

## Response Reviewer 1

We would like to thank the reviewer for the feedback on our manuscript and we are grateful for the comments on how it can be further improved. We provide below a point by point response to the reviewer comments/suggestions.

### General Comments

The dramatic decline of Antarctic sea ice in Austral Spring 2016 was in marked contrast to long-term positive trends, and the current authors join a small group of previous authors who have attempted to shed light on this. They provide some interesting additions, in particular the presentation of rank maps for understanding the long-term context, the use of lagged correlations with local climate variables (rather than indices) and the discussion of October preconditioning, and the consideration of moisture transport.

However, I judge that the paper in its current form does not provide sufficient insights or conclusions to merit publication. In particular, the main focus and novel feature of the paper is the analysis of water vapor transport but the authors do not justify (from prior work or physical arguments) why water vapor transport would be expected to impact sea ice, or demonstrate in their results that it gives novel information over temperature alone. In addition, the substantial long term context discussion on SIC and circulation overlaps with previous work and more acknowledgement of this is required. I am also not convinced that the presented analysis of the SAM adds value to the paper.

Concerning the first two paragraphs of the reviewer's comments we see a discrepancy in the reviewer comments and so we have some problems following the main arguments of the reviewer. In the first paragraph the reviewer states and we cite: "They provide some interesting additions, in particular the presentation of rank maps for understanding the long-term context, the use of lagged correlations with local climate variables (rather than indices) and the discussion of October preconditioning, and the consideration of moisture transport." In the following paragraph the reviewer states and we cite: "However, I judge that the paper in its current form does not provide sufficient insights or conclusions to merit publication. In particular, the main focus and novel feature of the paper is the analysis of water vapor transport but the authors do not justify (from prior work or physical arguments)...".

From our point of view these two paragraphs contradict each other. On the one hand the reviewer states that we bring new addition to this particular topic, on the other hand the reviewer states a lack of novelty.

In our opinion we strongly demonstrated with this paper that we present new and novel insights regarding the topic under discussion, namely an exceptional anomalous long-term sea ice retreat in austral spring 2016. In the following we like to highlight them again in a short overview:

1. The rank maps. To our knowledge and due to intensive literature research, the performed study is the first one making such an analysis on sea ice extent and putting the 2016 event into a long term perspective both from a spatial and as well as from a temporal point of view.

2. The use of lagged correlations with climate fields, rather than pre-defined climate indices. To our knowledge and supported by an intensive literature research, previous studies on this topic (e.g. Turner et al., 2017, Schlosser et al., 2017, Stoecker et al., 2017) have not employed lagged correlation analysis to study the relationship between the water vapor transport and Antarctic sea ice, at regional scale. The lagged analysis is definitely novel on this particular topic and our results indicate also that there is some predictive skill in the regional Antarctic sea ice from the previous month's background conditions.

3. The consideration of moisture transport. The inclusion of the moisture transport as a preconditioning for the development of Antarctic sea ice is again a novel idea in this context.

4. The stability maps. This is also a novel addition to the topic under discussion.

We agree with the concerns of the reviewer that the discussion of the water vapor transport and its impact on the sea ice needs further elaboration and argumentation, but we feel that this reason alone doesn't take away the novelty of our analysis. Therefore, in the revised version of the manuscript we have extended the discussion regarding the influence of moisture transport on the sea ice and performed additional work on actual literature, adding new and additional references. We also improved/added new figures (Figure 3, 9 and 10) to strengthen our findings and to underline the novelty and importance of our paper.

Following the reviewer's comments we have removed the SAM part (former Section 3.6). Furthermore, we have focused the revised version of our manuscript more on the water vapor transport as suggested. The according references have been added and acknowledged in an appropriate manner.

I do think that a substantially re-written paper building on the current moisture transport analysis could be a beneficial addition to the literature.

As stated above, in the revised version of the manuscript, we have added a more detailed discussion about the moisture transport analysis and its impact on the Antarctic sea ice (see Introduction, Section 3.5, and the Discussion part). This discussion was elaborated and extended according to the suggestions.

In terms of method, the stability maps method is clear; I would like to see some further justification of its robustness in the context of the short time series available in the Antarctic. More clarity is also needed on the water vapor variables used.

This good suggestion of the reviewer has been implemented in the revised version of the manuscript. A discussion regarding the use of stability maps and their robustness with short time series has been added for clarification (Section 2.2 – Methods).

Regarding presentation, the structure of the paper is clear and the title and abstract are appropriate summaries of its content. However, the introduction does not appropriately introduce the paper. The discussion is also rather general, but I hope that if the authors make edits to the content of the paper, they will be able to draw some more specific conclusions in the discussion section.

The “Introduction” and “Discussion and conclusions” parts have been re-written following the reviewer’s suggestions. By this we believe that the both sections now are straight forward regarding the framing of the work as well as in putting the results in a proper context.

The figures and captions also need some improvement.  
All these points are detailed upon below.

## **Specific Comments**

All the specific comments of the reviewer haven been taken into account in the revised version of the manuscript. In the following we will answer how each of the specific comments have been considered I the revised version of the manuscript.

Introduction: This is a general introduction to the importance of sea ice and to the differing observed and modelled behavior observed at the two poles. It does not introduce the specific questions addressed in this paper. The authors need to introduce:

- o The work of previous authors (as already referenced in the discussion) on understanding the 2016 Austral Spring anomalies, and the gaps in these analyses which the authors address in this paper

The work of previous authors has been added in the revised version of the manuscript. (page 2, lines 15 – 23). New references have been also added in the revised version of the manuscript.

- o Why they address moisture transport. Presumably the physical argument concerns downwelling longwave radiation? Some work has addressed this in the Arctic (e.g. Mortin et al, Yang and Magnusdottir) and it would be helpful to cite these.

We have discussed this extensively issues on page 2 (lines 24 – 35) and page 3 (lines 1 – 3) of the revised version of the manuscript.

