Response to Ref. #1:

We would like to express our gratitude to Ref. #1 for the thorough and constructive review. His/her suggestions helped us to identify and resolve a number of weak or unclear points and formulations as well as to provide some additional analysis to support our conclusions. We will give a detailed response below.

Main points:

1. This paper discusses the atmospheric influences in the anomalously large variation of Antarctic sea ice observed in 2016. It claims that the early and large retreat of Antarctic sea ice was the result of atmospheric flow patterns, predominantly related to a zonal-wave three pattern until October 2016. Thereafter an atmospheric meridional flow during November, consistent with a negative SAM index, resulted in a "large meridional exchange of heat and moisture". It is generally well written with some nice analysis, although there are a number of missing references and citation errors.

We have included the suggested references and some additional ones to better reflect upon the current state of research in literature. We also carefully checked all citations and resolved all existing errors.

2. The paper is quite descriptive. There is no direct objective analysis of atmospheric heat or moisture and no analysis discounting the influence of ocean surface temperatures playing their role in the 2016 event (as mentioned in line 127 regarding the paper by Stuecker). The analysis of zonal-wave three and SAM is similarly rather descriptive and not conclusive. Without an objective analysis I would unfortunately suggest that the paper's claims are not substantiated. That said, I would encourage the authors to complete further analysis and resubmit the paper. More detailed discussion is included below.

As the title and text define, our study restricts itself and focusses on the *atmospheric* influences on the sea ice behaviour. The *oceanic* influences are not a part of our study, even though they are certainly an important factor. We re-wrote the introduction and the discussion to make it clearer that the topic of our study were the local atmospheric influences on the sea ice, but that the oceanic influence and teleconnections, which we have not been analysing here, play an important role, too.

Although our study is mainly qualitative (as stated in the discussion), it is not just "descriptive". It is a non-quantitative and objective analysis of the contribution of different areas to the total ice loss and investigates the prevailing synoptic situations and processes associated with the sea ice retreat. There are clear physical relationships between the atmospheric flow patterns and the ice behaviour, which can explain the atmospheric influence on the ice melt and its initiation. Our study contains an explanation and interpretation of the interrelations and identifies processes responsible for the 2016 anomalies and is therefore more than purely descriptive. Our analysis of the meridional heat transport is also "objective", since there is a clear physical relation between the atmospheric circulation and meridional heat transport. In order to better illustrate this relation to the reader and provide a more quantitative measure of the meridional heat transport, we added a figure with the calculated vertically integrated meridional heat advection (from ERA-Interim) and combined it with Fig. 3 and Fig. 4. Then we discuss the SIC anomalies together with the advection field and the surface pressure field. We agree with the reviewer that we did not analyse the meridional moisture transport and therefore removed this from the related sentence in the results section

Naturally, we are aware of the fact that the atmosphere-ice-ocean system is highly complex and we agree that further, quantitative (modelling) studies would be necessary to better understand the processes involved, both in the atmosphere and in the ocean, and also their relative contributions. We extended this thought in the discussion. Such an investigation is, however, beyond the scope of our study.

Line 23 (and Line 59): "when combined with reduced Arctic SIE" – I don't think this is shown or referenced in the text at all, it just seems to be stated as a fact without proof.
We added a reference here in the introduction section. (it is highly unusual to give references in the abstract).

Line 30: It might pay to be cautious in referring to the November 2016 SIE as "extraordinary". The relevance of the apparent sudden variability in net SIE (2014-2016) and the record low monthly SIC for November should perhaps be place into context with longer term variability (e.g. the past variability of SIE as shown in Hobbs et al 2016 and Jones et al 2016) in comparison to the relative short period of observations examined within this current paper. Would "...unprecedented low November SIE, based on the post 1979 satellite data." be more appropriate?
We agree that this should be formulated more cautiously. Since we exceed the desired maximum number of 250 words in the abstract already, we changed this in the text accordingly and also added some remarks about the time period that was used for comparison in the discussion.

Line 51f: "reaching record extents in 2013, 2014 and 2015 ..." This should be "reaching record extents in 2012, 2013 and 2014...", and perhaps cite Reid and Massom, 2015 which covers all of 2012 through 2014.

We agree and corrected this and also included the suggested reference.

Line 75: Please insert reference for Su 2017.
Done.

Line 81f: Please insert reference for Lee et al 2017.
Done.

Line 92: "Haumann , 2011" should be "Haumann, 2011".

Done.

Line 92: Note that Holland and Kwok's excellent study covers the relationship between wind and SIC trends for the period 1992-2010 and may not necessarily be extrapolated upon without caution. See Kwok et al 2017 for example – as referenced below.

We included that Holland and Kwok (2012) only cover a sub-period of the satellite record. However, both the study by Haumann et al. (2014) and Kwok et al. (2017) show that meridional winds are also an important driver of long-term trends (entire satellite era; see their respective conclusions). Kwok et al. (2017) show that there are also regions were the relation between meridional winds and drift does not always hold, especially in coastal regions, but also argue that there might be issues with atmospheric reanalysis data in these coastal regions.

Line 102: Is the term "Usually" based on data since 1979 and your Figure 1? If so then perhaps this should be stated, otherwise please cite some research showing this.

Yes, we changed the formulation accordingly.

Line 124f: The sentence beginning with "Ross Sea and West ..." probably needs rewriting.

Done.

Line 127ff: It probably should be noted that apart from Stuecker 2017, several BAMS State of the Climate sections mention 2016 Antarctic sea ice, please see the references below. In particular, Clem et al decomposes the atmospheric component, while Mazloff et al mention the ocean influence and Reid et al discuss the sea ice in general.

We added all the BAMS citations and referred to them in the text.

Line 182f: This sentence probably needs rewriting.

Done.

Paragraph beginning at Line 243: Some of this paragraph confused me. There is mention of, for example, SIE in some regions being close to the long-term average – please see below for direct examples. I think perhaps you are confusing SIE with latitudinal extent, or otherwise could you please make this clearer.

We re-wrote this paragraph.

Line 249f: "...with negative anomalies..." – negative anomalies of what?

Of SIC, we changed this in the text.

Line 249f: "Largest negative anomalies". What is this a reference to: SIC, SIA, SIE or latitudinal extent? Note that SIE, as you have defined it, and latitudinal extent are two different things. If this is a reference to SIC or latitudinal extent (the contours on Figure 3?) then perhaps there should be reference to Figure 3a? If this is in reference to SIA or SIE then perhaps this should be shown in another way.

We reformulated this.

Line 251ff: The sentence beginning "In the Western..." should perhaps be rewritten.
Done.
There is also some apparent confusion between what is showing "negative deviations" at approximately 130E and SIE – at least I'm confused!
See above. We checked this and corrected this paragraph accordingly.

Line 252: "approximately130" should be "approximately 130" – please insert a space.
Done.

Line 256: perhaps this should read, "However, in February 2017 the monthly mean SIA ..." as otherwise this is a little ambiguous.
We don't understand the reviewer's point here, since the provided line number does not match the text. If the reviewer refers to line number 226 of the original manuscript, we agree that adding "February 2017" is less ambiguous and changed this sentence accordingly.

Line 267: "Hall and Visbeck should be 2002, not 2001?
We corrected this.

Line 276ff: Other research (Clem et al 2017) has suggested that the SIC anomalies in this region are not necessarily related to atmospheric flow, and that they are related more to weaker ocean stratification and deeper convection over Maud Rise. The opening of the polynya in this region during August 2016 caused quite a bit of media attention.
Thank you for pointing out that we did not really address the re-occurrence of the Weddell Sea polynya in 2016 and 2017. Actually, this is a very important point and we think that our study can at least partly explain its initial development in November 2016 due to a strong surface divergence, which might have triggered oceanic feedbacks now discussed in the manuscript. We included the polynya in the discussion and quoted the suggested reference.

Line 307: "This is shown in Figure 6e" should probably be referring to Figure 4e?
The Figures 3 and 4 have been combined now and the numbers changed accordingly.

Paragraph beginning at Line 314: There is a concluding summary here for section 3.2.1 that is not reflected directly by the analysis, and revolves around the words "strong warm air advection".
We removed this paragraph.

Not once through the paper is atmospheric temperature directly analysed. There is some nice analysis and discussion within this paper, but much of the analysis that leads to this conclusion is descriptive rather than an objective analysis.
We added a new figure with the northward heat advection from ECMWF-Interim Re-analysis to quantify our result discussed together with the surface pressure field and related winds. The meridional heat advection agrees very well with our qualitative results shown so far.

Also, a number of papers (and you have cited one) have suggested that the 2016 Antarctic sea ice anomalies were possibly the result of a combination of atmosphere and ocean anomalies. Here you are suggesting the anomalies were the result of a warm atmosphere only, and I don't feel that you have directly shown this. You have not discounted the ocean impacts or objectively shown that a warm atmosphere specifically was responsible for the SIC anomalies. Given your concluding remarks and such a large anomaly in net SIE, surely you would be able to show that there was a large atmospheric temperature anomaly – or ocean surface anomaly?

We did not state that the observed behaviour of the sea ice were the result of a warm atmosphere only and we agree that oceanic influences and feedback mechanisms might play an important role as well. Our study investigated the atmospheric influences only, but we also mentioned that the ocean is important, too. We reformulated the introduction and the discussion and added a number of studies addressing these issues to make this point clear, also including the effects of teleconnections with ENSO. Nevertheless, our analysis of the temporal evolution of the regional SIA and SIE anomalies imply an atmospheric origin of the anomalies in many regions that is associated with the warm air advection events and a rapid response of the SIA and SIE triggered by the event. We argue that if the ocean was initiating these anomalies, they would occur much more gradually and persist already over a longer time period. However, this gradual evolution of the anomalies occurs partly in the Western Indian Ocean sector and the Amundsen and Bellingshausen Seas, where it is likely that the ocean plays a critical role, as we now explicitly state.

Line 330: The sentence beginning, "The start of the melt period..." probably needs rewriting.
Done. .

Line 335ff: From Figure 5u it would appear that R7 contributes significantly to the sea ice decay – in contrast to what is said here.
We changed this accordingly.

Line 348ff: From, "It shows generally good agreement...". Again, this is based on some quite subjective analysis.
See above.

Paragraph starting on Line 358: There is discussion here about the first third of the month of November being significant, and there is reference to Figure 4e. But there is no corresponding pattern of sea ice drift for this time period.
We do not think it is necessary to show the ice drift for this period since melting is the predominant factor that influences sea ice decay during this period. However, we agree that the previous formulation was a bit confusing and might have implied that such a Figure existed. We rewrote this paragraph.

Line 361: "...leading to compaction..." and "...decreasing SIC" are not really consistent. Should you split this discussion into something like and inner and outer ice pack?
We agree that this was confusing and not quite correct. We corrected this.

Line 374ff: ZW3 plots are given for the years 2013-2016, but with no real explanation as to why these years were chosen. ZW3 is put into perspective with the preceding three years, but there is no suggestion here that an August-October averaged ZW3 index of ~0.4 is significant or not. Is this ZW3 value 1, 2 or 3 standard deviations above normal for this time of the year, has it ever happened before and if so what was the consequence on the sea ice? Indeed, it would appear that for August 2014 the ZW3 was considerably well above that of 2016. In fact, looking at Raphael 2004 it would appear that there are long periods of positive ZW3, but there is no mention of the corresponding SIE, SIC for these years.

The plots for 2013-2015 are shown to put 2016 into perspective. The index is normally so variable that it does not make much sense to calculate an average. 2016 is distinctly different from the preceding years. While in 2013-2015 the ZW3 index alternated between positive and negative values throughout the year, in 2016, the ZW3 index was almost continuously positive in the winter months. This is unusual and hints at a preconditioning of the sea ice for the later intense melt. We now added a new Figure 8, which shows the meridional heat flux anomalies of the year 2016 with respect to the period 1979-2015. The anomalies reveal a clear ZW3 pattern, which further supports our argument that the year 2016 was clearly exceptional during the period of the satellite record.

Line 444: Please reference Schlosser 2015, or should this be Schlosser 2016?
Yes, 2016, we corrected that.

Line 510: There is no citation of Hobbs et al. Please remove or cite within text.
We included this citation in the text.

Line 517: There is no citation of Kottmeier and Sellmann 1996. Please remove or cite.
We included this citation in the text.

Line 545: Please remove or cite Peng et al.
We removed it.

Line 557: Please remove or cite Schlosser 1988.
We removed it.

Line 566ff: Please remove or cite both Simmonds papers.
We cite both papers in the text now.

Line 576ff: Note that Turner et al 2009 has been referenced twice – please remove one.
Done.

Line 581ff: Note that Turner et al 2014 should be Turner et al 2015.
Corrected.

General comments: Is the term Mio, used throughout the text in reference to "million", suitable for this Journal?

We replaced "Mio." by "million" accordingly to the journal's guidelines.

I suspect that within the text there are some instances where reference to Figure 3 and Figure 4 get confused, or that perhaps that there should be reference to both Figures 3 and 4? For example, Lines 269, 281 and 291 discuss SIC anomalies but both times there are references to the figure showing MSLP (Figure 4).

Since we combined Fig.3 and Fig. 4 in the revised version, we had to check all references to those figures and corrected them accordingly.

"Figure" and "Fig" seem to be variously used through the text. Chose one of these that is appropriate for this Journal and be consistent through the text.

Here we followed the journal's rule that „Figure" is not abbreviated when it occurs at the beginning of a sentence, but it is abbreviated when it occurs in the middle of a sentence (see https://www.the-cryosphere.net/for_authors/manuscript_preparation.html). We made sure that all occurrences follow this rule.

Table 1: There appear to be some discrepancies in the longitudes within this table.

Thanks for pointing this out. We corrected that. (Some 1s had disappeared due to change of column width.)

Figure 3: What do the coloured contours represent on these figures?

The green line represents the monthly mean SIE 1979-2015 the black line the SIE in 2016 for the corresponding month. We added this information in the figure caption and in the text, where it occurs for the first time.

Figure 4: I have some concerns with this figure. Are the arrows hand drawn and coloured – there is no mention in the text or in the figure caption as to how they are derived? They look rather subjective than objective.

Since our publication was submitted to The Cryosphere, we address a readership that not always has knowledge about atmospheric dynamics and even meteorologists get a bit mixed up sometimes when it comes to clockwise or anti-clockwise rotation on the Southern Hemisphere, we tried to facilitate the reading of the figure by adding arrows that indicated the warm or cold air advection. The arrows agree well with the blue and red areas in our new figure of meridional heat advection, the latter not explaining the reason for the advection, though. Thus, we would like to keep the figure with the pressure fields, including the illustrating arrows.

We added an explanation of the arrows in the discussion of the new Fig. 3.

Figure 7b: There is no mention of the hatching in this figure.

We added this information.

Suggested References:

Clem, K.R., S. Barreira, and R.L. Fogt: Atmospheric Circulation [in "State of the Climate in 2016"]. Bull. Amer. Meteor. Soc., 98 (8), S156–S158, 2017.

Jones et al, 2016 Assessing recent trends in high-latitude Southern Hemisphere surface climate. Nature Climate Change 6, 917–926 (2016), 2016.

