// R (DJF melt / JJA+SON smb) = 0.11(p=0.53) ////

We conclude that the lag between ENSO and melt rates is not explained by preconditioning of the snowpack in previous seasons.

3- Ocean/sea-ice memory: If the lag is not explained by snow, then it has to be explained by the other slow media, i.e. the ocean/sea-ice system. Here also, the literature provides some indications. First of all, Clem et al. (2017) mentioned stronger lagged correlation between SON ENSO and DJF sea ice cover than synchronous correlation in DJF. This lag relationship was shown to affect DJF surface air temperatures over West Antarctica (warmer for El Niño phases). Pope et al. (2017) found that El Niño events developing in MAM created a dipole of sea ice anomalies, with decreased (increased) concentration in the Ross Sea (Amundsen and Bellingshausen Seas). Using a novel sea ice budget analysis, they showed that the decreased concentration in the Ross Sea was then advected eastward, reaching the Amundsen Sea in SON and DJF.

There is also another possible pathway for lagged ENSO/sea-ice relationship. The zonal wind stress over the Amundsen Sea continental shelf break is a good proxy for the transport of Circumpolar Deep Water (CDW) onto the continental shelf (Thoma et al. 2008; Holland et al. 2019). Steig et al. (2012) noted significant correlations between that wind stress and ENSO in JJA and SON but not in DJF. All these studies pointed out scales of a few months for the build up and advection of CDW on the continental shelf then into the ice shelf cavities where they produce basal melting. As stronger ice-shelf melt rates tend to decrease sea ice in this region due to the entrainment of warm CDW towards the surface (Jourdain et al. 2017; Merino et al. 2018), this deep ocean pathway may also explain a part of the lag between ENSO and DJF sea ice in the Amundsen Sea.

To complement these analyses, we have added a composite of DJF sea ice cover anomalies for El Niño events in JJA (6-month lag Fig.14). This composite is dominated by a significant negative anomaly, confirming that ENSO in austral winter has a significant effect on sea ice 6 months later, which could arguably explain the increase in humidity and favor high melt rates and high SMB. There are several possible reasons for such a lag, it could be related to the slow advection of winter sea ice anomalies from the Ross Sea, or to the slow advection of ocean temperature anomalies (CDW) towards the ice shelves then towards the surface through the meltwater pump, but we leave the quantification of these aspects for future research.

Minor Comments : Line 16 – change to “Amundsen Sea glaciers” Done Line 58 – change “underlaying” to “underlying” Done Line 114 – remove the ‘;’ at the beginning of the line Done Line 140 – change “estimates” to “estimate” Done Line 185-186 – remove the sentence “These data were collected over the Thwaites and Pine Island basins.” as it is redundant with Lines 181-182. Done Section 2.3 : Are these indices derived from ERA-Interim for consistency with the MAR output? If not, please state that and justify their use. We have added this information in section 2.3 Line 273 – Are “overestimate” and “underestimate” confused? Shouldn’t it be “The model tends to underestimate and overestimate highest and lowest wind speeds”? We agree with the Reviewer’s comments and this has been modified. Line 299 – Remove “(Medley et al. 2013, 2014)” as it is already mentioned in the sentence. Done Line 382 - add “is” after “mechanism” Done Figure 10/11 – Please add in the legend that blue represents moisture convergence for clarity. Figure 10 and 11 have been changed, we now choose to show the Integrated Vapor Transport instead of humidity convergence following concerns from reviewer #2 and D. Bromwich. Paragraph beginning with 530 – Perhaps it is important to mention here that DJF makes up the smallest percentage of annual accumulation, so it is not surprising that the findings do not match Medley and Thomas. Done

Please also note the supplement to this comment:
https://www.the-cryosphere-discuss.net/tc-2019-109/tc-2019-109-AC1-supplement.pdf