“Due to the fact that the Arctic and Antarctic regions are moisture flux convergence areas, atmospheric moisture transport is a primary input of water into these regions. Moreover, through the cloud-radiative forcing the moisture transport directly or indirectly affects the snow, sea ice and ice sheet over the polar regions. For the Arctic region, Kapsch et al. (2013) demonstrated that a significantly enhanced transport of humid air during spring produces increased cloudiness and humidity, thus accelerating the sea ice retreat in summer. Therefore, atmospheric moisture transport is a crucial component for the water balance, especially over the polar regions. While for the Arctic regions there is a large number of studies dealing with the influence of the moisture transport on the sea ice variability (Mortin et al., 2016; Yang and Magnusdottir, 2017; Park et al., 20125), over the Antarctic region little attention has been paid to transport variations of moisture from the Extratropics (Nieto et al., 2017). As such, the objectives of our paper are as follows: (a) to characterize the temporal and spatial extent of the spring 2016 exceptional sea ice melting event using both daily and monthly sea ice data; (b) to analyze the key drivers of the event, with a special emphasis on the role played by enhanced moisture transport and warm intrusions into the Antarctic region; (c) to place the austral spring 2016 into a long-term perspective. The

paper is structured as follows: in Section 2, we introduce the data used in this study; the main results of our analysis are shown in Section 3, while the concluding remarks are presented in Section 4.”

o The SAM and other circulation drivers and their relationship to sea ice

Most of the SAM analysis has been removed from the revised version of the manuscript.

P2, ~L12: ‘In this respect’: this is a slight leap from the argument for understanding physical processes behind the increase, to this paper addressing the dramatic opposite behavior in Austral Spring 2016. Please reword.

This sentence has been reworded and clarified.

Data, P2L22: clarify that the linear interpolation is a standard part of the sea ice product (i.e. it is not an addition that you have made, therefore you do not need to justify it)

This has been rephrased accordingly.

Data, P3L2: How exactly is water vapor transport calculated from the ECMWF variables described, and which variables are used at which stage of the analysis?

This information has been added in the revised version of the paper. Furthermore, we have stated out more precisely which variable is used at which stage of the analysis.

Data, P3L7: please expand on the reanalysis’ performance as relevant to the current paper; e.g. Bracegirdle and Marshall showed this reanalysis gave good trend/variability of SLP and T at coastal locations. As far as I know there is not an evaluation of reanalysis IWV, due to lack of observations; perhaps clarify this as an irreducible uncertainty on your results?

We agree with the reviewer’s concern regarding the uncertainty of the ECMWF data over Antarctica. We have tried to add more information regarding this issue in the revised version of the manuscript (see Section 2.1 Data) and added some new references to frame this issue.

Data, P3L12: please give a brief description of the SAM and this SAM index.

This is done and new references are included

Methods, Stability Maps: The stability map method could be very beneficial in the Antarctic context. However, I am concerned about the shorter record (under 40 years compared to 100 years) and by necessity shorter moving windows (21 instead of 31) compared to your previous work. In particular, given 1979-2016 time series there must be 21-yr windows, none of them independent? Presumably this affects the interpretation of the stable correlations? Please comment. I was unsure about the defensibility of using 80% significance, but reassured by the fact you only pursue analysis where significance is over 95%; perhaps clarify this in the introduction to the method.

An analysis and justification regarding the use of stability maps and their robustness with short time series has been added in the revised version of the manuscript. By this the questions of the reviewer should be answered. This will surely help to make the method applied for Antarctic time series more understandable. (see section 2.2 Methods).

Sections 3.1-3.3: the long term discussion overlaps significantly with previous work. More care is needed in citing these other papers (and perhaps shortening your description accordingly) e.g. BAMS state of the climate 2016 report sea ice section and relevant points from papers you already cite in the discussion. In particular at pg 5, line 2 (end of section 3.1) reference Turner et al 2017, who explicitly show the anomalous sea ice retreat in November 2016; and at page 5 line 20 cite BAMS state of the climate: Antarctica: Atmospheric circulation.

This is a very helpful suggestion to strengthen the references and work already done and not yet clearly presented in the paper. Nevertheless, the overlapping discussion with the other papers is fairly low and we have acknowledged the contribution of the other studies in the revised version of the manuscript. Without having a short discussion about some of the atmospheric drivers (e.g. SLP and air temperature) it would have become almost impossible for us to have a clear story regarding the 2016 event.

P4 L24: I don't think WPO contributes notably to September SIE anomalies (Figure S2)

The text has been changed accordingly in order to have the proper statement in the paper.

P4 L27-28: Figure S2 shows WS does not become negative until the second half of November?

The text has been changed accordingly.

P5 L23: I do not think you can argue the westerlies resulted in positive temperature anomalies; rather, all associated with same patterns of variability.

The text has been modified.

Section 3.2: Be careful in your use and discussion of the SAM, if retained.

o It's not clear which behaviour you are saying 'projects onto the positive phase of the SAM'; the wavenumber 3 behaviour or the zonally symmetric annular structure. The Marshall index describes primarily zonally symmetric behaviour, whereas EOF based Antarctic Oscillation indices do capture the 3 centres of action.

o I'm not sure it's useful; in some months (September and November) the circulation does have three centres of action in the expected places. However in October in particular it is not 'SAM-like' at all (either in the zonal-mean or zonally asymmetric sense). I would therefore suggest writing the discussion without reference to the SAM, and concluding the section with a short section, perhaps referencing a map of the SAM's typical behaviour (e.g. Spring SLP regressed onto the Marshall index, as a supplementary figure) and noting the months in which the circulation looked very SAM-like and the remarkable values of the index in this month. It would also be worth checking whether the SAM rankings are broadly robust to use of a different index.

We agree with the reviewer's comment regarding the two paragraphs above. Based on the aforementioned comments, we have removed most of the SAM results from the revised version of the manuscript. We kept just some information in the discussion part (Page 10, lines 25 - 35).

Section 3.3 and throughout: please ensure you are clear and consistent in your use of the terms 'water vapour', 'water vapour transport', 'total column water vapour', 'integrated water vapour' etc and their associated acronyms. They were used inconsistently to the extent of my being unable to understand what was being used at all points

We fully agree with this comment. We have changes the terminology to be more clear and consistent.

Section 3.4: To me, the conclusion to be drawn from the maps and indices here (figs 5 and 6) is that there is a lagged local effect between temperature/water vapour and SIC in the regions analyzed. This is perhaps not very surprising although I'm not aware of previous lagged analysis. Some questions to address to interpret the results:

o To what extent is this a manifestation of persistence in SIE anomalies?

Persistence plays definitely a role, but we strongly believe that without a strong atmospheric/oceanic forcing an event like 2016 is rather impossible to occur.

o What are the results for the Weddell Sea in December (where anomalies are greater than in the Ross Sea)? 2016 saw rapid development of WS anomalies in November, implying that at least in this year, it was not just anomaly persistence.