Kwok, R, et al 2017 Sea ice drift in the Southern Ocean: Regional patterns, variability, and trends. Elem Sci Anth, 5: 32, DOI: https://doi.org/10.1525/elementa.226

Mazloff, M.R., Sallée, J.B., Menezes V.V., Macdonald A.M., Meredith, M., Newman, L., Pellichero V., Roquet F., Swart, S., Wahlin, A.. State of the Southern Ocean in 2016, BAMS, 98 (8), S166-S167, 2017.

Reid, P. & Massom, R. in State of the Climate in 2014 (ed. Blunden, J. & Arndt, D. S.) Spec. Suppl. Bull. .Am. Meteorol. Soc. 96, S163–S164 (2015).

Reid, P., S. Stammerjohn, R. A. Massom, J. L. Lieser, S. Barreira, and T. Scambos, Sea ice extent, concentration, and seasonality [in "State of the Climate in 2016"]. Bull. Amer. Meteor. Soc., 98 (8), S163–S166, 2017.

Thank you for the additional references. We included all of them.

Response to Ref #2

We would like to express our gratitude to Ref. #2 for the thorough and constructive review. His/her comments helped us to identify and resolve a number of weak or unclear points and formulations as well as to provide some additional analysis to support our conclusions. We will give a detailed response below.

General Comments

The study is well written, well organized, and a joy to read. However, I do find the study to be a bit too much on the qualitative/descriptive side with many of the claims made on how the atmosphere "influenced" the sea ice being a bit speculative. Furthermore, I am not sure if we are learning anything new here. As stated by Referee #1, many of the descriptive details surrounding the sea ice, atmospheric circulation, and SAM pattern during 2016 are already discussed in the State of the Climate in 2016 Antarctica chapter. Without more quantification of mechanisms, such as quantifying advection, melt, and the role of the ocean, I don't see what new information is being presented here. I also strongly encourage the authors to place their findings more in context with other work, particularly Turner et al. (2017). I recommend the authors perform a major revision and resubmit at a later time.

As we stated already in our response to Ref#1, although our study is mainly qualitative (as stated in the discussion), it is not just "descriptive". It is a non-quantitative and objective analysis of the contribution of different areas to the total ice loss and investigates the prevailing synoptic situations and processes associated with the sea ice retreat. There are clear physical relationships between the atmospheric flow patterns and the ice behaviour, which can explain the atmospheric influence on the ice melt and its initiation. Our study contains an explanation and interpretation of the interrelations between atmospheric circulation and sea ice anomalies and identifies processes responsible for the 2016 anomalies. Therefore, it is more than purely descriptive. Our analysis of the meridional heat transport is also not speculative, since there is a clear physical relation between the atmospheric circulation and meridional heat transport. In order to better illustrate this relation to the reader and provide a more quantitative measure of the meridional heat transport, we added a figure with the calculated vertically integrated meridional heat advection (from ERA-Interim) and combined it with Fig. 3 and Fig. 4. Then we discuss the SIC anomalies together with the advection field and the surface pressure field. Our previous qualitative results were strongly supported by the quantified meridional advection.

Compared to Turner et al. (2017) and the BAMS paragraphs, we not only quantify the advection now, we also analyse the temporal and spatial development of the sea ice decline in considerably more depth and detail than the previous studies and investigate ZW3 in more detail. In addition, we analyze the sea ice area change (temporal derivative) of the daily sea ice area, which provides new insights into the development of the anomalies.

Naturally, we are aware of the fact that the atmosphere-ice-ocean system is highly complex and we agree that further, quantitative (modelling) studies would be necessary to better understand the processes involved, both in the atmosphere and in the ocean, and their relative contributions.

We extended this thought in the discussion. Such an investigation is, however, beyond the scope of our study.

Specific Comments:
There is a lot of referencing to place names (particularly ocean basins and seas) throughout the study, and so I recommend the authors include a map to go along with Table 1. I also recommend giving new names to the regions (R1, R2, etc.) so there is some connection to their respective geographic place names (e.g., western Ross Sea as wRS, etc.). This will also reduce instances of referring to both the place name and the respective "region" name for clarification in the text (for example, lines 329-331), which is confusing and makes the R1, R2, etc. names seem unnecessary. If sensible region names are defined, they could be used throughout the manuscript without requiring further clarification.

Thank you for this suggestion. We agree that the suggested naming of the sub-regions would make it easier for the reader to follow. Accordingly, we changed them to EWS, WIO, EIO, WP, ERS, ABS, and WWS.

Line 116: Please add citation Meehl et al. (2016) and their finding that tropical Pacific variability also influence meridional winds and associated sea ice extent.
Done.

Line 117-118: As you mention below in lines 125-127, Turner et al. (2017) already established northerly wind/warm air advection was a major contributor to the 2016 record sea ice loss. What are we learning here that we don't already know?

The study by Turner et al, as the purpose of GRL publications is defined, provides quick information about a recent topic in a relatively brief publication. They describe in relative detail the climatological behaviour of the sea ice and then try to explain the features observed in 2016. Our study investigates the temporal and spatial development of SIA and SIE in considerably more detail and depth than a short GRL paper can do. We also added the meridional heat advection for quantification now. Turner et al. use more general phrases, whereas we give detailed information to all single sub-areas and time periods that show that the situation is much more complex than described earlier, i.e. where and why did the warm air advection occur and what was the response of the sea ice. For example, Turner et al. wrote "rapid ice retreat in the Weddell Sea took place in strong northerly flow after an early maximum ice extent in late August". We show that the western and eastern parts of the Weddell Sea behaved differently (thus more sub-regions than in the Turner paper), and particularly the Eastern Weddell Sea did not contribute substantially to the ice retreat before November. (the western Weddell Sea not before October). Equally the BAMS chapters are rather short and less detailed than our study.

Line 245-246: How does adding two extra sub-areas compare/expand upon the results of Turner et al. (2017)? Please make these new insights clear by placing them into context of Turner et al. (2017).

Our definition of sub-areas closely followed the observed sea ice anomalies and not a climatology established earlier. This very specific definition of sub-areas allowed a detailed investigation and explanation of the observed phenomena and the evolution of the sea ice anomaly. Especially the sub-division of the Weddell Sea was necessary due to the different behaviour of the eastern and western Weddell Sea. We added this reasoning in the text.

We discussed Turner et al. in more detail in the discussion now and explained the differences to our study: Our results agree well with the general findings of Turner et al. (2017), but give more details due to the higher spatial resolution used in our study and also quantify the meridional warm air advection that was discussed only qualitatively by Turner et al. (2017). While they stress the comparison of conditions in 2016 with the climatological means of amount and timing of SIE minima and maxima as well as mean location and intensity of cyclones, our study looks more closely at both the temporal and spatial evolution of SIA and SIE, investigates the contribution of the different parts of the Southern Ocean to ice melt in more detail, discusses the role of ice drift and the relationship between sea ice decay, SAM and ZW3.

Figure 3: Please specify in the caption what the green and grey lines are. I assume green is the average SIE and grey is the 2016 SIE, but it needs to be specified.

We explained this now in the caption and also in the text.

Line 255-256: The negative SIC anomalies in the Amundsen and Bellingshausen Seas actually appear quite similar in magnitude to those in the Indian Ocean. Without quantifying this, I don't think it can be said here.

We reformulated this and referred to the position of the sea ice edge rather than SIC. The differences can be clearly seen in Fig. 3.

Line 309-310 and 314-316: Although I appreciate the schematic arrows, without quantifying advection there is no way of determining that warm air advection explained any portion of the sea ice loss. Furthermore, actual surface air temperature over the sea ice would likely need to be analysed to determine if, even in the presence of warm air advection, temperatures were actually warm enough to melt the ice as the authors claim.

See above: following also the advice of Ref.#1, in order to provide a more quantitative measure of the meridional heat transport, we added a figure with the calculated vertically integrated meridional heat advection (from ERA-Interim) and combined it with Fig. 3 and Fig. 4. Then we discuss the SIC anomalies together with the advection field and the surface pressure field. Our arrows agree very well with the areas of warm and cold air advection from ECMWF-Interim calculations in the new Fig. 3.

Lines 332-334: This seems highly speculative.

We used a careful formulation for this, we do not say that we are talking about facts, but suggest possible reasons. We would not call this speculative.

Please add DOIs to bibliography
Done.

Technical Corrections

Line 94: SIC has not been defined. Please define it here and use SIC for the remainder of the study
Done.

Line 124: remove "were"
Done.

Line 128: change to "December"
Done.

Line 130: remove "rather"

Done.

Line 137: ECMWF is never defined

We explained it in introduction section now.

Line 163: change "today" to "present"

Done.

Line 205: please clarify what "Mio." Means

We changed this according to the Journal style requirements.

Line 210: no longer need to continue defining SIC, SIE, SIA as they are already defined

Agreed. We changed this accordingly.

Line 259: Change "Figure 6" to "Figure 4", and please clarify whether this is sea level pressure (as stated in caption) or surface pressure (as stated in text)

The figure numbers have changed because of the inclusion of new figures and change of Fig. 4 and we checked the correct usage of the numbers. We corrected surface to sea level pressure in the text.

Line 269-270: Already defined as the Amundsen Sea Low / ASL, so just use ASL here

Done.

Line 275: Please remove the words "masses" and "right"

We deleted "right", but kept "masses", since "air masses" is a standard meteorological term.

Line 288: Would say ASL instead of "Pacific low"

Corrected.

Line 305: Just put "periods" in parenthesis

Done.

Line 307: Please change to Figure 4e

The figure numbers were changed due to the addition of new figures and are now numbered correctly.

Response to Ref. #2

We would like to express our gratitude to Sarah Cross for her careful and thorough review.

1 General Comments

Schlosser et al. explain and investigate a range of atmospheric influences that lead to the anomalous sea ice decay in Antarctica in 2016. The rate of melt in this year was much higher compared with averages from previous years, at 2 Mio. km2, and there are many variables that can explain this. The paper establishes that some factors affecting the rate of ice decay include cyclonic activity, regional evolution of Sea Ice Extent (SIE) and Sea Ice Area (SIA), and atmospheric flow patterns. Mainly through analysis of the ZW3 (zonal wave 3) feedbacks and the SAM (Southern Annular Mode). This is significant as some of the research covered in this paper can be used to determine the exact atmospheric influences on sea ice decay and how anthropogenic forcing can influence this, hence giving it relevance to climate change and other major controversies. There is a clear distinction between expected outcomes and unexpected outcomes in this paper.

The anomalous results were clearly explained and identified, whilst the expected results were outlined from the beginning and both were used in the discussion of the atmospheric influences on sea ice decay.

Specific Comments

2.1 The authors clearly outline the aim of the paper, to discuss the possible reasons for the anomalous ice decay, in the introduction. The further explanation and previous work is written in clear and scientific language, however one suggestion would be that terms should be defined earlier. The terms ZW3 and SAM are used in the introduction with no explanation, and whilst they are covered later in the text this could be initially confusing.

We agree that this might be confusing for readers not familiar with the subjects. We now give a short explanation where the terms occur for the first time in the "introduction and previous work" section (combined in the revised version) and leave the detailed explanation for the respective sections.

2.2 In addition, some alternative ideas could be discussed, for example Stuecker et al. 2017 discuss the role of greenhouse gases and ozone forcing in addition to other atmospheric influences. Although great detail would not be relevant for this paper, mentioning these factors could help to link the results to other important parts of the cryosphere and give a wider picture of the papers significance.

Stuecker et al. (2017) was published after we submitted our paper, we included it in the revised version. We also added some other points to the discussion, e.g. the occurrence of the Weddell Polynya (close to Maud Rise) in 2016 and teleconnections with ENSO.

2.3 Although relevant figures were used and they were well referenced in the text itself, having the figures and figure captions separate at the end of the paper was a little confusing. My suggestion would be to group them together and keep them at the end of the paper for ease of access.

We did this for the uploaded revised version. In the final version, the figures will be included in the text anyway in the usual TC layout.

2.4 Finally, the paper is well referenced and a large variety of literature was used. However most of these references were from before 2010 with one even dating back to 1902. One suggestion would be to use some more up to date references, as this is especially important considering the recent advances in this field of ice decay. The older references are not necessarily invalid however conditions and attitudes at the time of these papers were much different from today, and this could be clarified within the paper.

We agree. We added 15 new references in the revised version, of which 12 are not older than from 2012, 10 stem from the years 2016 and 2017.
Concerning the reference from 1902: We like to give credit to the researchers, who originally found the mentioned results, which was F. Nansen in this case. (Something that (in our (ES') opinion) tends to be neglected frequently nowadays, particularly when the reference is not available online.)

2.5 In summary, the paper clearly analyses a wide range of available data and draws relevant hypotheses based on this, the sections are well laid out and clearly labelled and there is strong emphasis on past work and a wide range of references are cited. However, there are some minor errors that could be amended, therefore I suggest a review of the paper to correct these, after which it could be accepted.

3 Minor Corrections

3.1 Line 85- there is an unnecessary bracket (Enomoto and Ohmura (1990) should be (Enomoto and Ohmura, 1990)

Corrected.

3.2 Line 128- misspelled December as Dezember

Corrected.

3.3 Line 129- an accent is required for El Niño

Corrected.

3.4 Line 243- the comma after "to investigate" is unnecessary

Corrected.

3.5 Line 360-365- sentence is too long, needs to be broken up

We re-wrote the entire paragraph, thus the sentence does not occur in the original form and length anymore (we agree that it had been too long and a bit hard to read).

3.6 Line 421- repeated word "accelerated ice melt melt"

Corrected.

3.7 Line 430- in my opinion this line would work better as a list of three i.e. "sea ice decay, SAM and ZW3" instead of repeating the ands

What we meant was the relationship between sea ice decay and SAM, and the relationship between sea ice decay and ZW3. However, of course, SAM and ZW3 are related, too, (if not as straightforward as it may seem, though), so we follow this advice.

3.8 Line 445- again a matter of opinion but this could perhaps be broken into two sentences “. . . extremely zonal flow conditions. Whereas 2009 exhibited. . .”
We broke this sentence into two sentences, as suggested.

References

Stuecker M.F., Bitz C.M. and Armour K.C., 2017. Conditions leading to the unprecedented low Antarctic sea ice extent during the 2016 Austral spring season, Geophysical Research Letters, 44, 17, 9008-9019

We included this reference.