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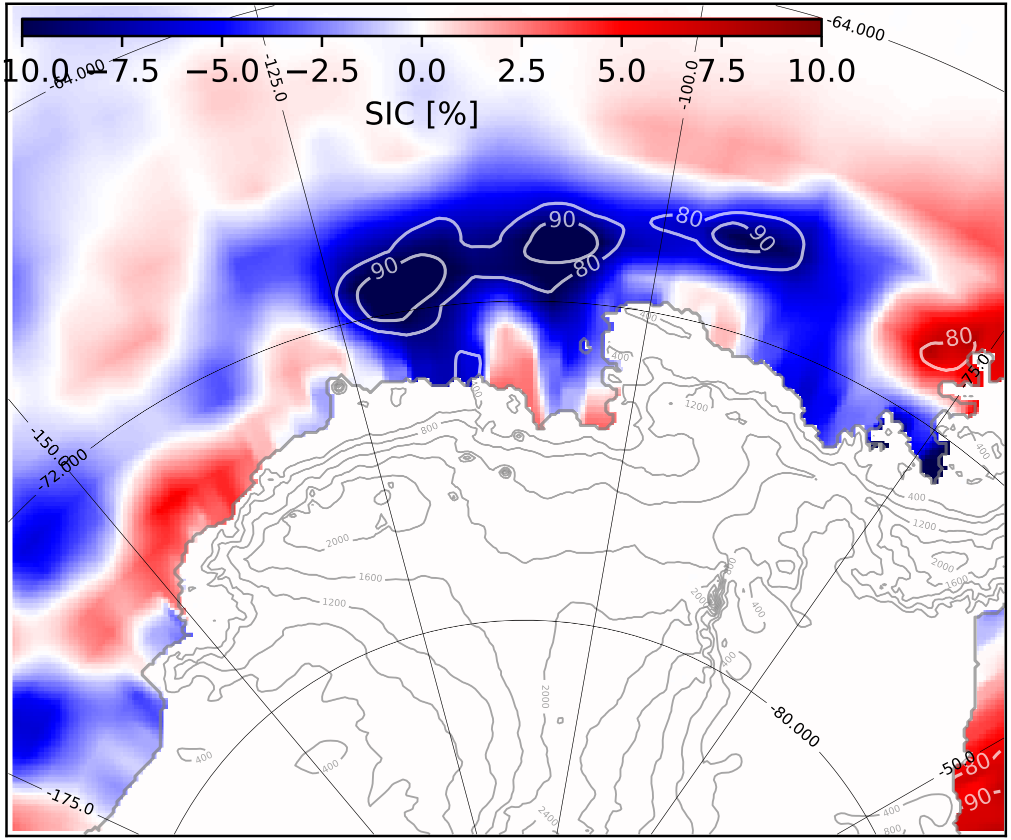

Fig. 1.

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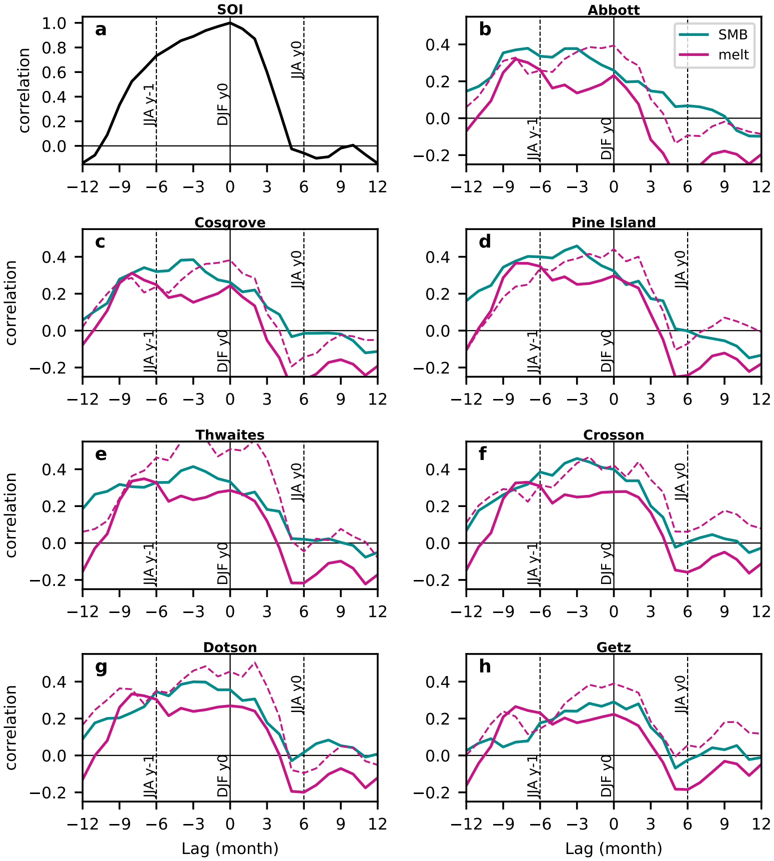
SOI
a
1.0
0.8
0.6
0.4
0.2
0.0
correlation
JJA y-1
DJF y0
JJA y0
Abbott
b
SMB
melt
Cosgrove
c
Pine Island
d
Thwaites
e
Crosson
f
Dotson
g
Getz
h
0.4
0.2
0.0
−0.2
−12
−9
−6
−3
0
3
6
9
12
Lag (month)

Fig. 2.