In the revised version of the manuscript we have added a more detailed discussion regarding the Weddell Sea and removed the discussion regarding the Ross Sea, to be consistent in our analysis, especially in the Sections 3.4 and 3.5.

o Does IWV add more (statistical) information, or more physical understanding, over T alone? Figures 5 and 6 show the same regions in the stability maps for IWV and for T, and the timeseries look very highly correlated. A physical discussion and some supporting evidence is needed: is the same circulation bringing in heat and moisture? Or are water vapour anomalies radiatively driving temperature anomalies? Since this seems to me to be the main result of the paper, it is necessary to argue either that the water vapour has some independence from and therefore added predictive power over temperature, or that it adds physical understanding to the sea ice anomalies which cannot be inferred from temperature alone.

Although we strongly agree with this comment, the aim of our manuscript is not to figure out which one of the two variables has a more important role in driving the sea ice anomalies. We strongly feel that such an analysis requires not only observational data, but also model simulations and sensitivity studies. Our aim was to show that extreme warm and moist intrusions are able to trigger negative sea ice anomalies like the one in 2016. We are hoping that our study can be use as an indicator that moisture transport should be considered in future studies regarding the Antarctic sea ice variability. But in order to analyze the contribution of each variable to the sea ice variability, one needs to make designated studies, which is not the aim of our current paper.

o You discuss a dipole of stable regions. This could be related to the ASL, which would cause co-variability in the Ross and Amundsen-Bellingshausen sea, although the footprint in the Weddell sea is larger and further to the east than I'd expect in this case.

ASL could play a role, at least partially, but due to the location of the centers of the dipole we feel that a general discussion is more appropriate compared to relating this just the ASL

variability. As already commented by the reviewer, the footprint in the Weddell Sea is rather different compared to the one observed for ASL.

P7L5: note that the highest SIE over this area is broadly true even when normalized anomalies are used (BAMS state of the climate figure 6.9); i.e. even accounting for natural variability these regions are exceptional in 2016

P7 L7; give the main results from the maps before discussing the indices.

Modified the order as suggested.

Section 3.5:

o It is unclear which water vapour variables are used. Which figures show IWV and which show IWVT? Please check units, acronyms etc.

The text has been modified following these suggestions to make it more clear and easy to follow. All the units and acronyms will be carefully checked.

o I found this hard to follow. I suggest rewriting this section such that each 2-day regional mini case study, is addressed with a little more care (maybe use 'first the ABS', 'second the IO', 'thirdly the RS'). Can you link these transport events to e.g. cyclones?

In the revised version of the manuscript we have rephrased the aforementioned section to make it more clear and easy to follow.

o Take care over extrapolating to 'decline in first two weeks of December'. The anomalous decline in early December was in the WS (Fig S2) so I don't think you can robustly link it to the event shown.

The text has been modified following the reviewer's suggestions.

Section 3.6: This analysis does not add anything to the discussion about 2016, nor much to understanding of SAM-sea ice relationships in general. Table 2 is valuable but I think this discussion could be removed and replaced with a few sentences in the discussion e.g. 'Given the dramatic SAM anomalies in some months, we investigated the long term relationships between regional SIE and the monthly SAM. However, significant relationships were found for only three month-region combinations (of 20) and thus consistent with previous studies [...], we find the SAM's role in sea ice variability is complex.' The moving window method could be used to enhance this if the analysis is felt to be critical to the paper. Unless the relationship of the SAM to moisture transport is explicitly addressed, I do not think it adds to the novel scientific content of the paper.

P9 L14; Is this lowest for November, or lowest overall? Is it true for other SAM indices?

As stated above, the discussion regarding SAM has been shortened and changed following the suggestions made by the reviewer. Section 3.6 has been completely removed. Just a small discussion regarding the influence of SAM on the regional SIE variability has been retained in Section 4.

P9 L31; you say you've shown moisture and temperature anomalies could 'also' have led to different anomalies. 'Also' implies it's something different; are the anomalies you've shown

not manifestations of the circulation anomalies discussed? 'poleward advection of warm': you don't show heat transport so this is a slight assumption, although I think Schlosser et al do please cite.

At the submission date of our paper to ESD (17.11.2017) the Schlosser et al paper (under discussion at that time) does not show figures regarding the heat transport. Nevertheless, the final version of Schlosser et al paper has been recently published, with the addition of the heat transport figure, and now the paper has been cited and referred accordingly. Moreover, in the revised version of the manuscript we have included a new figure representing the vertical integral of northward heat flux and the vertically integrated heat transport from September until December 2016 (Figure 4). This underlines our statements.

P10 L13 ; 'poleward advection of moist and warm air': increased moisture is not necessarily due to increased moisture advection?

We agree with the reviewer's comment and we have modified the text accordingly.

P10 L21; The study of Woods et al was about the Arctic. It's not clear it is relevant here.

The reference has been removed.

## Technical Corrections

Abstract, Line 13: 'lowest daily sea ice concentration anomalies' -> 'largest magnitude negative daily sea ice concentration anomalies'

Although it's almost certain readers know what SIE is, give the abbreviation at first mention (Pg 1 L25) or at first use in methods section (Pg 2 L23) [rather than at P2 L8 as done in this version].

Page 1 Line 23: Artic -> Arctic

P2, L7: Colins -> Collins

P2, L11: clarify from offset what months 'Austral spring' is.

P3, L20: on time -> in time

P3, L21: Bracketed 'e.g.s' unnecessary and make text more confusing.

P3, L31: Ionita et al (2017) reference should be Ionita (2017)?

P4 : there is inconsistency between use of abbreviations ('WS') and full names ('weddell sea')

P4 L4: 'problematic' a little emotive. Try 'challenging' or 'confusing'?

P4 L5: '8' -> 'eight'

P4 L6: 'positive SIE anomalies over the whole Antarctic region' -> 'positive pan-Antarctic SIE anomalies'. I don't like the phrase 'pan-Antarctic' much, but 'whole' implies 'everywhere'.

P4 L20-21: rewrite e.g. 'In December the whole RS, and most of the ABS and IO were characterised by negative SIC anomalies'

Pg 5 line 5: 'to the zonal' -> 'of zonal'.

P5 L13: 'were' -> 'where'

P5 L19: 'warming' -> 'warm anomalies'

P6 L5: 'particular' -> 'exceptional'

P6 L7: delete sentence 'The rank maps are computed...'

P6 L10: 'to be able to clearly capture...2016 was' -> 'for clarity'

P6 L13: delete 'Figures 3a,b and c indicate that'

P6 L19, L23, L28: 'southern', 'eastern' and 'north-west' should be 'northern', 'western' and 'north-east'? Please check!