Atmospheric influences on the anomalous 2016 Antarctic sea ice decay

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Abstract In contrast to the Arctic, where total sea ice extent (SIE) has been decreasing for the last three decades, Antarctic SIE has shown a small, but significant increase during the same time period. However, in 2016, an unusually early onset of the melt season was observed; the maximum Antarctic SIE was already reached as early as August rather than end of September, and was followed by a rapid decrease. ~~The decline of the sea ice area (SIA) started even earlier, namely in July.~~ The decay was particularly strong in November where Antarctic SIE exhibited a negative anomaly (compared to the 1979–2015 average) of approximately 2 ~~Mio.~~million km^2~~, which, combined with reduced Arctic SIE, led to a distinct minimum in global SIE.~~. ECMWF-Interim reanalysis data ~~were used to investigate possible atmospheric influences on the observed phenomena. The~~showed that the early onset of the melt and the rapid decrease in sea ice area (SIA) and SIE were associated with atmospheric flow patterns related to a positive zonal wave number three (ZW3) index, i.e. synoptic situations leading to strong meridional flow and anomalously strong southward heat advection in the regions of strongest sea ice decline. A persistently positive ZW3 index from May to August suggests that SIE decrease was preconditioned by SIA decrease. Particularly, in the first third of November northerly flow conditions

in the Weddell Sea and the Western Pacific triggered accelerated sea ice decay, which was continued in the following weeks due to positive feed-back effects, leading to the ~~extraordinary~~unusually low November SIE. In 2016, the monthly mean Southern Annular Mode (SAM) index reached its second lowest November value since the beginning of the satellite observations.~~ SIE decrease was preconditioned by SIA decrease.~~ A better spatial and temporal coverage of reliable ice thickness data is needed to assess the change in ice mass rather than ice area.~~-~~

1 Introduction and previous work

Sea ice plays a critically important role in the cryosphere as well as the global climate system. It modifies heat~~,~~ and mass exchange processes. Sea ice has a very high albedo compared to open water, thus when present, it greatly increases the surface reflectivity. It also reduces the exchange of heat and moisture between the ocean and the lower atmosphere. Strong positive feedback effects related to sea ice changes have consequences for both atmosphere and ocean. Melting of sea ice rapidly decreases the surface albedo and increases turbulent heat exchange between ocean and atmosphere; it thus strongly influences the surface energy balance of the ocean (e.g. Stammerjohn~~,~~ et al., 2012), which in turn affects sea ice itself. Formation and melt of sea ice also influences the sea water salinity by releasing salt (brine rejection) upon freezing and fresh water upon melting. These fluxes dominate the surface freshwater flux balance of the seasonally sea~~-~~ ice covered Southern Ocean and thereby strongly influence the ocean overturning circulation (Haumann et al., 2016), which is critical for exchanging heat and carbon between the deep ocean and the atmosphere. Therefore, Antarctic sea ice plays an active role in the global climate system.

While in the Arctic the total sea ice extent (SIE) has been decreasing for more than three decades~~,~~ (e.g. Simmonds, 2015), Antarctic SIE has shown a small, but significant increase during the same time period (1.5 % per decade over the period 1979 to 201~~2),~~3; Turner et al., 2015), reaching record extents in 2012, 2013, and 2014 ~~and 2015 (e.g. (~~Massonnet et al., 2015; Reid and Massom, 2015). However, in 2016, an unusually early onset of the seasonal ice melt was observed. The maximum Antarctic SIE was reached a month earlier, in August, rather than end of September, and was followed by rapid ~~and continuous~~ decrease until the summer when record minimum SIE was observed. The sea ice area (SIA), the total area actually covered by ice, started to exhibit values below the long-term average as early as July, with only a brief return to normal in late August when the general sea ice retreat began. The decay was particularly strong in November, when Antarctic SIE exhibited a negative anomaly (compared to the 1979~~-~~–2015 average) of 1.84 ~~Mio.~~million km^2, which is unprecedented in the satellite era (since 1979) and, combined with reduced Arctic sea ice, led to a distinct minimum in global SIE~~.~~ (NSIDC, 2016).

The present study is motivated by this unusual behavio~~u~~r of Antarctic sea ice in 2016. Sea ice retreat~~,~~ is influenced by atmospheric as well as oceanic processes. Local atmospheric influences on sea ice, both dynamic and thermodynamic, act on a relatively short time scale with an immediate response of the sea ice. In this study, we solely focus on the local atmospheric influences on sea ice retreat and discuss related possible reasons for the observed anomalous sea ice decay.

~~2 Previous work~~

~~Changes in sea ice can be induced by both atmospheric and oceanic processes. Locally, they~~Locally, changes in SIE and SIA can be caused by melting or freezing and by sea ice dynamics that influence ice advection, ice divergence and convergence (e.g. Enomoto and Ohmura, 1990). On a short time scale (days to weeks), both processes are strongly dependent on atmospheric influences, i.e. thermodynamics of the ocean~~-~~–atmosphere interface and wind stress on the floating ice (e.g. Watkins and Simmonds, 2000). Oceanic influences mainly play a role on longer time scales, such as seasonal and interannual variations (e.g. Gordon~~, 1975~~ and Huber, 1990; Martinson, 1990). In particular, while changes in the timing of sea ice retreat seem to have a strong influence on the timing of the following advance, advance and subsequent retreat are only weakly related (Stammerjohn et al., 2012). This relation suggests a strong oceanic thermal feedback that accelerates or decelerates autumn freeze onset (Stammerjohn et al., 2012). In a recent study, Su (2017) stated that the location of the sea ice edge at the SIE maximum is strongly correlated with the upper-ocean stratification in early winter (April~~-~~–June~~).~~), consistent with the findings by Lecomte et al. (2017). The seasonal influence of the ocean on ~~sea ice extent~~SIE has been the subject of a number of studies. Hall and Visbeck (2002) show that the strength and position of the westerlies influence northward Ekman transport and therefore the ~~sea ice extent~~SIE as well as upwelling of warmer water closer to the continent. This effect can cause stronger retreat of sea ice in summer, when the ice edge is farther south, and expansion of sea ice in winter (e.g. Lee et al., 2017).

Enomoto and Ohmura (1990) investigated the relationship of the sea ice edge advance~~/~~ and retreat and the semi-annual oscillation of the circumpolar trough. The ice drift depends on the position of the sea ice edge relative to the Antarctic convergence line (Enomoto and Ohmura ~~(~~, 1990), which moves according to the semi-annual oscillation of the circumpolar trough (Meehl, 1991). This leads to ice divergence when the ice edge is north of the convergence and transport of ice towards the coast, when the ice edge is south of the Antarctic convergence line. The velocity of the ice drift amounts to 1~~-~~–2 % of the surface wind speed; the direction of the ice drift is turned by 10~~-~~–40° to the left of the direction of the atmospheric flow, an average value of approximately 30° was found (Kottmeier et al~~,~~., 1992~~,~~; Kottmeier and Sellmann, 1996; Nansen, 1902). Therefore, the meridional ice transport that affects the latitudinal extent of the sea ice is primarily driven by meridional winds, but also zonal winds can have ~~a substantial~~an influence~~ on the meridional ice transport and the SIE~~, particularly in the Ross and Weddell Seas where the sea ice edge extends to lower latitudes into the westerly wind belt during winter (Haumann~~-~~, 2011). Holland and Kwok (2012) investigated the influence of surface winds on Antarctic sea ice changes over the period 1992 to 2010. They state that while in most parts of West Antarctica mainly wind-driven changes in ice advection are responsible for the observed sea ice concentration (SIC) trends, wind-driven thermodynamic changes dominate in all other parts of the Southern Ocean. Haumann et al. (2014) and Kwok et al. (2017) show that meridional wind changes also play a major role in driving the sea ice trends over the entire satellite record. In some regions, zonal winds are also important for zonal redistribution of the ice (Haumann, 2011; Kwok et al., 2017). This means that both changes in the ~~zonal and~~ meridional and zonal components of the atmospheric circulation can induce sea ice anomalies, either through associated temperature anomalies or through ice transport anomalies.

Raphael (2007) studied the influence of atmospheric zonal wave number three (ZW3) on Antarctic sea ice variability. ZW3 (together with ZW1) describes the asymmetry in the generally strongly zonally symmetric circulation in the extratropical Southern Hemisphere. It is related to a pattern of alternating northward and southward flow, which influences the temperature difference between ocean and atmosphere and thus their exchange of sensible heat. Raphael (2007) states that sea ice responds to these heat fluxes. Pezza et al. (2012) investigated the relationship between recent SIE ~~and~~ extremes and the Southern Annular Mode (SAM~~/~~), the dominant mode of atmospheric variability in the extra-tropical Southern Hemisphere (Marshall, 2003), as well as El Niño-Southern Oscillation (ENSO~~.~~). They found that the relationship is not uniform for all longitudes and that the natural variability of SIE and the SAM is so large that a longer reliable time series of sea ice and climate data would be necessary to establish a causal relationship between the two variables. Simpkins et al. (2012) show that the relation of SAM and ENSO with Antarctic sea ice anomalies exhibits a strong regional and seasonal dependence through the associated atmospheric circulation patterns. Simulations with global climate models indicate that also the oceanic response to SAM leads to interannual variations of Antarctic sea ice, with an initial expansion of the sea ice due to positive SAM anomalies during austral summer (Holland et al., 2017). Moreover, modeling studies suggest a strong influence of interannual and decadal tropical variability, especially in the Pacific, on Antarctic sea ice anomalies through the atmospheric circulation (Meehl et al., 2016; Purich et al., 2016; Schneider and Deser, 2017) and oceanic feedbacks (Stuecker et al., 2017).

~~Usually~~In the past 37 years covered by satellite data, variations in the total Antarctic SIE ~~are~~have been small since large contrasting regional variations, both positive and negative deviations from the mean, cancel each other. Large regional anomalies in SIC can be caused by stable synoptic situations, where atmospheric flow conditions that persist over several days or are dominant over several weeks lead to a southward (northward) ice transport combined with warm (cold ~~(warm~~) air advection (e.g. Massom et al., 2006~~,~~; Schlosser et al., 2011). ~~In a recent study,~~ Turner et al. (2009) stated that the long-term increase in Antarctic SIE is mostly caused by an increase in the Ross Sea sector, which is strongly influenced by the strength and position of the Amundsen Sea Low (ASL) (Raphael et al., 2015). Turner et al. (2009) also related stratospheric ozone loss to the observed increase in Antarctic SIE and found that the strengthening of the westerlies, which is related to ozone depletion, deepens the ASL. They conclude, however, that the observed SIE increase might be still within the limits of natural variability.

Haumann et al. (2014) found that, on multidecadal time scales, changes in Antarctic SIE are linked to changes in the strength of meridional winds that are caused by a zonally asymmetric decrease in high-latitude surface pressure, the latter possibly being related to stratospheric ozone depletion ~~or~~, greenhouse gas increase~~.~~, or natural variability. While increased southerly (and potentially westerly) winds most likely fuel~~l~~ed the long-term increase of Antarctic sea ice over the satellite era, we here hypothesize that increased northerly winds and an associated warm air advection triggered the negative Antarctic sea ice anomaly in 2016.

Two recent studies investigated the observed unusually fast retreat in the spring of 2016. Turner et al. (2017), after a discussion of the climatological mean behavio~~u~~r of Antarctic sea ice, consider the spatial differences of SIE anomalies and their temporal changes for five different sectors of the Southern Ocean. While in the Weddell Sea a marked change from positive to negative SIE anomalies occurred in November, the ~~ABS and~~Amundsen-Bellingshausen Seas and the Indian Ocean showed mainly negative anomalies throughout the melt season. The Ross Sea and West Pacific ~~were~~sectors exhibited both positive and negative SIE anomalies during the entire period. ~~The~~They argue that the decrease of SIE at a record rate is linked to record surface pressure anomalies, mainly in the Weddell Sea and Ross Sea sectors of Antarctica, and the related meridional flow and corresponding warm air advection (Turner et al., 2017). Alternatively, Stuecker et al. (2017) hypothesize that the anomalously low SIE in November~~-~~–De~~z~~cember 2016 was largely related to positive ~~SST~~sea surface temperature anomalies due to the extreme El Ni~~n~~ño event peaking in December~~-~~–February ~~(DJF)~~ 2015/16 that persisted throughout the winter and the concurrent ~~rather~~ negative phase of the SAM.

Generally, changes in both oceanic and atmospheric processes could have been responsible for the observed 2016 anomaly. In the present study we investigated in detail the onset and temporal evolution of the sea ice retreat (considering both SIA and SIE, as well as SIC) and the contributions of various parts of the Southern Ocean. A detailed analysis of the evolution of the SIA and SIE deficits shows a rapid growth of regional anomalies, suggesting an atmospheric origin of these changes. We compared those changes to ice drift data and related it to the general atmospheric flow conditions derived from the European Centre for Medium-Range Weather Forecasts (ECMWF~~-interim-)~~ reanalysis data and ~~also~~ considered the relationship to SAM and ZW3 indices and patterns.

2 Data and methods

2.1 Sea ice data

Sea ice data are provided by the National Snow and Ice Data Center (NSIDC). ~~Sea ice concentrations (~~SIC~~) are~~ is derived from Nimbus-7 SMMR and DMSP SSM/I-SSMIS passive microwave data~~.~~ (Maslanik and Stroeve, 1999). The data set is generated from brightness temperature and designed to provide a consistent time series of ~~sea ice concentrations.~~SIC. The data are provided in polar stereographic projection at a grid cell size of 25 km x 25 km. We use the Climate Data Record version 2 NASA Team algorithm (CDR NT; Meier et al., 2013, updated 2016) data for the period 1979 to 2015 as a baseline climatological record. These data are compared to the Near-Real-Time data (NRT; ~~)~~http://nsidc.org/data/NSIDC-0081; Maslanik and Stroeve, 1999) from January 2015 to June 2017, which are also derived from passive microwave data using the NASA Team algorithm. Days with a large number of missing pixels in the ~~sea ice area~~SIC have been removed from the NRT data. The resulting SIE anomalies for the overlapping year 2015 agree well (Fig~~ure~~. 1). To create monthly mean ice drift fields the low~~-~~-resolution sea ice drift product of the EUMETSAT Ocean and Sea Ice Satellite Application Facility (OSI SAF, ~~)~~www.osi-saf.org; Lavergne et al., 2010) were used.

~~Sea ice extent (~~SIE~~)~~ is defined as the spatial sum of the area of grid boxes that have a ~~sea ice concentration~~SIC of at least 15~~%. Sea ice area~~ %. SIA is defined as the spatial sum of the ~~sea ice concentration~~SIC times the grid box area for grid boxes that have a ~~sea ice concentration~~SIC of at least 15 %. The daily SIA~~-~~ change was computed by first calculating the daily SIA and then taking the difference in SIA from one day to the next. We computed daily and monthly anomalies as well as SIE and SIA deficits with respect to the climatological daily and monthly means of the CDR NT record over the period 1979 to 2015. Long-term trends shown in Fig~~ure~~. 1 are computed using linear regression analysis.

2.2 ECMWF ~~Re-analysis~~reanalysis data

ECMWF~~—~~-Interim ~~Re-analysis~~reanalysis (ERA-Interim) data were employed to investigate atmospheric flow conditions. The ~~re-analysis~~reanalysis data are available from 1979 to ~~today~~present. The horizontal resolution is T255, corresponding to approximately 79 km. The model has 60 vertical levels, with the highest level being at 0.~~1hPa~~1 hPa. A detailed description of ERA-Interim is given in Dee et al. (2011). We used monthly mean sea level pressure and vertically integrated northward heat flux, derived from the daily mean values. The ~~re-analysis~~reanalysis data were used for investigation of ZW3 patterns and analysis of surface pressure fields and cyclone activity.