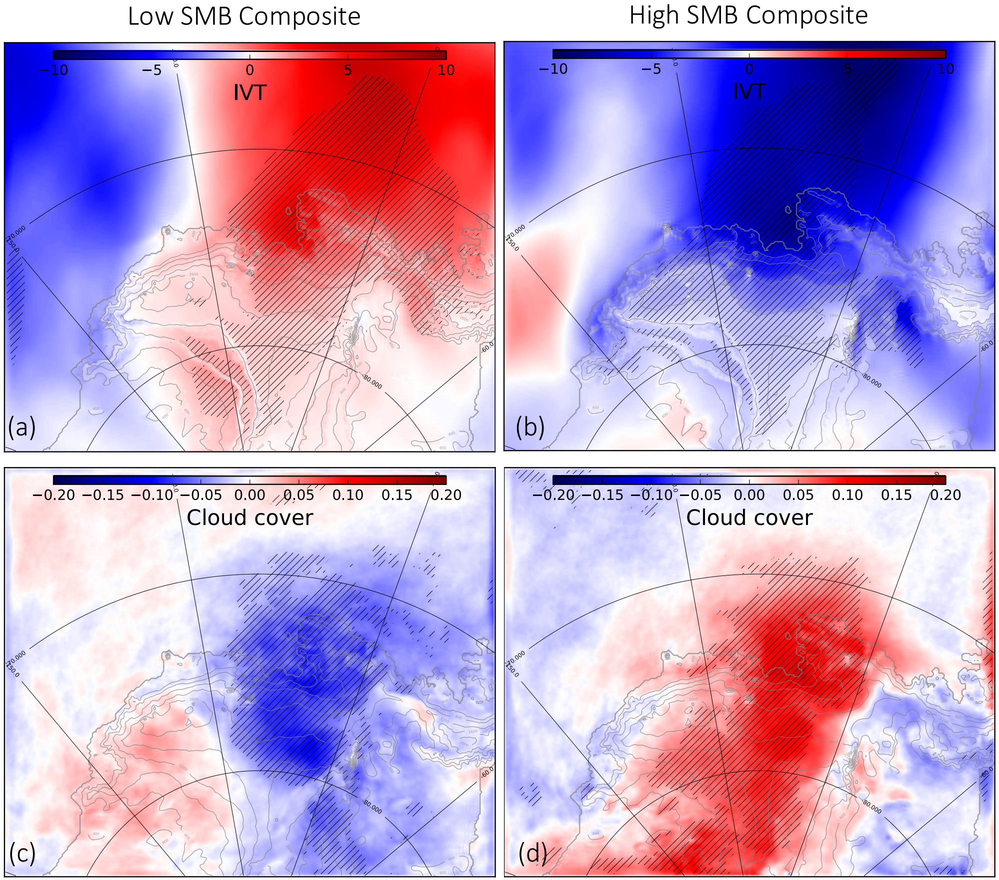

Fig. 3.

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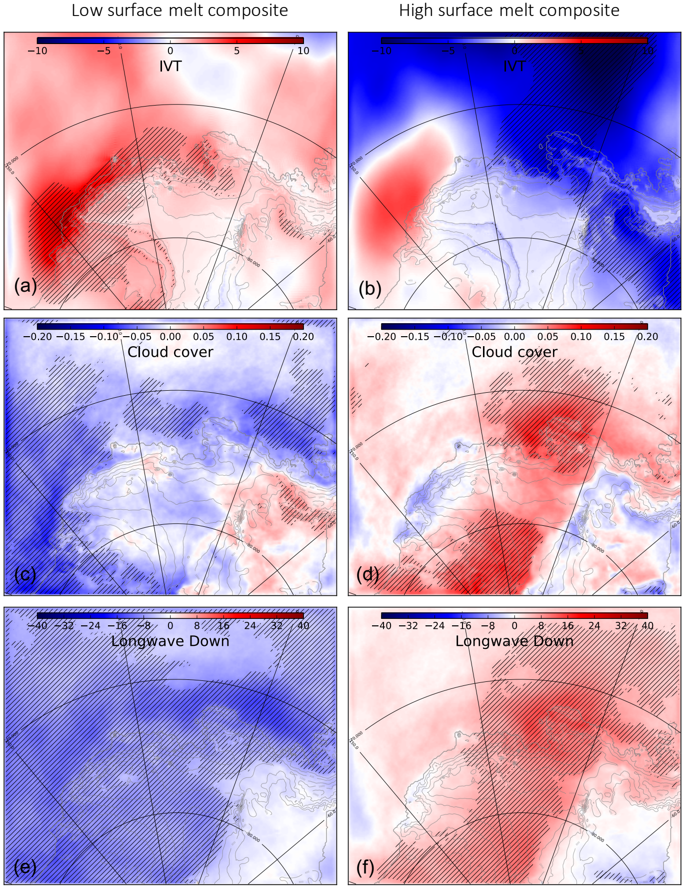

Fig. 4.

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