P7L6, 16; delete 'respectively'  
 P7 L9: 'considered' -> 'consider'  
 P7 L24; 'December TT' -> 'December TT2'.  
 P7 L27; delete 'a' before 'predictive'  
 P8 L2 'there' -> 'three'  
 P8 L3; 'employing' -> 'spatially averaging'?  
 P8 L4 'region' -> 'regions'  
 P8 L5: delete comma after 'IWV'  
 P8 L10: reference Fig 7d  
 P8 L13: 'BAS' -> 'ABS'.  
 P8 L24: 'trimming' -> 'timing'.  
 P8 L17: Reference Figure S2.  
 P9 L15 'led to' -> 'associated with' (the SAM is in part expressing the behaviour of the westerlies. It is not a physical driver.).  
 P9 L31 'lead' -> 'led'.  
 P10 L16 'this' -> 'these'  
 P10 L16 'moist' -> 'moisture'.  
 P10 L21; 'In recent' -> 'In a recent'.

All the aforementioned technical corrections have been addressed and inserted in the revised version of the manuscript. We are thankful for the very careful reading of the reviewer at this point.

#### Corrections: Figures

Figure 1: Optional, but inclusion of topography and lines of latitude could make this a more useful reference figure for readers not as familiar with the Antarctic.

A figure with topography does not add much value to our overall Figure 1, mainly because we are focusing our analysis on the sea ice anomalies.

Figure 2: The vectors are too small to be legible, and are not described in the caption. Repeating sector names in-plot is unnecessary here and the legibility is poor, so I suggest removing.

The figure has been changed according to the suggestions. We have removed the sector names from Figure 2.

Figure 3: As Figure 2 for sector labels. Remove '2016' in subfigure label titles. I also suggest you change the caption text to 'Ranking of 2016 monthly: sea ice concentration (SIC, first column, '1' means lowest SIC in period); integrated water vapour (IWV, second column, '1' means wettest month in period); temperature (TT, third column, '1' means warmest month in period). The period is 1979-2016. Rankings below 5 appear white.'

The aforementioned suggestions have been taken into account and the figure caption for Figure 3 (now Figure 5) has been modified accordingly.

o Technical question; how do repeated '0's rank (i.e. if several years have SIC=0?)

The years with SIC = 0 are treated as NaN's and they are not taken into account.

o The colour scale is probably not colour-blind friendly. Please improve. Figure 5 and 6

We have tried to find a color-blind color scheme (see new figure 5 and S3).

o The correlations in e) and f) would be clearer if the SIE anomaly were negated.

We have negated the SIE anomalies, but the new figure is more difficult to follow compared to the original one, as such we have decided to keep the original figure.

o Add title to color bar.

Done.

o Simplify caption text for panels a-d to (Fig 5 example): 'The stability maps between November Indian Ocean (IO) sea ice extent and a) October IWV, b) November IWV, c) October TT, d) November TT.

Modified as suggested.

o Please check panel refs in caption to Fig 6; both time series panels referred to as c).

Done.

Figure 7

o Check journal standards on color scale (avoiding use of green-red for example).

o It would be helpful to show again in this figure the squares used to define regions.

o What are the vectors?

o Please clarify the dates shown in time series (are all days shown or only October and November) and check use and consistency of IWT/IWVT etc (see my general comments) and units.

The figure has been modified following the reviewer's suggestions. The only thing that we did not take into account was to add the delimitating lines for the sea ice extent regions. Adding this line will make the figure almost impossible to follow.

Supplementary Figure 1: In caption, mention 2016 just once, and state what the red number in each panel is (the ranking of that month's regional SIE).

Modified as suggested.

SF2: It would be helpful to include full regional names once more and to either change colors or find another way of making them clearer (IO, ANT and WS are very hard to distinguish) and of separating the full Antarctic time series from the individual regions. Y axis: Sie-> SIE.

Modified as suggested.

SF3: Interpolation of contours here is unhelpful as there is no propagation of anomalies in the x-direction. I suggest using a block rather than interpolated contour. Also please change colour scale and use less classes for legibility.

Figure S2 has been removed from the revised version of the manuscript.

SF4: See comments on (main text) Figure 3 caption and color scale.

Modified as suggested.

#### References

Mortin et al (2016): Melt onset over Arctic sea ice controlled by atmospheric moisture transport. DOI 10.1002/2016GL069330.

Yang and Magnusdottir (2017): Springtime extreme moisture transport into the Arctic and its impact on sea ice concentration. Doi 10.1002/2016JD026324.

## Response Reviewer 2

We would like to thank the reviewer for the positive feedback on our manuscript and we are grateful for the comments on how it can be further improved. We provide below a point by point response to the reviewer comments/suggestions.

### Summary and overall comments

The manuscript describes the dramatic retreat of Antarctic sea ice in Oct-Dec 2016 in detail, and relates it to anomalies in the atmospheric circulation, in particular surface temperature, total column water vapor and total column water vapor flux. The methodology was previously unknown to me, and the results are interesting, warranting publication in ESD. However, the writing in the manuscript needs improvement. I therefore recommend publication after minor revisions.

### Specific comments

Fig. 2: Please indicate in the caption what is shown. What are the arrows in left column plots? In right column, are colours IMV (integrated water vapour) and arrows the IMVT (integrated water vapour transport)? Also, please insert reference arrow.

Figure 2 caption has been modified following the reviewer's suggestions.

Fig 3: For comparison with Fig 2, please swap center and right columns so that temperature is in middle and IMV to the right.

We have modified Figure 2 and added two new figures (Figure 3 and Figure 4) so Figure 2 and 3 are distinct and cannot be compared directly in the revised version of the manuscript.

Fig 4: This figure is referenced on lines 26, 29 on page 3, but I think you mean Fig 5 or 6? In that case, Fig 4 is only referenced to once in the paper, and is somewhat unnecessary. The relation between high temperatures and low sea ice is already made in Fig 3. I strongly suggest to remove it or add it to Supp. material.

We decided to keep figure 4 (now Figure 6) mostly because is based on observation data, thus giving more confidence regarding the reanalysis data.

Fig. 6: From Fig 6a,c, my guess is that there is an SLP anomaly somewhere over the Antarctic Peninsula driving the changes in advection. Hence, the 2nd box is correlated to WS sea ice, but is likely not causing the anomalies in WS sea ice? Also, the caption describes Fig 6c three times, but never Fig 6e or 6f.

The text and figure captions have been modified following the reviewer's suggestions.

Page 1, Line 11,12: Throughout the paper, the authors use the unusual abbreviations "IWV" for integrated water vapour and "TT" for 2m temperature. For the former, "VIWV" (vertically integrated water vapour) would be a better name so that the direction of integrations is explicit, or the authors could use "TCWV" (total column water vapour) or "IWVC" (integrated

water vapour column) which are more common. Rather than "TT", perhaps "T2m" or "Ts" would be better?