2.3 SAM and ZW3 indices

Meridional transport of heat and moisture in the high latitudes of the Southern Hemisphere is carried out by the asymmetric component of the circulation also known as quasi-stationary waves (Raphael, 2004). Together, zonal wave one (ZW1) and ~~zonal wave three (~~ZW3~~)~~ represent the largest proportion of this asymmetry (van Loon and Jenne, 1972). The asymmetry described by these zonal waves is revealed when the zonal mean is subtracted from the geopotential height field and coherent pattern of zonal anomalies and their associated flow become apparent. Both ZW1 and ZW3 have preferred regions of meridional flow, guiding the meridional transport of heat and moisture into and out of the Antarctic. ZW1 and ZW3 vary with each other so that when ZW3 is strong, ZW1 is weak and vice versa. An index of ZW3 based on its amplitude defined by Raphael (2004) shows that ZW3 has positive and negative phases where a positive phase indicates strong meridional flow and a negative phase more zonal flow. ~~-~~A climatology of this index shows that ZW3 tends to be negative from September through December, a period of time when ZW1 is dominant in the field (Raphael, 2004). ~~Because~~Since it exerts control on the meridional flow, ZW3 influences the variability of Antarctic sea ice~~ by~~ dynamically and thermodynamically as illustrated in Raphael (2007).

The ~~Southern Annular Mode (~~SAM~~)~~ is the dominant mode of atmospheric variability in the extra-tropical Southern Hemisphere. Marshall (2003) calculated a SAM index based on the observed pressure difference between stations in Antarctica and at mid-latitudes. A large (small) meridional pressure gradient means a positive (negative) SAM index and, correspondingly strong (weak) westerlies. The stronger westerlies are usually connected to a more zonal flow, whereas in the case of a negative SAM index, the flow tends to meander in amplified Rossby waves. A positive SAM index is mostly related to positive SIC anomalies (Simpkins et al., 2012) since, apart from the Antarctic Peninsula, air temperatures are lower due to decreased meridional heat exchange and the stronger westerlies can lead to increased northeastward transport of sea ice. A northerly flow during periods of negative SAM index can lead to compaction of the ice and/or melting due to warm air advection. The corresponding southerly flow means offshore flow, cold air advection and thus new ice formation. A negative SAM thus usually is associated with large regional differences in SIC and SIE anomalies. However, the SAM explains only approximately one third of the variability (Marshall, 2007) and there can be large regional differences for both the positive and the negative mode of SAM, e.g. strong zonal flow in the Pacific ~~Ocean~~ and strong meandering in the western Atlantic ~~Ocean~~ at the same time. ~~-~~In the present study we use the ZW3 and SAM- indices to help explain the anomalous retreat of Antarctic sea ice in 2016.

3 Results

3.1 Temporal evolution of Antarctic sea ice extent and area

In Fig~~ure~~. 1 monthly SIE anomalies from January 1979 to ~~March~~June 2017 are displayed. Until 2015, only relatively small variations and a generally positive trend can be seen. This trend is abruptly interrupted in November 2016, when monthly mean SIE was almost 2 ~~Mio.~~million km^2 lower than in the preceding year. This value is clearly outstanding: the negative deviation from the mean reaches almost four times the standard deviation~~.~~ (2.06 million km^2) of the 1979 to 2015 period. Trends are calculated from the CDR data until the end of 2015 and for the period including the most recent ~~15~~17 months from NRT data, respectively. The extension of the period by these latter ~~15~~17 months reduces the positive trend from 0.24 ~~Mio.~~million km^2 per decade (1979–2015) to 0.~~17 Mio.~~16 million km^2 per decade.

Figure 2 shows the daily Antarctic ~~(~~SIE~~)~~ (Fig. 2a) and ~~sea ice area (~~SIA~~)~~ (Fig. 2b) for the year 2016 together with the 1979~~-~~–2015 average. The gray shading refers to the two standard deviations (1979~~-~~–2015). While, on average, SIE~~ extent~~ increases until the end of September, in 2016, a sudden decrease occurred in the last third of August. After the first week of September~~,~~ SIE fell below the long-term average and never recovered during the rest of the year. The monthly mean anomaly in SIE increased from ~~-~~−0.1 ~~Mio~~million km^2 in August, to a maximum deviation from the monthly mean of ~~-~~−1.84 ~~Mio.~~million km^2 in November. In December the anomaly amounted ~~-~~to −2.33 ~~Mio.~~million km^2. The SIA exhibited negative deviations from the mean already in ~~early~~June and July, briefly reached values close to the average again at the end of August and thereafter remained below the average for the rest of the year. The monthly mean SIA anomaly for November and December 2016 are ~~-~~−1.98 ~~Mio.~~million km^2 and ~~-~~−1.55 ~~Mio.~~million km^2, respectively~~.~~, and generally preceded the SIE anomalies. The SIE deficit (shaded pink vs. dashed grey ~~climatological average)~~two standard deviations (1979–2015)) also suggests that there were two distinct periods of decline, the first one in late August to mid-September, and the second one in the first half of November. While the first period saw a corresponding decline in SIA, the second period is not as distinct for SIA. The overall largest SIA deficit of 2.24 ~~Mio.~~million km^2 occurred on 18 November, whereas the largest SIE deficit of 2.8 ~~Mio.~~million km^2 was seen approximately one month later, on 14 December. The sea ice ~~did~~ never did recover in austral summer 2016/2017; in February 2017 the monthly mean SIE amounted to 2.27 ~~Mio.~~million km^2, which is the lowest February value since beginning of the satellite measurements in 1979. However, the monthly mean SIA was with 1.63 ~~x 10^6~~million km^2 only the second lowest one, here the absolute minimum occurred in February 1993 (1.4 ~~Mio.~~million km^2).

In Fig~~ure~~. 2c the SIA change (daily temporal derivative of the SIA) is shown. Again, the red and black lines refer to 2016 and the climatological mean (1979~~-~~–2015), respectively. The SIA change can be interpreted as ice melt~~/~~ or compaction when it is negative and as new ice formation when it is positive. The pink shading indicates anomalously high melt or low freezing periods, and the blue shading the opposite. A first, very short period with SIA decrease was observed as early as in mid-July when the SIA change ~~assumed~~reached negative values for the first time.~~-~~

It can be clearly seen that, until August, periods with growing and shrinking SIA deficit alternate, whereas from end of August on, almost only negative deviations from the mean are found, with negative SIA changes for the rest of the year. In addition to the periods mentioned above, a further period with strong sea ice decline can be seen in mid-October.~~ During the general ice retreat, periods with accelerated decline alternate with periods that exhibit a decline slower than on average.~~

3.2 Regional sea ice changes

3.2.1 SIC anomalies and corresponding influence of cyclonic activity

To investigate~~,~~ which areas contributed ~~most strongly~~predominantly to the observed changes, Antarctica was divided into seven sub-areas (see Table 1), the definition following specifically the regional SIC anomalies displayed in Fig. ~~3~~3a–d for the months August to November 2016. This division is finer than the five sub-areas used in previous studies ~~(.e.g. Turner et al., 2017).~~(e.g. Turner et al., 2017) and thus allows a detailed discussion of the temporal and spatial development of the sea ice retreat. In particular, the sub-division of the Weddell Sea was necessary due to the different behavior of the western and eastern part. The SIC anomalies, as usual, exhibit strong regional differences, areas with positive deviations alternating with areas of negative deviations. In August, the total SIE is only 0.1 ~~Mio~~million km^2 smaller than the long-term average (1979~~-~~–2015). The contributions of areas with negative SIC anomalies mostly counteract those of areas with positive anomalies. Largest negative SIC anomalies are found at the eastern edge of the Eastern Weddell Sea (EWS) and in the Western Indian Ocean~~,~~ (WIO), where also the sea ice edge (grey contour line in Fig. 3a) is already distinctly farther south than on average~~.~~ (green contour line). In the ~~Western Pacific,~~Eastern Indian Ocean (EIO), only a very small area, centered at ~~approximately130 °~~approximately 125° E shows negative ~~deviations~~anomalies of SIC, otherwise ~~SIE is very close to the mean value,~~ SIC anomalies are slightly positive. In the Western Pacific / Western Ross Sea~~, SIE~~ (WP), the sea ice edge is also close to the long-term average; positive deviations in SIC are found near 150° E and at the northern edge of the Ross Sea. The Amundsen~~ and ~~-Bellingshausen Seas ~~have smaller negative~~(ABS) show southward deviations from the mean ~~SIE than the Indian Ocean~~sea ice edge, whereas both the Western Weddell Sea ~~exhibits~~(WWS) and Eastern Weddell Sea (EWS) exhibit positive SIC anomalies between approximately 35° W and 0°, associated with a sea ice edge farther north than on average.

Generally, SIC depends on ice dynamics (advection) and thermodynamics, both, on short time scales, being strongly influenced by the atmospheric flow. Surface winds above the Southern Ocean depend mostly on the cyclone activity in the circumpolar trough (Simmonds et al., 2003). Figure ~~6~~3i–l shows the monthly mean surface pressure for the corresponding months. Arrows indicate the approximate main surface flow direction related to changes in SIC or ~~SIE~~sea ice edge. In the Southern Hemisphere, the air circulates ~~clock-wise~~clockwise around the center of a cyclone, meaning a northerly (southerly) flow at the western (eastern) flank of the cyclone. Northerly flow leads to compaction of the ice and/or advection of warmer air, and thus ~~reducing~~a southward displacement of the ~~SIE~~sea ice edge by compaction and/or melt~~, whereas~~. In contrast, a southerly flow is related to northward drift of the ice and formation of new ice close to the coast due to cold air advection from the continent over leads and polynyas that develop as the ice is pushed away. The strong westerly flow at the northern edge of the cyclone can, via Ekman transport (e.g. Hall and Visbeck, 200~~1~~2), also lead to net northward transport of sea ice and thus ~~an increase in SIE.~~ a northward displacement of the sea ice edge. In Fig. 3e–h the meridional heat advection is displayed. It shows the vertically integrated northward heat flux from ERA-Interim. Positive (negative) values correspond to cold (warm) air advection. The heat advection agrees very well with the general flow direction derived from the surface pressure field (see Fig. 3i–l and arrows herein).

In August (~~Figure 4a~~Fig. 3i), the Amundsen-Bellingshausen Sea Low, in the following called ~~Amundsen Sea Low (~~ASL~~)~~, was replaced by an extended cyclone centered above the eastern Ross Sea, ~~the~~causing strong southerly flow at its western flank ~~leading to the~~ and positive SIC ~~concentrations~~ in ~~eastern R4, correspondingly~~the WP. Correspondingly, the northwesterly flow at its eastern flank ~~causing~~ of the ASL causes negative SIC anomalies in ~~R5~~the Eastern Ross Sea (ERS) and in the ~~Amundsen-Bellingshausen Seas (R6).~~ABS. The small, but distinct negative SIC anomaly ~~east of 120°~~around 125° E is related to a low pressure system in the ~~Eastern Indian/Western Pacific Ocean,~~EIO/WP that steered relatively warm air masses from areas north of 55° S ~~right~~ towards the mentioned anomaly~~.~~ (Fig. 3e). The area is rather restricted due to the confluent flow. In the ~~Eastern Weddell Sea (R1)~~EWS and the ~~Western Indian Ocean (R3),~~WIO, there was a weak, but extended, low pressure system~~,~~ that caused a weak northerly flow and warm air advection towards the western edge of ~~R2~~the WIO associated with the negative SIC anomalies. However, most of the ~~R2~~WIO was under the influence of a very weak pressure gradient, and consequently no distinct flow conditions prevailed.

In September (~~Figure 4b~~Fig. 3b), positive SIC anomalies occurred in ~~R1, R3~~the EWS, EIO, and ~~R5~~ERS. The area with negative anomalies ~~just east of 120°~~around 125° E extended eastward across the entire ~~R4~~WP. Additionally, SIC anomalies in ~~R6,~~the ABS and ~~R7~~WWS were largely negative. The low pressure system in the Pacific Ocean (Fig. 3j) intensified and moved eastwards, extended across the Ross and Bellingshausen Seas, which resulted in positive (negative) SIC anomalies at its western (eastern) flank. ~~While R4~~The WP was still influenced by the warm air advection on the low centered in ~~R3,~~ the EIO. The positive anomalies in ~~R3 cannot be explained by this low since warm~~the EIO are associated with an area of cold air advection ~~would be expected here. Similarly, the~~(Fig. 3f and j). The negative SIC anomalies between 180° W and approximately 160°~~E~~ W (WP) are unexpected since this area is influenced by the ~~Pacific low~~ASL. In the northern parts of the ~~Eastern Weddell Sea~~EWS, positive SIC anomalies are observed, possibly related to the strong westerly flow resulting in ~~north-eastward~~ zonal and meridional ice advection (Fig. 6b) due to a northeastward Ekman transport.

In October (~~Figure 4c~~Fig. 3c), the SIC anomalies occurred in the same areas as in September, but were more strongly developed. The ASL stretched eastward (Fig. 3k) and is now true to its name and extended across the ~~Amundsen and Bellingshausen Seas.~~ABS. In the ~~Eastern Weddell Sea~~EWS, a strong low pressure system has developed, leading to a northerly flow and warm air advection in the ~~Western Indian Ocean~~WIO, where strong negative SIC anomalies are observed. The Eastern Indian Ocean/Western Pacific low extended northwards, although with a weaker pressure gradient. SIE in ~~R3~~the EIO (Fig. 5g) changed very little and slightly less negative SIC ~~concentrations~~anomalies occurred. The negative anomaly in SIE of ~~R2~~the WIO (Fig. 5d) remained nearly constant in September and October.

In November ~~(Figure 4d), R2~~, the WIO exhibited strong negative anomalies in SIC (Fig. 3d) and SIE ~~and SIC,~~(Fig. 5d), which contributed to the pronounced melt period in the first half of November (Fig. 2c). Also large negative deviations from the mean SIC (Fig. 3d) occurred in the ~~Eastern Pacific (R4), the Amundsen and Bellingshausen Seas (R6),~~WP, the ABS, and in the ~~western Weddell Sea (R7),~~WWS, whereas ~~strong~~ positive deviations in SIC were found around the sea ice edge in the ~~Eastern~~EWS, and the ERS. In the southeastern Weddell Sea (Fig. 3d), negative SIC anomalies prevail, and the opening of the Weddell Sea ~~and Lazarev Sea (R1),and the eastern Ross Sea (R5).~~ polynya (see also section 3.2.3), which reoccurred more strongly in 2017 (not shown), over Maud Rise becomes apparent.

~~Note that~~Since we are considering monthly means here~~. A~~, a signal that is still visible in a monthly mean has to have been predominant over the majority of days during that month or has to have been very strong over a shorter time period ~~(shorter time periods).~~. The latter was the case at the end of August, and also in November: in the first third of the month the prevailing northerly flow -with warm air advection was very strong and thus crucial for triggering the increased melt. This situation is shown in ~~Figure 6c~~Fig. 4, where the meridional heat advection (Fig. 4a) and the mean sea level pressure (Fig. 4b) for 1–~~-~~10 November 2016 is displayed. It demonstrates that the strongest contribution to the monthly mean meridional heat advection (Fig. 3h) stems from the first third of the month. Figure 4b shows the corresponding surface pressure.

Between an extended low pressure system above the Eastern Indian Ocean/Western Pacific and a high pressure ridge in the ~~Western~~ Ross Sea, a strong northerly flow with warm air advection ~~is related to~~

~~the~~ induced large negative SIC anomalies in that area. ~~Equally~~Similarly, in the western and central Weddell Sea, a northeasterly flow at the eastern flank of a low pressure system is associated with strong negative SIC anomalies. In the ~~Western Indian Ocean~~WIO, the picture is not as straightforward; oceanic memory effects may play a role here.