We strongly agree with this issue, and in the revised version of the manuscript we have improved the description of each variable and their corresponding abbreviation to make the paper easier to read. Each variable we use has been properly abbreviated in the data section. The text has been checked for inconsistencies and modified accordingly.

Page 1, Line 32: The sentence "Antarctica experienced..." could be changed to "Between September 2016 and April 2017, Antarctica experienced a dramatic shift featuring strong negative SIE anomalies".

The text has been modified accordingly.

Line 2, Line 2: "could be caused either by a potential change..". What is meant by "potential change"? Perhaps re-phrase to "could potentially have been caused by a change in the long-term trend or by natural climate variability"?

The text has been rephrased following the reviewer's suggestion.

Page 2, Line 20: Skip the comma between "utilize" and "the".

Done.

Page 3, Line 20: "does not change on time"? Do you mean "is time-independent"?

The text has been rephrased following the reviewer's suggestion.

Section 2.2: The method is interesting, but the description may need some clarification. If there are 37 years of data and you use a 21-year moving window, then you only have  $37 - 21 = 16$  data points in time? Does this mean that the maps in Fig. 5,6 are made from 16 time levels? And 80% of 16 is about 13, so you require significant correlations for 13 of 16 time levels?

A justification regarding the use of stability maps and their robustness with short time series has been added in the revised version of the manuscript (see Section 2.2 Methods).

Page 3, Line 26, 29: Should be Figure 5,6 instead of 4,5?

Yes indeed. The text has been modified accordingly.

Page 4, Line 22: Suggest "striking" instead of "very particular"

Modified as suggested.

Page 4, Line 29, 30: Perhaps use "SIE anomaly below  $-2.2$  mil. km<sup>2</sup>" instead of "more than 2.2" so that it is clear that the anomalies are negative. Same at Line 30.

Modified as suggested.

Page 5, Line 2: "1980's"

Modified as suggested.

Page 5, Line 12: At several places in the paper (e.g. Page 6, Line 32 and Page 7, Line 12), the authors use "positive temperature anomalies and enhanced water vapour". Why not use "positive anomalies in surface temperature and total column water vapour"?

In the revised version of the manuscript the text has been modified following the reviewer's suggestion.

Page 6, Lines 9, 15, 19, 20, 23: "wet" often refers to high precipitation. Use "most humid" instead? Also, do we know if these events are linked to high values of precipitation?

Throughout the revised version of the manuscript we use now "moist" instead of "wet". We agree that wet usually is associated with precipitation, thus the text has been modified accordingly.

Page 6, Line 32: Suggest change from "extreme warm temperatures and enhanced moisture" to "large positive anomalies in surface temperature and total column water vapour".

Modified as suggested.

Page 8, Lines 1-5: I found these sentences unclear. I would suggest "For October and November each year, we calculate daily IWVT (or TCWV or IWVC, see above comment) over three areas in the ABS, IO, RS respectively. The areas are those which rank as the warmest and most humid on record in 2016, and are marked in Figures 3e and 3h. The time series of IWVT for these areas are shown in Figures 7a, c, e. "

In the revised version of the manuscript we have modified almost entirely section 3.5 for a better reading.

Page 8, Line 8: "reaching the" rather than "penetrating until".

Modified as suggested.

Page 8, Line 13: "ABS" instead of "BAS"?

Modified as suggested.

# Moisture transport and Antarctic sea ice: Austral spring 2016 event

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**Abstract.** In austral spring 2016 the Antarctic region experienced anomalous sea ice retreat in all sectors, with sea ice extent in October and November 2016 being the lowest in the Southern Hemisphere over the observational period (1979 – present). The extreme sea ice retreat was accompanied by widespread warming along the coastal areas as well as in the interior of the Antarctic continent. This exceptional event occurred along with a strong negative phase of the Southern Annular Mode (SAM) and the moistest and warmest spring on record, over large areas covering the Indian Ocean, the Ross Sea and the Weddell Sea. In October 2016, the positive anomalies of the totally integrated water vapor (IWV) and 2m air temperature (T2m) over the Indian Ocean, Western Pacific, Bellingshausen Sea and southern part of Ross Sea were unprecedented in the last 39 years. In October and November 2016, when the **largest magnitude of negative daily sea ice concentration anomalies** were observed, repeated episodes of poleward advection of warm and moist air took place. These results suggest the importance of moist and warm air intrusions into the Antarctic region as one of the main contributors to this exceptional sea ice retreat event.

## 1 Introduction

Sea ice in both polar regions is an important indicator for the expression of global climate change and its polar amplification. It also plays an important role in modulating the global climate system by influencing the atmospheric and oceanic circulations (Cohen et al., 2018). Moreover, it has also a strong impact on the global economic system through changes in marine and natural resources development. Consequently, a broad scientific as well as societal interest exists on sea ice, its coverage, variability, and long term change (National Research Council, 2012). Recent observed changes in the Arctic have become the “face” for global climatic changes, especially due to the rapidly decreasing trend of the summer sea ice extent over the last two decades (Serreze and Stroeve, 2015). The trends in the Arctic sea ice extent (**SIE**) over the satellite observational record 1979 – present are negative for all months, with the largest trend recorded at the end of the melt season in September (Serreze et al., 2007; Stroeve et al., 2015), with an average decline of 12.9% per decade relative to the long-term mean of 1981 – 2010 September average (Grosfeld et al., 2016).

In contrast, over the Antarctic region the SIE shows an increasing trend over the satellite observational record, seemingly at odds with climate model projections. The increase in the Antarctic sea ice extent can be largely explained by natural climate fluctuations (Meehl et al., 2016), linked with different factors/drivers like: atmospheric temperature or wind stress (Liu et al., 2004; Turner et al., 2009; Lefebvre and Goosse, 2005), precipitation (Liu and Curry, 2010), ocean temperature (Jacobs and

Comiso, 1997), and feedbacks in the atmosphere or ocean (Stammerjohn et al., 2012; Zhang, 2007). The variability of the Antarctic SIE has been also related to several large-scale atmospheric circulation mechanism like: a) the southern annular mode (SAM) (Hall and Visbeck, 2002; Kwok and Comiso, 2002; Lefebvre et al., 2004; Simpkins et al., 2012; Raphael and Hobbs, 2014); b) the zonal wave 3 (ZW3) (Raphael, 2007, Schlosser et al., 2018) and c) the El Niño –Southern oscillation (Turner, 2004; Yuan, 2004; Stammerjohn, 2008).