~~Summarizing, the observed regional SIC anomalies in spring 2016 can to a large extent be explained by the atmospheric flow related to unusually strong and persistent low pressure systems leading to strong warm air advection from northerly directions and thus increased ice melt.~~

3.2.2 Temporal evolution of regional SIE and SIA

To get a deeper insight into the spatial origin of the anomalies in SIE and SIA, in Fig. 5 the daily values of SI~~C~~E, SIA, and SIA changes are displayed (similar to Fig. 2, for details see ~~F~~figure caption) for the different regions ~~1-7~~ shown in ~~the respective maps. Regions~~Fig. 3. The EIO and ~~5~~ERS regions did not contribute to the accelerated sea ice decay. They have predominantly positive anomalies in SIE, SIA and SIC. ~~Regions R1, R4~~The EWS, WP, and ~~R7~~WWS regions contributed to the negative SIE and SIA anomalies through strong events ~~caused by~~associated with the corresponding atmospheric flow discussed above, whereas ~~R2~~the WIO and ~~R6~~ABS exhibited more or less continuous negative deviations from the long-term mean. ~~This is~~These developments are most clearly seen in the respective deficits of SIE and SIA shown at the bottom of the Fig. 5 plots. In ~~R1~~the EWS, both SIA and SIE stayed above the long-term average, but contributed strongly to the negative anomaly through a distinct event evolving in November.

The first slightly negative SIA changes in ~~SIA in~~ mid-July occurred ~~only~~ in the ~~Western Pacific (R4)~~WP (Fig. 5l), the ABS (Fig. 5r), and ~~in~~ the ~~Amundsen Bellingshausen Seas (R6~~WWS (Fig. 5u). The start of the melt period at the end of August is also seen ~~here.~~in these sectors (except for the EWS). The ~~Western Indian Ocean (R2)~~WIO exhibited negative SIE (Fig. 5d) and SIC anomalies~~,~~ in August (Fig. 3a), even though the SIA change (Fig. 5f) hinted at anomalously high freezing in this area at the end of August. The negative anomalies in this area might be an oceanic memory effect since the area showed similar ~~features~~anomalies in the preceding months (Fig. 5d–e) and even in the preceding year (~~not shown here).~~Stuecker et al., 2017). The SIA change in the two regions ~~R4~~WP (Fig. 5l) and ~~R6~~ABS (Fig. 5r) also ~~most strongly~~ contributed to the continuation of the late August melting into the first half of September. The ~~Weddell Sea (R1 and R7)~~EWS did not contribute significantly to the sea ice decay in these early periods. In ~~mid-~~September~~/October~~, the contribution of the ~~Western Weddell Sea~~WWS increased considerably, whereas the ~~Eastern Weddell Sea/Lazarev Sea~~EWS (Fig. 5c) contributed late, but strongly from mid-November into December to the negative sea ice anomalies.

3.2.3 Ice drift

Ice drift influences SIE, SIA and SIC in various ways. For ~~SIC below 100%,~~example, northerly winds close to the ice edge lead to a southward sea ice compaction~~.~~ when the SIC is well below 100 %, and ridging and rafting, i.e. ice thickening, when the SIC is close to 100 %. Southerly winds close to the coast imply offshore ~~winds~~transports that can cause coastal polynyas. These polynyas are usually quickly closed by new ice formation due to associated cold air advection from the continent. Strong westerly winds can lead to ~~net north-~~an eastward redistribution of the ice with a northerly component due to Ekman transport. Apart from that, convergence/confluence and divergence/diffluence in the main atmospheric flow can locally change SIC.

Since sea ice drift is strongly influenced by surface winds and might have contributed to the 2016 SIC anomalies, we examine the monthly mean ice motion from August to November 2016, illustrated in Fig. 6. It shows generally good agreement with the sea level pressure fields shown in Fig. ~~4~~3, taking into consideration the corresponding wind fields discussed in section 3.2.1. Only in areas where SIE is already small, i.e. in ~~R3~~the EIO and the eastern half of ~~R6~~the ABS in October and November, the correlation between ice drift and wind direction more or less disappears due to the low resolution of the plotted ice drift. In August, the large low pressure system above the Weddell and Lazarev Seas is associated with clockwise ice drift in the Weddell Sea and drift towards the continent at its eastern flank. With an increasing pressure gradient in September, the ~~movement~~drift increases at the northern flank, whereas the southward drift at its eastern flank disappears due to a predominantly westerly flow in the Lazarev Sea. The ice drift connected to the ASL is best developed in September, with strong southerly (northwesterly) flow at the western (eastern) flank of the cyclone~~.~~, contributing to the positive SIC anomaly in the ERS (Fig. 3b).

In November, ~~similar to the SIC anomalies, the first third of the month is crucial for~~ the monthly mean sea ice drift~~. The~~ direction and strength ~~of the ice drift is~~(Fig. 6d) are strongly connected to the average sea level pressure field ~~for Nov 1st to 10th~~, which is largely induced by anomalies during the first third of the month (1–10 November 2016, shown in Fig. 4~~e~~b). The patterns of the strong clockwise circulation in the Western Weddell Sea~~,~~ lead~~ing~~ to a southward compaction and ~~ice melt,~~ thus a quickly decreasing SIC~~, –~~ around the northern ice edge region. The divergent atmospheric flow over the southeastern Weddell Sea in August and November (Fig. 3i and l) leads to a strongly divergent sea ice drift in southeastern Weddell Sea, especially in November (Fig. 6d), which potentially contributed to the first reoccurrence of the Weddell Sea polynya since the 1970s (Mazloff et al., 2017; Reid et al., 2017). The dynamical removal of the sea ice from this region just before the ice melt, when the ocean surface density stratification is weak, can trigger strong positive feedbacks (Gordon, 1991) that might have led to an even more pronounced reappearance of the Weddell Sea polynya in 2017 (not shown). The drift towards the coast in the ~~Western Pacific~~WP (negative SIC anomaly in Fig. 3d) and the offshore drift in the ~~We~~Eastern Ross Sea~~, connected to the positive~~ (positive SIC anomaly in the ERS in Fig. 3d) in November are contributing to the SIC anomalies, and~~ SIE anomaly,~~ can be clearly related to the pressure field and the corresponding surface winds.

3.3 General atmospheric flow conditions during the melt season 2016~~/17~~

After having investigated in section 3.2.1 the local meridional atmospheric flow related to sea ice changes specifically for individual low pressure systems (cyclones) observed during the melt period, we now want to consider the large-scale general atmospheric flow conditions.

3.3.1 ZW3

The monthly mean sea level pressure and meridional heat advection shown in Fig. ~~4 has~~3 have a clear signal of ZW3, most strongly in August and October. Given ~~this~~these patterns, we examine the ZW3 index for the period of ice decay. Figure 7a shows the daily ZW3 index for 2013~~-2016.~~–2016. The years 2013–2015 are shown to put 2016 into perspective. Clearly, 2016 shows a distinctly different picture from the preceding years 2013~~-~~–2015. ~~However,~~While in 2013–2015 the ZW3 index alternated between positive and negative values throughout the year, in 2016, the ZW3 index was almost continuously positive over a longer time period. The largest differences occur in the cold season, namely mid-April to June, and, with short interruptions, well into August. In 2016, the positive ZW3 index is predominant from mid-April far into July and, with short interruptions, until mid-October. The sudden and unexpected decrease in SIE at the end of August comes after a prolonged period of positive ZW3 indices, whereas in November, when the record minimum SIE was observed, the ZW3 index is highly variable, both positive and negative. Given the influence of ZW3 on the sign and strength of the sensible heat flux between atmosphere and ocean and thus on sea ice growth or melt (Raphael, 2007), we suggest that the persistent presence of a positive ZW3 index in the winter months preconditioned the ice for melt.

Since an increased meridional exchange can also be related to ZW1, we looked at the ~~500hPa~~500-hPa geopotential height anomaly shown in Fig. 7b. It is created by subtracting the long-term zonal mean at each latitude, from the mean 500-hPa geopotential height field in November 2016, thus elucidating the asymmetry in the circulation suggested by the index. In August, as expected from the sign of the ZW3 index and the mean sea level pressure distribution in Fig. 6a, a distinct ZW3 pattern can be seen, leading to fairly strong meridional flow and thus meridional heat exchange in the respective areas described in section 3.2.1. While in September the pattern is disturbed in the Atlantic sector (no distinct meri~~o~~dional flow, see Fig. 4b), in October it reappeared, but was no longer as well-defined as in August. In November, while no clear ZW3 pattern is found, a distinct meridional flow can be seen around the Ross Sea and in the Weddell Sea in the first third of the month (see Fig. 4e). A clear ZW3 pattern is not expected here since the amplitude of the wave as shown in Fig. 7a is negative for most of the month. However, while a positive ZW3 index is not coincident with the decrease in November, its persistence in the preceding months will have preconditioned the ice so that the effect of any other activity that promotes ice loss would be amplified. The flow pattern associated with the strong negative anomaly in the 500hPa500-hPa geopotential height above the Weddell Sea is consistent with the strong melt there due to warm air advection from the north.

Figure 8 illustrates the 2016 anomaly in the meridional heat flux for the entire year 2016 (Fig. 8a) as well as the period August to November 2016 only (Fig. 8b) with respect to the climatological mean of the period 1979–2015. Both the positive and the negative anomalies are stronger developed in the latter period, which agrees well with the prevailing ZW3 pattern described above.

3.3.2 Southern Annular mMode

Figure 89 shows the monthly mean SAM index based on the calculation of Marshall (2003) for 2016 and the climatological monthly means calculated for the period 1979––2015. In November, the months with the largest ice loss, the SAM index is highly negative, in fact, the second lowest SAM index since the start of the satellite sea ice observations occurred. This low SAM index would suggest a rather meridional flow, resulting in a comparatively large meridional exchange of heat and moisture. Different from ZW3, which has been strongly positive already from May on and continuing during the entire winter months, thus hinting at increased meridional flow, the SAM index is positive in most months. However, as mentioned above, it should be kept in mind that SAM explains only part of the variability of the circulation, and large regional differences in the flow pattern can occur. Additionally, the monthly means are not always meaningful since periods with positive and negative indices can cancel each other.

4 Discussion and conclusion

The record minimumanomalies in Antarctic SIE in Novemberaustral spring 2016 waswere associated with an unusually early start of the melt season with negative anomalies in SIA (SIE) observed as early as July (August). Although other components of the climate system, such as the ocean must havecertainly contributed to this anomalous melt, our analysis suggests that increased meridional heat exchange with middle latitudes due to strongly meandering westerlies played a significant role. ThisThis anomalous circulation pattern is expressed by a persistently positive ZW3 index, a measure of the meridionality of the flow, during most of the winter and early spring., which was also discussed by Clem et al. (2017). The influence of ZW3 is reduced in November, whereas the phase of the SAM was strongly negative~~,~~; its index reaching an almost record negative value. The first third of November was under the influence of strong warm air advection in the areas with negative sea ice anomalies. This relatively short, but intense, period triggered the accelerated ice~~ melt~~ melt, which was being continued in the following weeks due to the positive feed-back effects of the ice melt, i.e. lower albedo of the open vs. ice-covered ocean and increased turbulent heat flux from the ocean. The timing of this triggering was crucial for the increased melt; it happened exactly at the height of the melt season when conditions were set for melt anyway (strong radiation, high air temperatures).~~-~~

Our results agree well with the general findings of Turner et al. (2017). While they stress the comparison of conditions in 2016 with the climatological means of amount and timing of SIE minima and maxima as well as mean location and intensity of cyclones, our study looks more closely at both ~~SIA~~the temporal and spatial evolution of SIA, SIE, ~~investigates~~and the development of the anomalies. In particular, we investigate the contribution of the different parts of the Southern Ocean to ice melt in more detail, ~~discusses~~and discuss the role of ice drift and the relationship between sea ice decay~~ and~~, SAM, and ZW3. Additionally, we found a clear relationship between the sea ice anomalies, low pressure systems, and meridional heat advection.

~~Distinct~~Three distinct anomalous melt periods were observed at the end of August, in the first half of September, in mid-October and in the first half of November~~. Three~~, exhibiting SIC anomalies that are reminiscent of a ZW3 pattern. Four main areas of ice loss are found: The Amundsen-Bellingshausen Seas, the Weddell Sea, the Western Indian Ocean and the ~~Ea~~Western Pacific/Western Ross Sea. This loss is only partly counteracted by a positive anomaly in SIE off Marie Byrd Land, east of the Ross Sea (centered at approx. 1~~3~~40° W) and at the northeastern edge of the Weddell Sea. In November, ~~also~~ the entire Weddell Sea strongly contributed to the accelerated sea ice retreat. The strong melting in the Amundsen-Bellingshausen Seas was caused by an extended and eastward-shifted ASL and consequent warm air advection at its eastern flank. The Western Pacific/Western Ross Sea experienced strong ice loss due to persistent warm air advection between September and November. The Western Indian Ocean exhibits negative anomalies in SIE and SIC, however, they do not increase significantly before November. The positive feedback mechanisms mentioned above further accelerated the sea ice decay. We argue that the quick development of most of these anomalies point towards an atmospheric origin of these anomalies. Two exceptions are probably the anomalies in the Western Indian Ocean and the Amundsen-Bellingshausen Seas that persisted throughout most of the winter and might have been preconditioned by warm anomalies in the previous year and reinforced by warm air advection during the austral fall 2016 (Stuecker et al., 2017).

The thermodynamic influence of atmospheric flow patterns described by positive ZW3 indices and negative SAM indices results in increased ice melt only ~~close to~~shortly before and during the melt period, i.e. when the air masses advected from the north have temperatures above the freezing point. A comparison of July SIE in the years 2009 and 2010, which had extremely different flow conditions

(Schlosser et al., 201~~5~~6), shows no significant difference in total SIE~~, even though~~. While 2010 had extremely zonal flow conditions, ~~whereas~~ 2009 exhibited strong amplification of Rossby waves with increased meridional heat exchange. The monthly mean SIE of July, however, was almost equal in those two years. In winter, atmospheric flow patterns are not sufficient to cause increased ice melt, since air temperatures are generally too low to cause ice melt, in spite of strong "warm" air advection.

Compaction of the ice by northerly atmospheric flow is only efficient if the SIC is clearly lower than 100~~%. In winter,~~ % or significant amounts of ridging and rafting occur. Northerly winds can in this case ~~the compaction of the ice leads~~lead to ~~formation~~a decrease of ~~new ice at~~SIE along the ice edge~~, which is thinner and has a lesser snow cover than the ice formed early in the winter~~ and ~~thus can be melted rapidly as soon as temperatures get sufficiently high~~an increase in ice thickness towards the coast. The persistently positive ZW3 indices from mid-April to June (Fig. 7a) suggest that in 2016 the sea ice underwent the described preconditioning due to compaction. This process is also supported by the early decline in SIA in July.

In the ~~N~~northeastern Weddell Sea, positive SIC anomalies are found far into the melt season. These are probably~~ mainly~~ caused by ice dynamics rather than thermodynamics, the strong westerlies in that area causing ice divergence and thus northeastward transport of the ice. Supporting thermodynamical influence is found in August and October, where a southerly flow with cold air advection from the continent prevailed at the western flank of a distinct low pressure system centered at the eastern border of the Weddell Sea. In contrast to the positive SIC anomalies around the ice edge in the northeastern Weddell Sea, the southeastern Weddell Sea experienced negative SIC anomalies, especially during August and November when the Weddell Sea polynya (also called Maud Rise polynya) reoccurred for the first time since the 1970s (Mazloff et al., 2017; Reid et al., 2017). This anomaly and most likely its reappearance in 2017 might be related to a strong regional sea ice divergence in 2016.