Whereas the coupled atmosphere-ocean-sea ice models, which are driven by realistic natural and anthropogenic forcing, are able to replicate the decreasing Arctic trend (Stroeve et al., 2012), they also have the tendency to simulate a significant decrease in Antarctic sea ice cover (Turner et al., 2013), in contrast with the observed increasing trend. Shu et al. (2015) showed that only one out of seven CMIP5 models is able to simulate the sign of the Antarctic sea ice trend correctly. As the confidence on numerical simulations relies on an adequate representation of the late-twentieth-century changes (Collins et al., 2014), the understanding of the physical processes generating the Antarctic SIE trend and variability is crucial for the relevance of the projected Southern Hemisphere sea ice extent decrease. Consequently, the analyses of observed, reconstructed, and reanalysis data are critical for the investigation of their causes. Following this line, here we analyze the exceptional Antarctic austral spring (September – October – November) of 2016, from a climatological point of view and try to identify the drivers responsible for triggering this particular event. This study is an additional contribution in the discussion about the possible drivers of the 2016 extremely low sea ice event over the Antarctic region. Turner et al. (2017) considered the spatial differences of the SIE anomalies and their temporal change at regional level. They related the low SIE over the Antarctic region to the warm air advection and the strong negative values of SAM in November and December 2016. Schlosser et al. (2018) have shown that the rapid decrease in the sea ice area and extent were associated with atmospheric flow patterns reminiscent to a positive zonal wave number 3 (ZW3) index. The strong meridional flow associated with a positive ZW3 index triggered an accelerated sea ice decline, especially at the beginning of November. From a pre-conditioning point of view, Stuecker et al. (2017) showed that the extreme low SIE in November and December 2016 was partially driven by the 2015/16 El-Niño event and the negative phase of SAM.

Due to the fact that the Arctic and Antarctic regions are moisture flux convergence areas, atmospheric moisture transport is a primary input source of water into these regions. Moreover, through the cloud-radiative forcing the moisture transport directly or indirectly affects the snow, sea ice and ice sheet over the polar regions. For the Arctic region, Kapsch et al. (2013) demonstrated that a significantly enhanced transport of humid air during spring produces increased cloudiness and humidity, thus accelerating the sea ice retreat in summer. Therefore, atmospheric moisture transport is a crucial component for the water balance, especially over the polar regions. While for the Arctic regions there is a large number of studies dealing with the influence of the moisture transport on the sea ice variability (Mortin et al., 2016; Yang and Magnusdottir, 2017; Park et al., 20125), over the Antarctic region little attention has been paid to transport variations of moisture from the Extratropics (Nieto et al., 2017). As such, the objectives of our paper are as follows: (a) to characterize the temporal and spatial extent of the spring 2016 exceptional sea ice melting event using both daily and monthly sea ice data; (b) to analyze the key drivers of the event, with a special emphasis on the role played by enhanced moisture transport and warm intrusions into the Antarctic

region; (c) to place the austral spring 2016 into a long-term perspective. The paper is structured as follows: in Section 2, we introduce the data used in this study; the main results of our analysis are shown in Section 3, while the concluding remarks are presented in Section 4.

## 2 Data and methods

### 2.1 Data

For the daily sea ice concentration (SIC) we utilize the passive microwave sea ice concentration data using the National Snow and Ice Data Center (NSIDC) bootstrap algorithm (Comiso and Nishio, 2008; Meier et al., 2013) over the period 1979 – 2016. Prior to 1987, data are only available every other day; hence data for missing days were produced by linear interpolation for each pixel between the fields of the previous and next days. **The linear interpolation is a standard procedure of this sea ice product.** The monthly SIE index (Fetterer et al., 2016) over the Antarctic region has been extracted from the NSIDC ftp server (<ftp://sidads.colorado.edu/DATASETS/NOAA/G02135/north/>). Sea ice extent (SIE) is defined as the total area of all satellite pixels where the sea ice concentration equals or exceeds 15%. Following previous studies (Zwally et al., 2002; Turner et al., 2017), we examine the anomalies of the daily and monthly SIC and SIE for the Southern Ocean as a whole and for five separate sectors (Figure 1): the Ross Sea (RS) (160°E–130°W), Amundsen - Bellingshausen Sea (ABS) (130°W–60°W), Weddell Sea (WS) (60°W–20°E), Indian Ocean (IO) (20°E–90°E), and Western Pacific Ocean (WPO) (90°E–160°E).

**For the Southern Hemisphere (SH) temperature and atmospheric circulation, we use the monthly means of air temperature at 2m (T2m), zonal wind at 10 m (U), meridional wind at 10 m (V), mean sea level pressure (SLP), the vertical integral of water vapour (IWV), the vertical integral of eastward water vapour flux ( $Q_u$ ), the vertical integral of northward water vapor flux ( $Q_v$ ), the vertical integral of eastward heat flux ( $H_u$ ), and the vertical integral of northward heat flux ( $H_v$ ) from the European Centre for Medium-range Weather Forecasts (ECMWF) Interim (ERA-Interim) reanalysis fields (Dee et al., 2011). IWV,  $Q_u$ ,  $Q_v$ ,  $H_u$  and  $H_v$  are produced by the ERA post processing budget software. Details how the basic fields are post-processed are given in the IFS documentation (<https://www.ecmwf.int/sites/default/files/elibrary/2017/17738-part-vi-technical-and-computational-procedures.pdf>). ERA-Interim uses a four-dimensional variational assimilation scheme with a twelve-hour analysis window. The data assimilation system is based on a 2006 version of the ECMWF Integrated Forecast Model. The spatial resolution of the model is T255 (~80 km) on 60 vertical levels from the surface up to 0.1 hPa (Dee et al., 2011). The data are continuously updated in real time from 1<sup>st</sup> January 1979 to present. The ERA-Interim fields are reliable across high southern latitudes from 1979 and are considered to be the best reanalysis data set for depicting recent Antarctic climate (Bracegirdle and Marshall, 2012). **They are typically considered to have the highest quality relative to other reanalysis data from the water cycle, with a better representation of mass fluxes including water vapour (Lorenz and****

Kunstamnn, 2012). ERA-Interim dataset has been also shown to significantly improve humidity fields in Antarctica and the Southern Ocean (Uppala et al. 2008; Simmons et al. 2010).