The results presented here are~~ so far~~ mostly qualitative. A regional atmospheric flow model combined with surface energy balance modelling would be necessary to quantify the ice melt in dependence on available energy due to warm air advection. The present study is focus~~s~~ed on the atmospheric influence on the sea ice behavio~~u~~r in the melt season of 2016. The oceanic influence usually has longer time scales and reaction times, but cannot be neglected. Even though the memory effect is more important for the formation than for the melt of sea ice (Stammerjohn et al., 2012), there might be processes on a larger time scale that play a role here, too~~.~~, especially with respect to the strong El Niño event in the previous year that might have preconditioned some of the anomalies due to the presence of warm surface waters in some regions (Stuecker et al., 2017). Our results suggest that the exceptional sea ice conditions in 2016 are owing to a superposition of se~~r~~veral events in different parts of the Southern Ocean.

While the here discussed extreme decline of the Antarctic sea ice in austral spring 2016 is clearly unusual in the satellite record (since 1979), paleoclimatic records and modelling studies indicate that the natural variability of Antarctic sea ice might be substantially larger than the observed changes over the past decades (Hobbs et al., 2016; Jones et al., 2016). The large magnitude of the anomaly considerably affects the long-term trend of Antarctic SIE recent decades. Our analysis shows that including the period up to June 2017 leads to a reduction of the SIE trend by about one third, yielding 0.16±0.02 million km^2 per decade compared to the 1979–2015 trend of 0.24±0.02 million km^2 per decade. It remains to be seen how fast the Antarctic sea ice recovers from the unusual conditions in 2016 and whether those conditions will influence sea ice in the following ~~year~~years and even further reduce the long-term increase.

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Author contribution~~:~~

The scientific analysis was jointly done by all authors, ES wrote the manuscript with contributions of MR and FAH; MR performed the ZW3 analysis, and FAH carried out all other calculations and graphics.

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Table 1.

Regions used for the regional analysis (Fig. 5).

R1EWS	Eastern Weddell Sea / Lazarev Sea	20° W – –20°W
R2WIO	Western Indian Ocean	–25°E – 85° E
R3EIO	Eastern Indian Ocean	–85°E – 130° E
R4WP	Western Pacific / Western Ross Sea	130° E – –30°E –
R5ERS	Eastern Ross Sea	155°W – – 125° W
R6ABS	Amundsen-Bellingshausen Seas	125° W – –25°W
R7WWS	Western Weddell Sea	–60°W – 20° W

Figure captions

Fig~~.~~ure 1~~-~~.

Monthly mean ~~sea ice extent (~~SIE~~)~~ anomalies since 1979 with respect to the 1979 to 2015 climatology. The period 1979 through 2015 is derived from the ~~Climate Data Record NASA Team (~~CDR NT~~)~~ data (green; Meier et al., 2013, updated 2016; provided by NSIDC). The period January 2015 through June 2017 is derived from the ~~Near Real Time (~~NRT~~)~~ data (red; Maslanik and Stroeve, 1999, updated daily; provided by NSIDC). Green shading shows the ±2 standard deviation of the CDR NT record and the green dashed line the respective long-term trend derived from linear regression analysis. The red dashed line shows the long-term trend for the period 1979 through June 2017 when extending the CDR NT record using the period January 2016 through June 2017 from the NRT record.

Fig~~.~~ure 2.

Seasonal cycle of the daily **(a)** ~~sea ice extent (~~SIE~~)~~,, **(b)** ~~sea ice area (~~SIA~~)~~,, and **(c)** sea ice area change, calculated as the temporal derivative of SIA. The black lines show the climatological mean daily values for the period 1979 through 2015 derived from the ~~Climate Data Record NASA Team (~~CDR NT~~)~~ data (Meier et al., 2013, updated 2016; provided by NSIDC). The red lines show daily values for the year 2016 derived from the ~~Near Real Time (~~NRT~~)~~ data (red; Maslanik and Stroeve, 1999, updated daily; provided by NSIDC). (a and b) Grey shading shows the ±2 standard deviations of the CDR NT record and red shading the deficit of the year 2016 with respect to the CDR NT record. (c) Positive (negative) SIA change is associated with a gain (loss) of SIA. Red and blue shading indicate periods in which the 2016 SIA deficit was growing and shrinking, respectively, with respect to the 1979 to 2015 period. The dashed line indicates the ±1 standard deviation of the CDR NT record.

Fig~~.~~ure 3.

(a–d) Monthly mean ~~sea ice concentration~~SIC anomalies for the months August to November 2016 ~~(a to d)~~ derived from the ~~Near Real Time (~~NRT~~)~~ data (red; Maslanik and Stroeve, 1999, updated daily; provided by NSIDC). Anomalies are calculated with respect to the climatological monthly mean derived from the ~~Climate Data Record NASA Team (~~CDR NT~~)~~ data from the period 1979 through 2015 (Meier et al., 2013, updated 2016; provided by NSIDC). Regions for the regional analysis (Fig. ~~4~~5) are indicated by the black lines and defined in Table 1. The gray and green contour lines denote the 2016 and the climatological (1979–2015) mean sea ice edge (15 % SIC), respectively.

Fig. 4

(e–h) Monthly mean vertically integrated meridional heat fluxes (positive northward) from ERA-Interim (Dee et al., 2011) for the months August to November 2016.

(i–l) Monthly mean sea level pressure a)from ERA-Interim for the months August, b) September, c) October, d) to November 2016, and e) mean sea level pressure 1 – 10 Nov 2016. Arrows indicate the mainapproximate atmospheric flow direction related to .

Figure 4.

Mean vertically integrated meridional heat fluxes (positive northward) **(a)** and sea level pressure **(b)** from ERA-Interim (Dee et al., 2011) for the period 1–10 November 2016. The gray contour line denotes the mean sea ice drift andedge (15 % SIC anomalies (Data from ECMWF Interim-Reanalysis)).

Fig. 5

As **Figure 5.**

As Fig. 2, but for each of the seven regions separately. Regions are indicated in the inset map and Figure. 3, and are defined in Table 1.

Fig.ure 6.

Monthly mean sea ice drift (arrows) for the months August to November 2016 **(a to d)** derived from the low resolution sea ice drift product of the EUMETSAT Ocean and Sea Ice Satellite Application Facility (OSI SAF, ; (www.osi-saf.org; Lavergne, et al., 2010). White shading shows the respective monthly mean sea ice concentrationSIC derived from the Near Real Time (NRT) data (red; Maslanik and Stroeve, 1999, updated daily; provided by NSIDC). The grey contour line shows the 15% sea ice concentration % SIC line.

Fig.ure 7.

(a) Daily Zonal Wave Number 3 (ZW3) index 2013 – 2016 (see section 2.3 for details).

(b) Monthly 500hPa500-hPa geopotential height zonal mean anomalies Aug – from ERA-Interim (Dee et al., 2011) for the period Aug–Nov 2016. Hatched areas indicate strongly negative values.

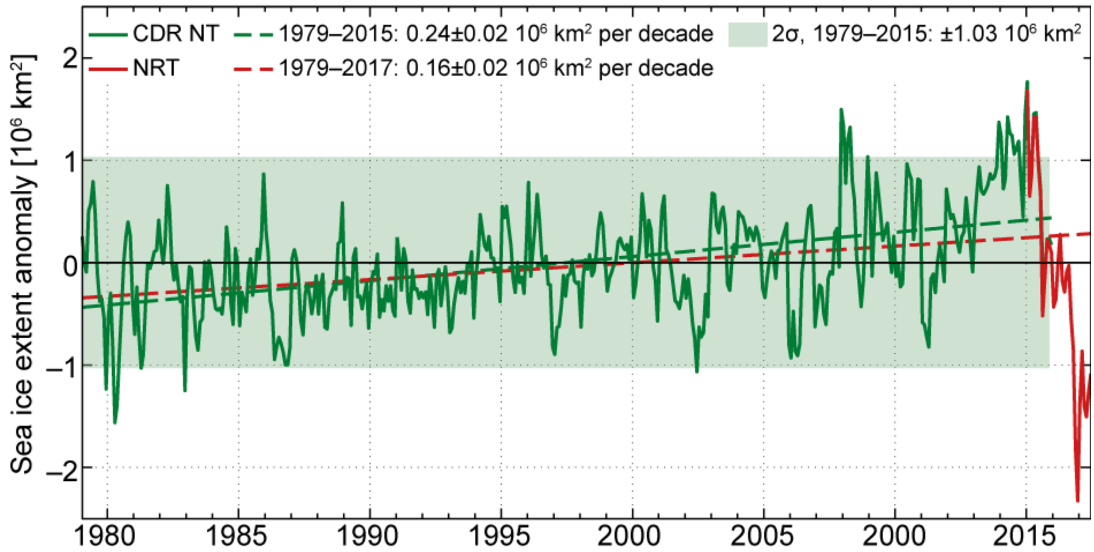
Fig.ure 8-.

Averaged monthly anomalies of the vertically integrated meridional heat fluxes (positive northward) from ERA-Interim for the year 2016 **(a)** and the period August to November 2016 **(b)** with respect to the climatological monthly means of the period 1979 to 2015. The gray contour line denotes the November 2016 monthly mean sea ice edge (15 % SIC).

Figure 9.

Monthly mean SAM index for 2016 and climatological monthly mean SAM index 1979-–2015 (after Marshall, 2003)

).



CDR NT
NRT
1979–2015: 0.24±0.02 10⁶ km² per decade
1979–2017: 0.16±0.02 10⁶ km² per decade
2σ, 1979–2015: ±1.03 10⁶ km²
Sea ice extent anomaly [10⁶ km²]
2
1
0
–1
–2
1980
1985
1990
1995
2000
2005
2000
2015

Figure 1.

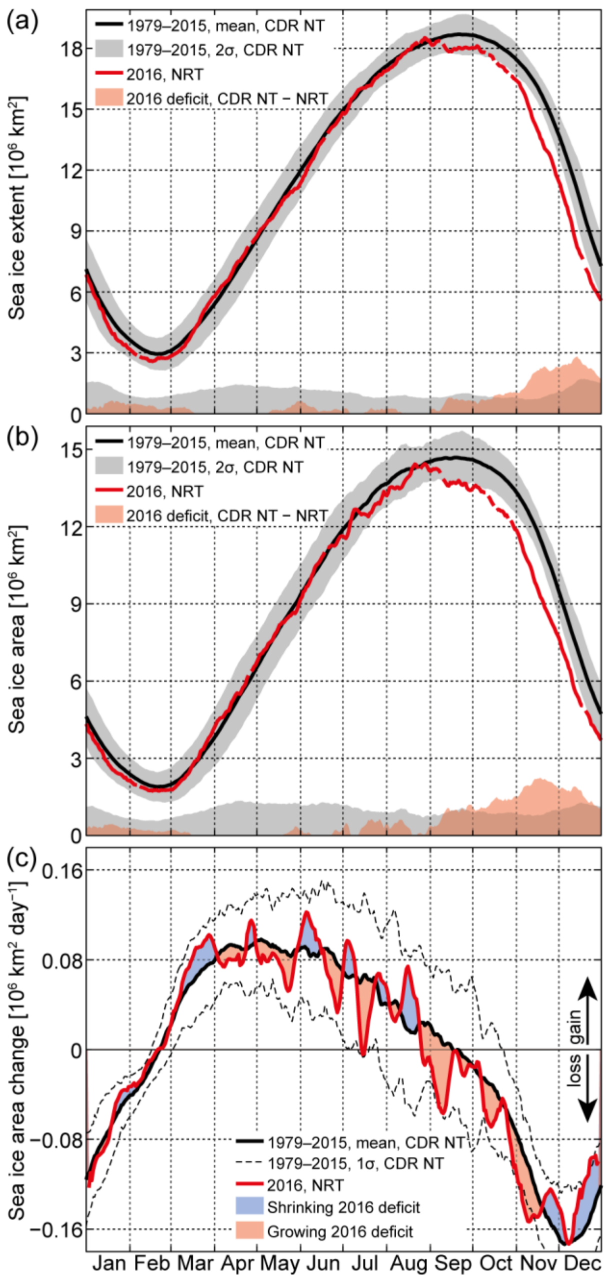

(a)
1979–2015, mean, CDR NT
1979–2015, 2σ, CDR NT
2016, NRT
2016 deficit, CDR NT − NRT
Sea ice extent [10⁶ km²]
18
15
12
9
6
3
0
(b)
1979–2015, mean, CDR NT
1979–2015, 2σ, CDR NT
2016, NRT
2016 deficit, CDR NT − NRT
Sea ice area [10⁶ km²]
15
12
9
6
3
0
(c)
Sea ice area change [10⁶ km² day⁻¹]
0.16
0.08
0
−0.08
−0.16
gain
loss
1979–2015, mean, CDR NT
1979–2015, 1σ, CDR NT
2016, NRT
Shrinking 2016 deficit
Growing 2016 deficit
Jan Feb Mar Apr May Jun Jul Aug Sep Oct Nov Dec

Figure 2.

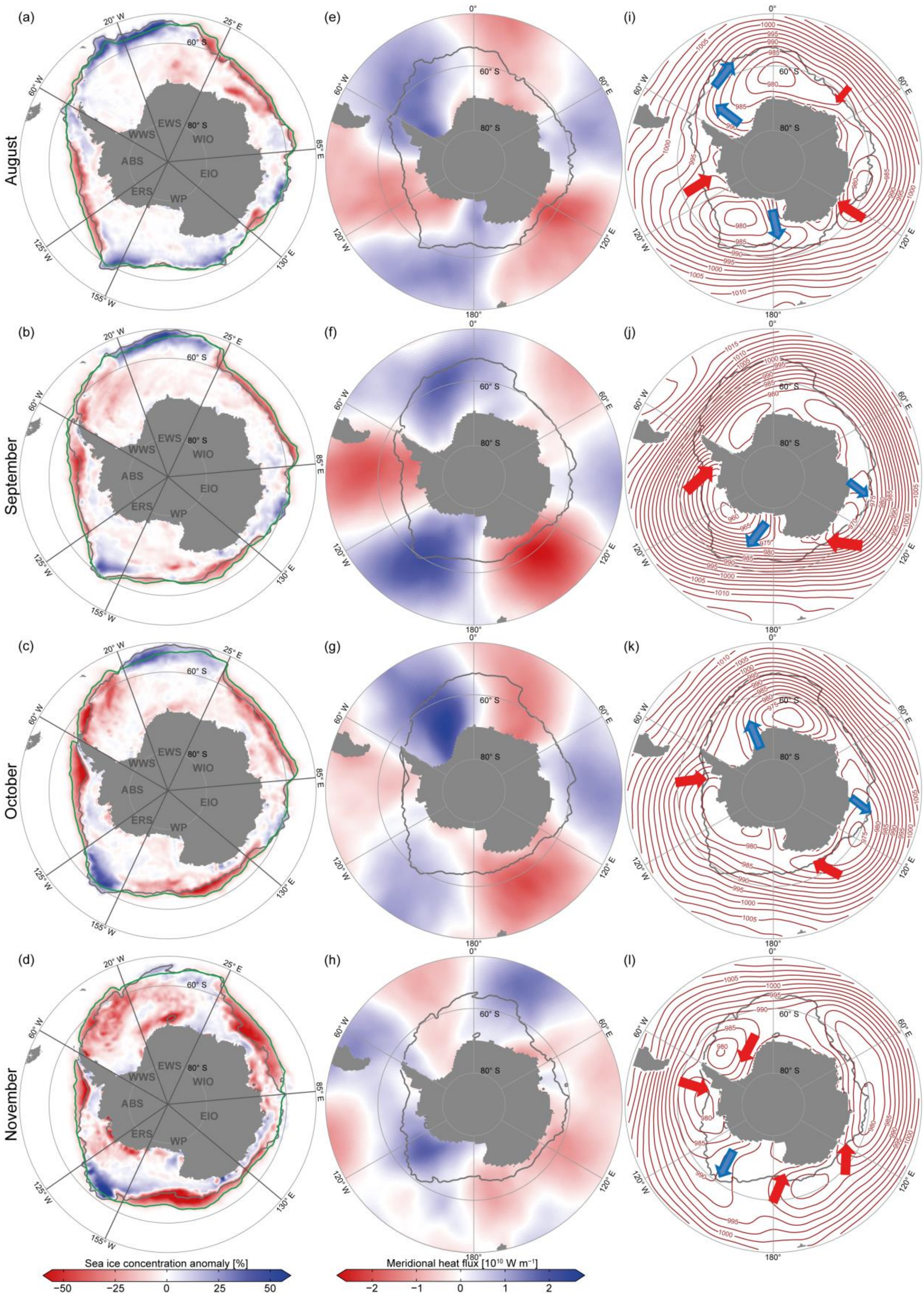
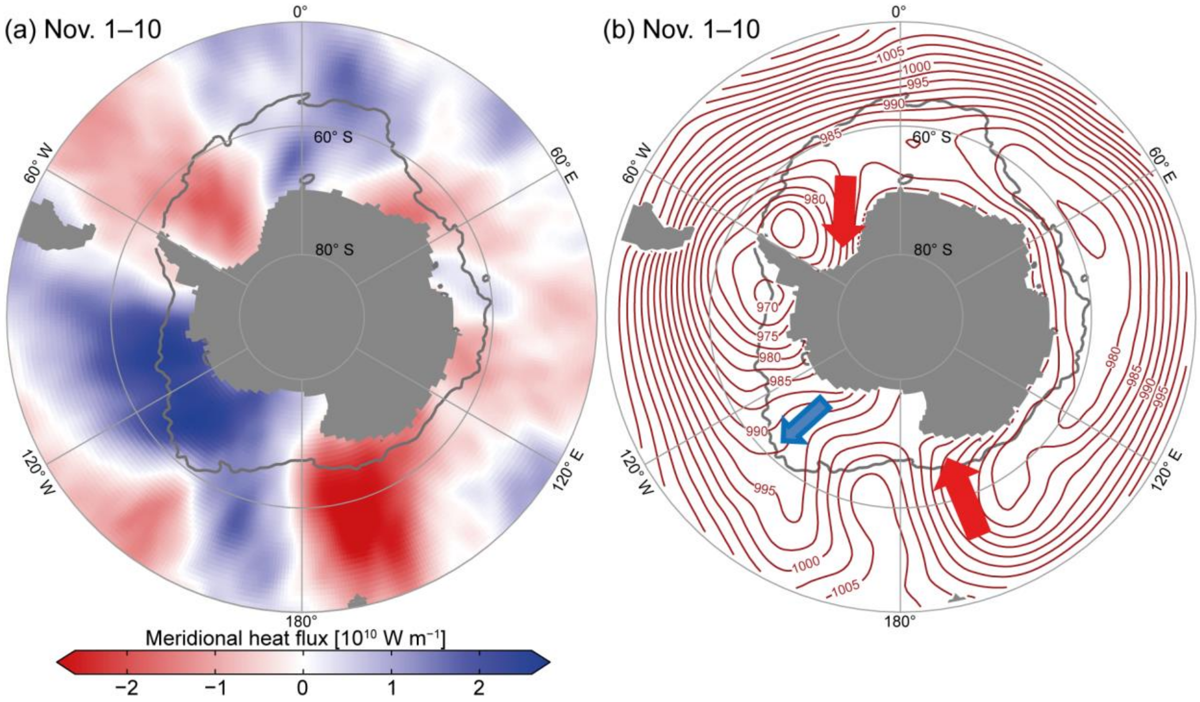
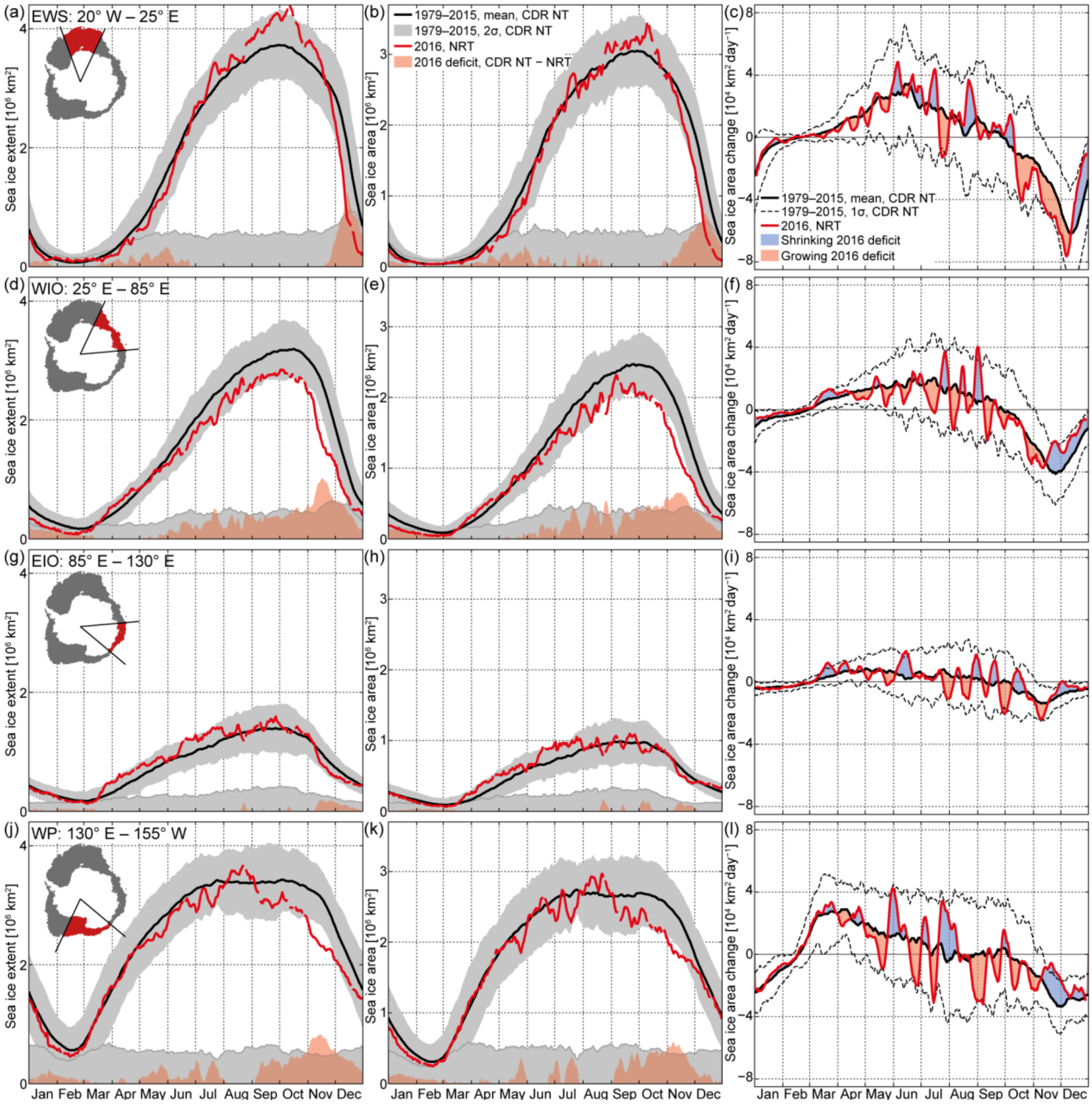

(a)
(b)
(c)
(d)
(e)
(f)
(g)
(h)
(i)
(j)
(k)
(l)
August
September
October
November
EWS
WWS
WIO
ABS
EIO
ERS
WP
60° S
80° S
20° W
25° E
60° W
85° E
125° W
130° E
155° W
0°
180°
60° E
120° W
120° E
Sea ice concentration anomaly [%]
−50
−25
0
25
50
Meridional heat flux [10¹⁰ W m⁻¹]
−2
−1
0
1
2

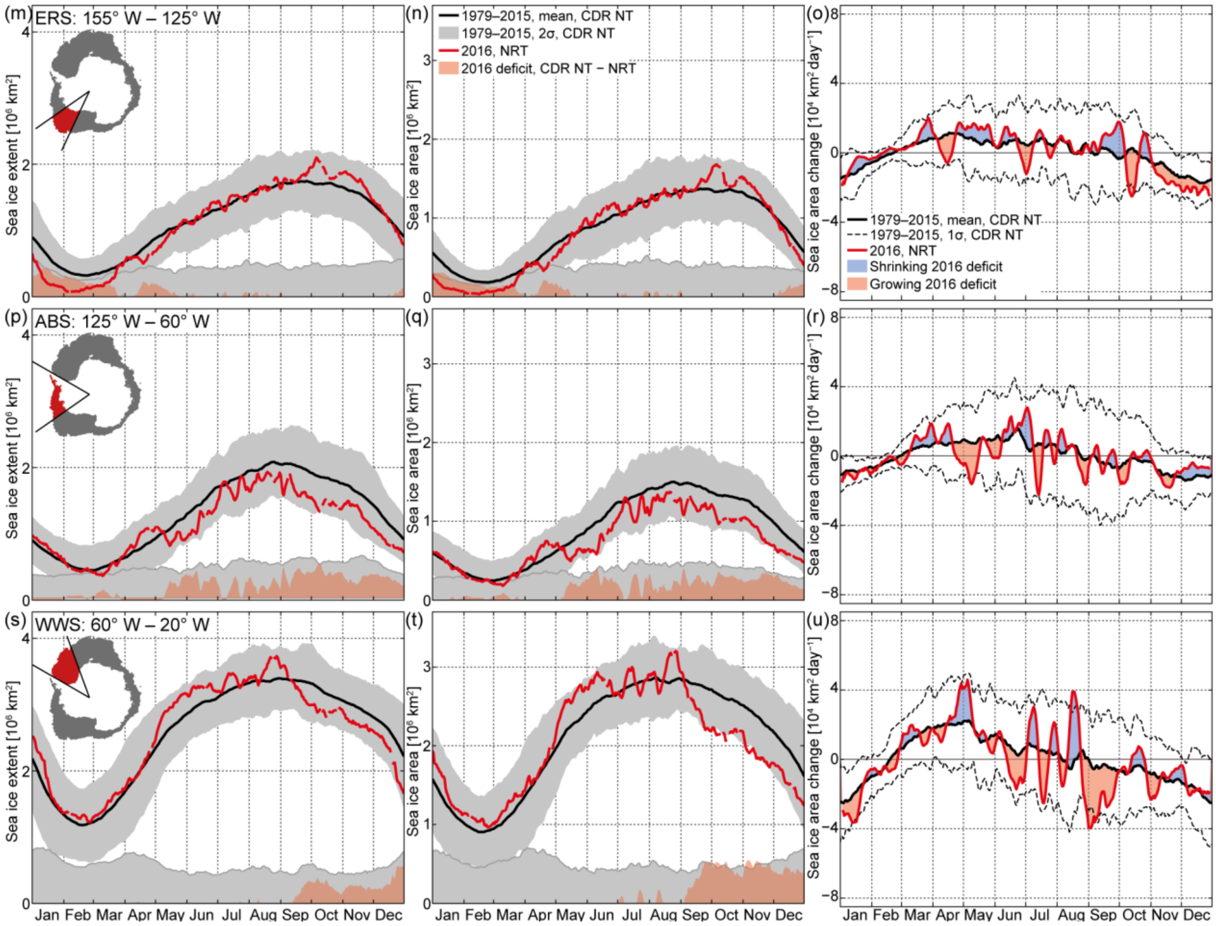
Figure 3.



(a) Nov. 1–10
(b) Nov. 1–10
0°
60° W
60° E
120° W
120° E
180°
60° S
80° S
Meridional heat flux [10^10 W m^−1]
−2
−1
0
1
2
1005
1000
995
990
985
980
975
970

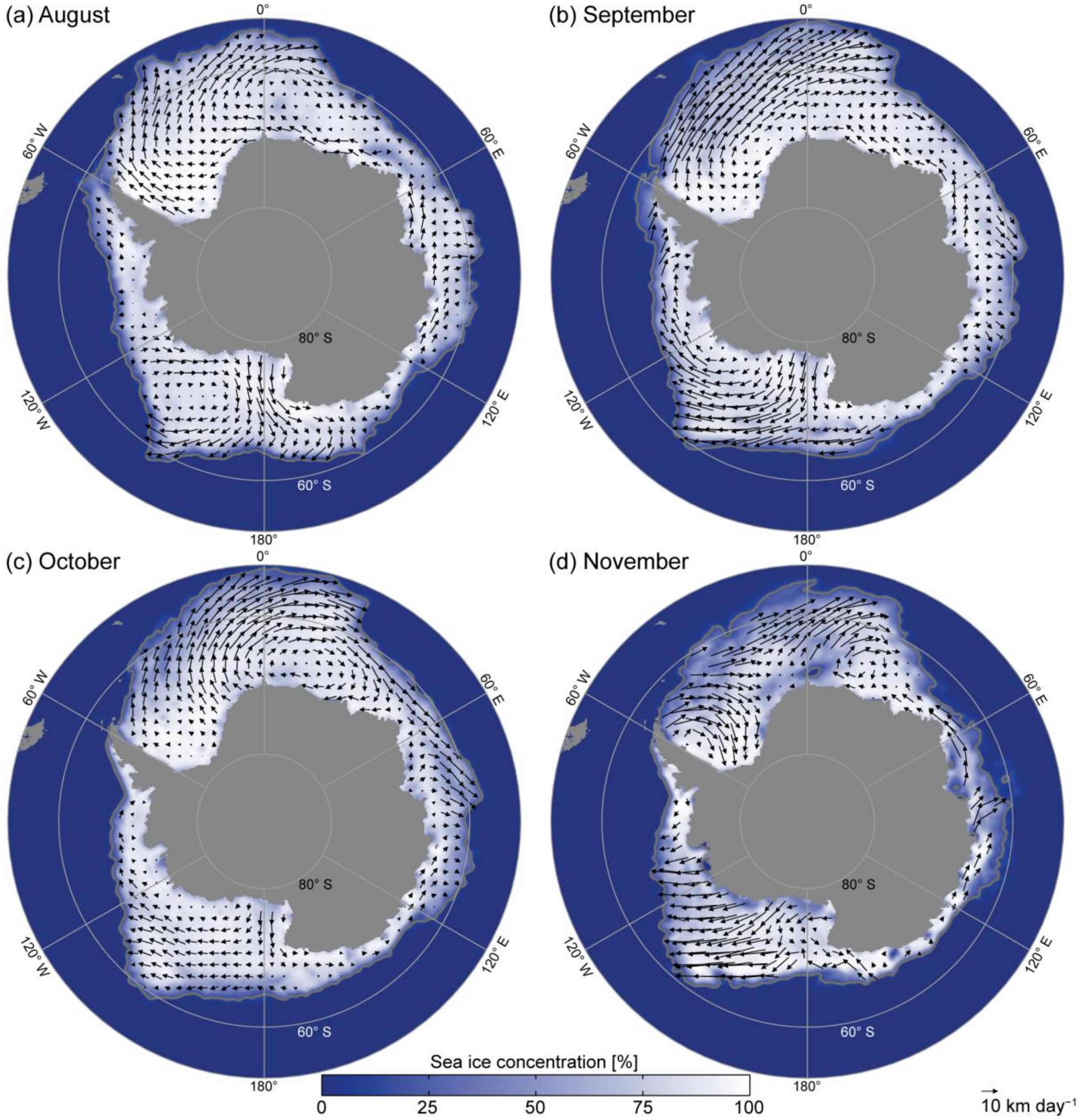
Figure 4.