The vertically integrated water vapor transport (WVT) (Peixoto and Oort, 1992) is defined as follows:

$$\vec{Q}(u, v, t) = Q_u \vec{i} + Q_v \vec{j} \quad (1)$$

- 5 where  $Q_u$  is the vertical integral of eastward water vapour flux and  $Q_v$  the vertical integral of northward water vapour flux.

The station based monthly mean temperature data has been extracted from the Reference Antarctic Data for Environmental Research (READER). The primary sources of data are the Antarctic research stations and automatic weather stations. The stations used in the current study have been downloaded from the following website: <https://legacy.bas.ac.uk/met/READER/data.html>.

- 10 For the Southern Annular Mode (SAM) index, we used the index from <https://legacy.bas.ac.uk/met/gjma/sam.html>. SAM index is available over the period 1957 up to date and the index is computed from surface meteorological observations from Antarctic coastal and Southern Ocean island stations (Marshall, 2003). SAM is the dominant mode of low-frequency atmospheric variability in the Southern Hemisphere. The SAM index measures a "see-saw" of atmospheric mass between the middle and high latitudes of the Southern Hemisphere. Positive values of the SAM index correspond with stronger-than-average westerlies over the mid-high latitudes (50S-70S) and weaker westerlies in the mid-latitudes (30S-50S) (Marshall, 2003). All the anomalies (SIC, SLP, TT, IWV, QU, QV, HU and HV) used in this study were computed relative to the climatological period 1981–2010.

## 2.2 Methods

- 20 The *stability maps* approach used in this study is based on a methodology that was successfully applied to predict the monthly to seasonal streamflow of Elbe and Rhine rivers (Ionita et al., 2008, 2015, 2017; Meißner et al., 2017). The basic idea of the stability maps is to identify regions with stable teleconnections (the correlation does not change in time) between SIE averaged over specific regions and meteorological/climatological gridded data. As such, we correlate the regional sea ice index with IWV and T2m gridded fields in a 21-years moving window. The correlation is considered to be *stable* for those grid points where the sea ice index and the gridded fields are significantly correlated at 95%, 90%, 85%, and 80% significance level, for more than 80% of the 21-years moving windows. The regions where the correlation is positive and stable will be represented as dark red (95% significance level), red (90% significance level), orange (85% significance level) and yellow (80% significance level) on the stability maps (see Figure 6 and 7). The regions where the correlation between the regional SIE index and the gridded data is stable and negative will be represented as dark blue (95% significance level), blue (90% significance level), green (85% significance level) and light green (80% significance level) on the stability maps (see Figure 6 and 7). For the current analysis only regions, where the correlation is above 95% significance level, are retained for further analysis. The results remain qualitatively the same if the length of the moving window varies between 15 and 25 years. Although the length of our time series is relatively short (40 years) the methodology proved to work also in cases of timer series < 40 years (Ionita et al., 2017a). Moreover, we use the same methodology, with the same number of

years (40 years), for the prediction of September Arctic and Antarctic Sea Ice (<https://www.arcus.org/sipn/sea-ice-outlook/2017/post-season>). A more detailed description of the *stability maps* approach can be found in Ionita et al. (2008) and Ionita (2017a).

### 3 Results

#### 5 3.1 Daily and monthly Antarctic sea ice extent

Antarctic sea ice has shown increased SIE, area, and concentration from the late 1970's until 2015. Even though the trend itself is modest (Yuan et al., 2017), it is somewhat **challenging to explain** in the context of the overall global warming signal. When looking at the SIE anomalies over the last 38 years, the first **eight** months of 2016 are not particularly anomalous (not shown). Both July (**Figure S1a**) and August (**Figure S1b**) 2016 were characterized by **slightly positive pan-Antarctic SIE anomalies**. However, starting from September 2016, the situation changed dramatically. The Antarctic SIE from September 2016 until December 2016 was characterized by significant negative anomalies, with November 2016 and December 2016 ranking as the lowest SIE for those respective months in the sea ice record (**Figure S1**). November mean SIE was more than five standard deviation below the 1981-2010 average (Stammerjohn and Scambos, 2017). September 2016 ranks as the 7<sup>th</sup> in term of lowest SIE on record, while October 2016 ranks as the second in terms of lowest SIE.

15 To have a clear picture of the spatial pattern of the extreme events in the austral spring 2016, we have computed the SIC anomalies in each grid point, from September 2016 until December 2016 (**Figure 1**). In September 2016, most of the Antarctic region was characterized by negative SIC anomalies (**Figure 1a**), with some exceptions over the eastern part of the WS and the eastern part of RS, where positive SIC anomalies prevailed. The same spatial pattern was present also in October 2016 (**Figure 1b**), but with much higher amplitudes (SIC anomalies < 40%) over the IO, WS, and the western part of RS. In

20 November 2016, the negative SIC anomalies become very high in amplitude over the western part of the WS and western part of ABS (**Figure 1c**). Weak positive SIC anomalies were present over the western part of WS, as well as over the north-eastern part of RS, and south-eastern part of ABS. Over the WPO, the SIC anomalies reversed their sign (negative to positive) in November compared to October 2016. In December 2016, the whole RS was characterized by negative SIC anomalies (**Figure 1d**), as well as ABS (with some small exceptions over the eastern part) and IO.

25 When looking at the daily evolution of the SIE anomalies throughout the austral spring 2016, some **striking** features are present. In September 2016, most of the negative SIE anomalies at the circumpolar Antarctic level were mainly driven by the daily SIE anomalies **over IO and ABS** (**Figure S2**). In October 2016, all regions, except Weddell Sea, were characterized by daily negative SIE anomalies, especially IO. The situation became very dramatic in November 2016, when daily negative SIE anomalies were recorded over all the analyzed regions (**Figure S2**), especially IO and WS (**in the second part of**

30 **November**). The combined effect of all regions, showing daily negative SIE anomalies throughout entire November 2016, was a SIE anomaly **below -2.2 Mio. km<sup>2</sup> around 20<sup>th</sup> of November**. In December 2016, the extreme daily SIE anomalies continued the decreasing trend, **with a SIE anomaly below -2.7 Mio. km<sup>2</sup> occurring in the middle of the month**. Most of the

contribution for the extreme SIE anomalies in December 2016 was coming from the WS. By analyzing the daily SIE anomalies throughout the year 2016, one of the most striking features is the abrupt drop of SIE of more than 1.7 Mio. km<sup>2</sup> from the beginning of November 2016 until the middle of December 2016, which is unprecedented since the beginning of the 1980's (not shown).