(a) EWS: 20° W – 25° E
(b)
(c)
1979–2015, mean, CDR NT
1979–2015, 2σ, CDR NT
2016, NRT
2016 deficit, CDR NT − NRT
1979–2015, mean, CDR NT
1979–2015, 1σ, CDR NT
2016, NRT
Shrinking 2016 deficit
Growing 2016 deficit
(d) WIO: 25° E – 85° E
(e)
(f)
(g) EIO: 85° E – 130° E
(h)
(i)
(j) WP: 130° E – 155° W
(k)
(l)
Sea ice extent [10⁶ km²]
Sea ice area [10⁶ km²]
Sea ice area change [10⁴ km² day⁻¹]
Jan Feb Mar Apr May Jun Jul Aug Sep Oct Nov Dec



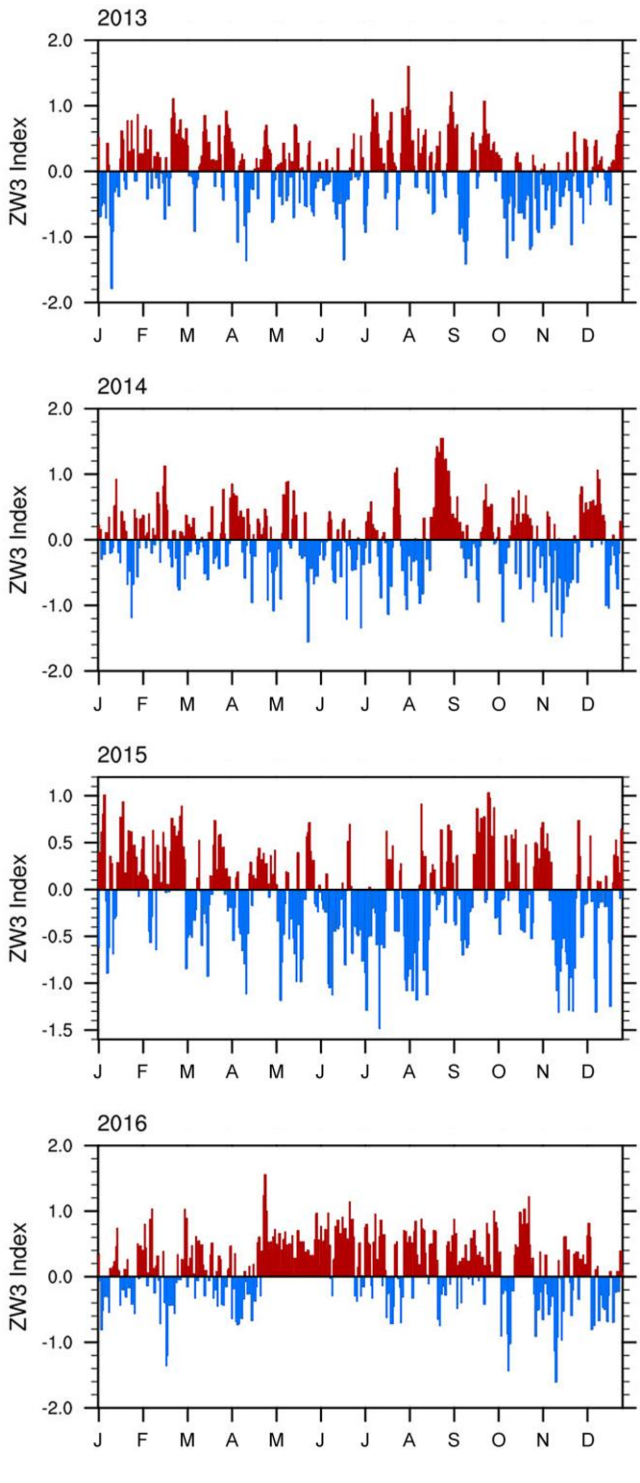
(m) ERS: 155° W – 125° W
(n)
(o)
1979–2015, mean, CDR NT
1979–2015, 2σ, CDR NT
2016, NRT
2016 deficit, CDR NT − NRT
1979–2015, mean, CDR NT
1979–2015, 1σ, CDR NT
2016, NRT
Shrinking 2016 deficit
Growing 2016 deficit
(p) ABS: 125° W – 60° W
(q)
(r)
(s) WWS: 60° W – 20° W
(t)
(u)
Sea ice extent [10⁶ km²]
Sea ice area [10⁶ km²]
Sea ice area change [10⁴ km² day⁻¹]
Jan Feb Mar Apr May Jun Jul Aug Sep Oct Nov Dec

Figure 5.



(a) August
(b) September
(c) October
(d) November
0°
60° W
60° E
120° W
120° E
180°
80° S
60° S
Sea ice concentration [%]
0
25
50
75
100
10 km day⁻¹

Figure 6.



2013
ZW3 Index
2014
ZW3 Index
2015
ZW3 Index
2016
ZW3 Index
J F M A M J J A S O N D

Figure 7a.

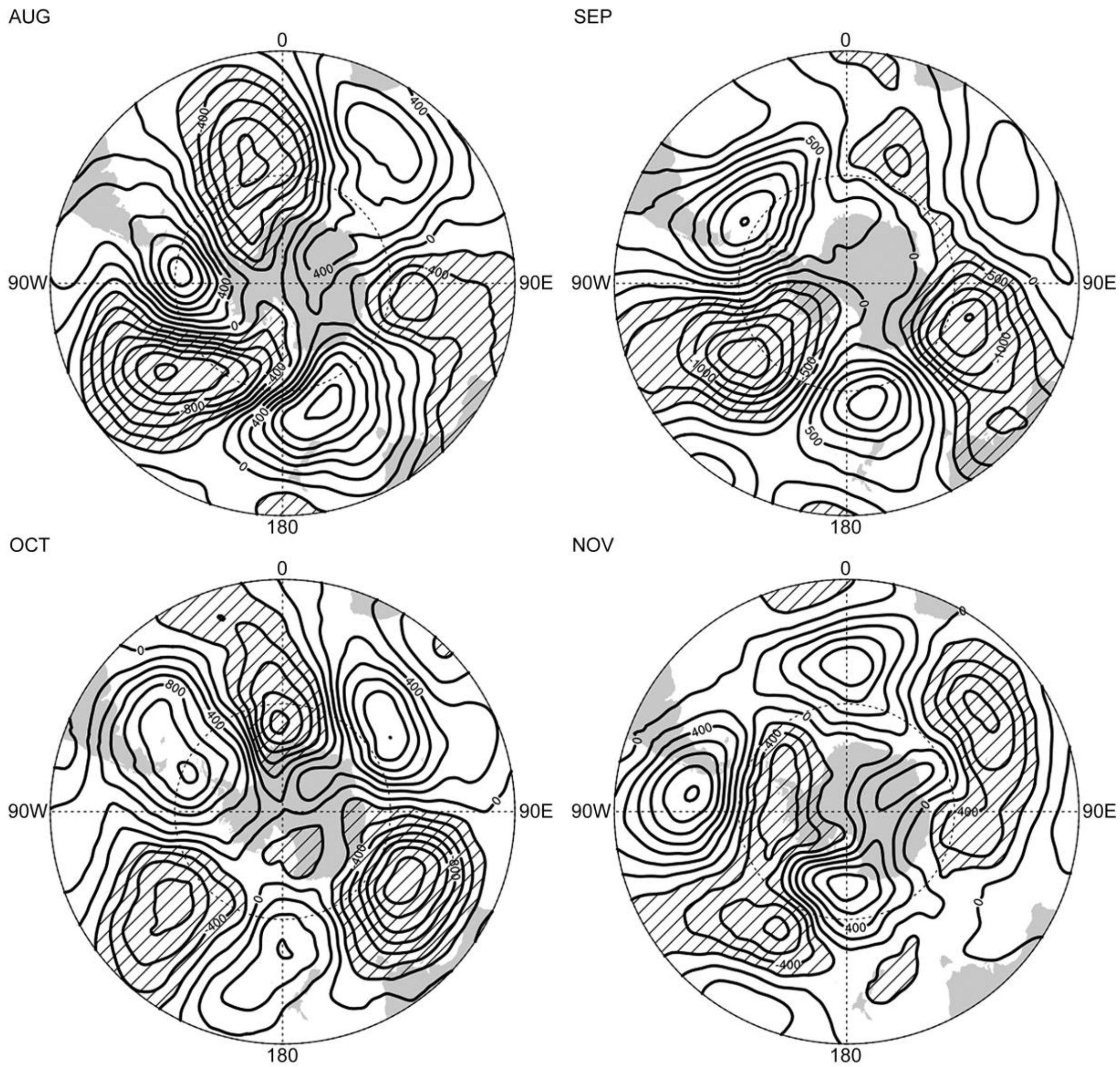


Figure 7b.

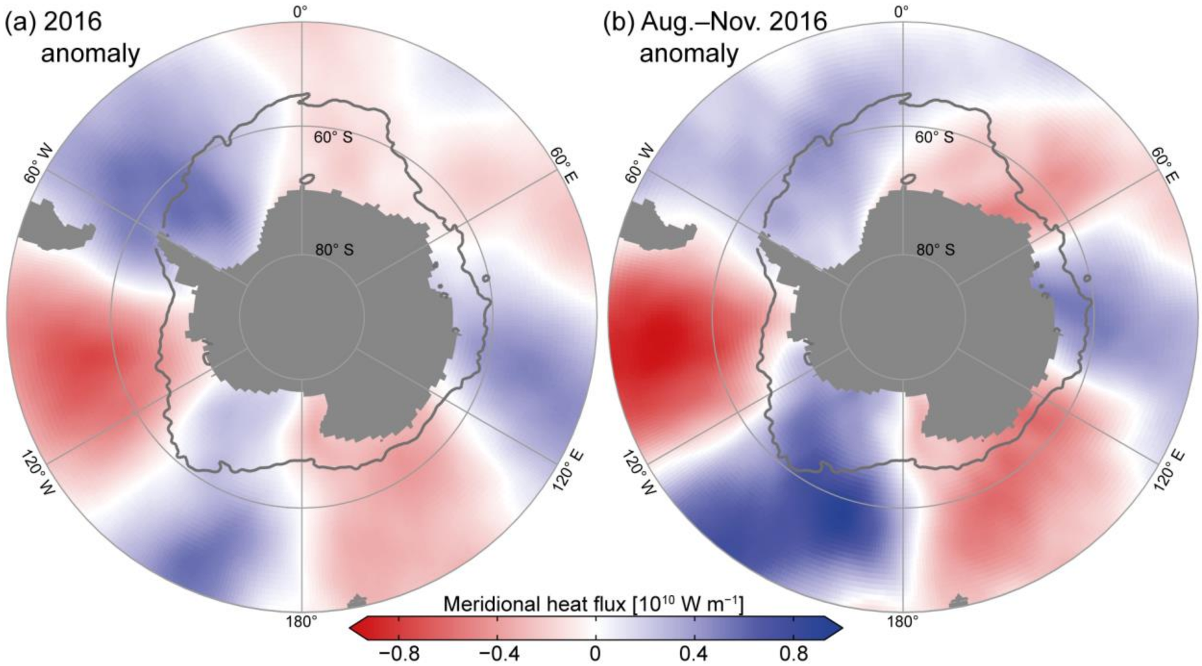

(a) 2016
anomaly
0°
60° S
80° S
60° W
60° E
120° W
120° E
180°
(b) Aug.–Nov. 2016
anomaly
Meridional heat flux [10^10 W m^-1]
−0.8
−0.4
0
0.4
0.8

Figure 8.

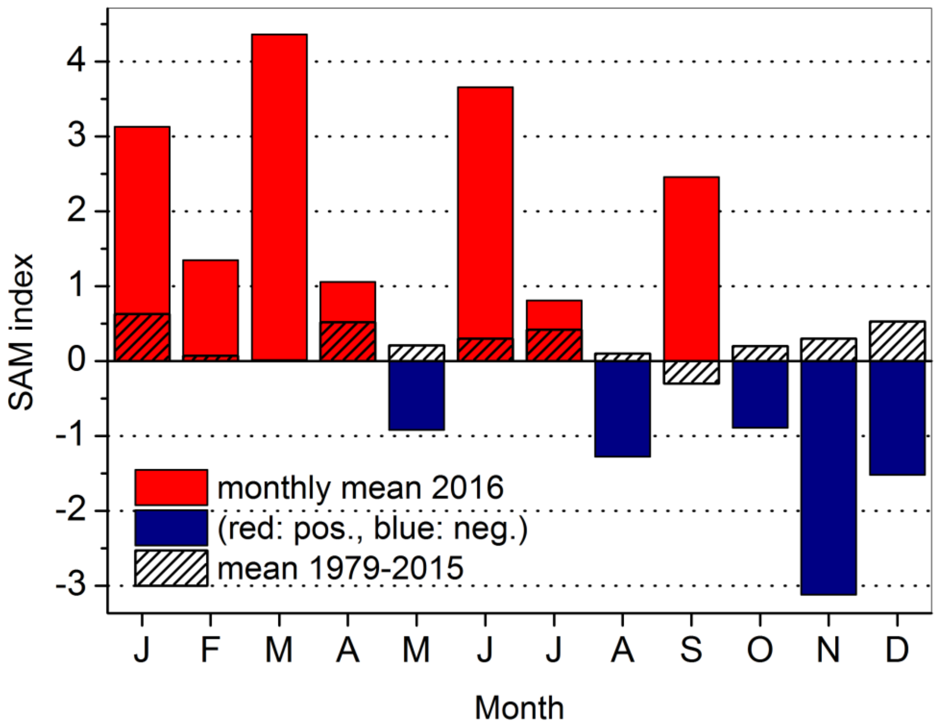

SAM index
4
3
2
1
0
-1
-2
-3
monthly mean 2016
(red: pos., blue: neg.)
mean 1979-2015
J
F
M
A
M
J
J
A
S
O
N
D
Month

Figure 9.