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### 3.2 Climatological analysis of the austral spring 2016

In September 2016, the atmospheric circulation features a center of negative SLP anomalies over the Antarctic continent flanked by three centers of positive SLP anomalies: one over the RS, one over IO, and one over WS. This SLP pattern was associated with positive temperature anomalies over the ABS, WS, IO, and eastern WS and negative temperature anomalies over most of the Antarctic continent, except the Antarctic Peninsula (Figure 2a). The three positive SLP centers were positioned in such a way that they enhanced the poleward advection of moist (Figure 3a) and warm air (Figure 4a), especially over IO, eastern RS, WS, and Bellingshausen Sea (Figure 2e). The areas, characterized by positive temperature anomalies and enhanced water vapor, correspond to the regions where the negative SIC anomalies, were occurring in September 2016 (see Figure 1a).

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In October 2016, the atmospheric circulation was more meridional and wavier, with altering positive and negative SLP anomalies surrounding the Antarctic continent (Figure 2b). SAM had a value of -0.89, ranking as the 14<sup>th</sup> lowest SAM index on record. This wavy SLP pattern favored, again, the advection of moist (Figure 3b) and warm air (Figure 4b) towards the continent and the coastal areas, the most affected regions in terms of sea ice reduction, corresponding to the regions where warm and moist intrusions occurred: WS, IO, ABS, and western WPO. October 2016 was also characterized by widespread warm anomalies along the coastal areas as well as in the interior of the continent, with some exceptions (Figure 2f). In November 2016, SAM index dropped to a value of -3.12, which ranks as the fifth lowest SAM index since 1958 (Stamerjohn, 2016). In terms of large-scale atmospheric circulation, an anomalous high pressure system developed over the polar cap, which resulted in the weakening of the westerlies. The high pressure system over the southern polar cap was surrounded by a band of negative SLP anomalies, stretching from IO - WPO - RS up to ABS (Figure 2c). Extreme positive temperature anomalies were recorded over the whole southern polar cap and the coastal areas (Figure 2h). Moreover, over ABS, WS, and RS, enhanced advection of moist (Figure 3c) and warm (Figure 4c) air from the lower latitudes led to a rapid melting of the sea ice over these regions (Figure 1c).

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In December 2016, the atmospheric circulation was similar to November 2016: high pressure system over the southern polar cap, surrounded by negative SLP anomalies over WS and IO (Figure 2d). The December value of the SAM index (-1.52, 10<sup>th</sup> lowest for December since 1957) was much smaller compared to November 2016. This is also visible in the amplitude of the SLP anomalies, over the polar cap, between the two months, with December 2016 featuring weaker (in amplitude) positive SLP anomalies over the Antarctic Continent and smaller temperature anomalies (by a factor of 4 between November 2016 and December 2016). In December 2016, positive (but weak) temperature anomalies prevailed over most of the

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Antarctic Continent, except for the central part (Figure 2h). Moist (Figure 3d) and warm (Figure 4d) conditions were also recorded over RS and parts of the coastal regions of IO and WPO (Figure 2h).

### 3.3 Long-term context of the austral spring 2016 event

5 To demonstrate that austral spring 2016 was a very exceptional year in terms of reduced SIC and warm and moist conditions over the Antarctic region and the surrounding areas, we have computed the rank maps for the monthly (September – December) SIC (Figure 5 – first column), IWV (Figure 5 – middle column), and T2m (Figure 5 – third column) over the period 1979 -2016. The red areas in Figure 4 indicate that 2016 was the year with the lowest SIC, the moistest, and the warmest year on record, over the period 1979 – 2016. The orange colors indicate that 2016 was the second lowest year in  
10 SIC, moisture, and warmth and so on. For clarity we have chosen only the top 5 ranks. The idea of ranking maps has been successfully used before to emphasize the “exceptionality” of a particular year/season/month (Ionita et al., 2017).  
September 2016 was the month with the lowest SIC over distinct areas in the WS, RS, and ABS, and ranks among the top five years with the lowest SIC over an extended band in the central IO (Figure 5a). The regions with the lowest SIC, in September 2016, were also the moistest (Figure 5b) and warmest (Figure 5c) on record. The regions with the lowest SIC in  
15 October 2016 (Figure 5d) are similar to the ones from September 2016, but the spatial extent of low SIC anomalies is larger compared to September 2016. October 2016 stands out as the moistest and warmest year on record over large areas covering the surroundings of Antarctica: almost the entire IO region stands out as the moistest and warmest on record, with small exceptions in the western part of it; the southern part of RS was also among the moistest and warmest regions on record, while the whole Bellingshausen Sea stands out in the first five moistest and warmest October on record (Figure 5e and 5f).  
20 The largest regions affected by low SIC were recorded in November 2016 (Figure 5g), with central IO, south-eastern RS, and small parts of WS being the areas with the lowest SIC on record. In terms of moist and warm, the regions that stand out as very extreme, in November 2016, are located over the western part of RS, and the eastern part of Antarctica as well as over the WS (Figure 5h and 5i). Around the coastal areas of East Antarctica all stations where measurements are available recorded the highest monthly mean temperatures in October and November 2016 (Casey: -3.7°C; Davis: -2.2°C, Syowa: -  
25 4.7°C, Figure 6a and 6b) (Keller et al., 2017). In December 2016, the spatial extent of the extreme low SIC is much smaller (Figure 5j) compared to the previous months, being restricted just to the southern part of RS and eastern part of ABS. The same is valid for IWV and TT. The north-eastern part of RS ranks as the moistest on record (Figure 5k), while small regions in WS rank as the warmest on record (Figure 5l).

### 30 3.4 Long term relationship between regional Antarctic sea ice, moisture availability and temperature

As shown in Section 3.3, the period October - December 2016 was characterized by large positive anomalies in the surface temperature and the vertical integral of water vapor covering large areas in the Antarctic region (Figure 2 and Figure 3). To examine the long-term relationship between moisture and temperature on one hand and the regional Antarctic sea ice variability on the other hand we have computed the stability maps between IO SIE (November) and IWV and T2m (October

and November), as well as the stability maps between WS SIE (December) and November and December IWV and T2m (November and December), over the period 1979 – 2016. We performed the analysis, both in phase as well as with 1-month lag (IWV and T2m leading the regional SIE index) to have a clear picture of the relationship between SIE and IWV and T2m. We opted for November IO SIE and December WS SIE due to the fact that the highest SIE anomalies were recorded over these particular regions in 2016 (Figure S2 and Table 1).

The stability maps between November IO SIE and October/November IWV and T2m are shown in Figures 7a-d. In general, negative SIE anomalies over IO, in November, tend to occur in association with enhanced moisture and positive temperature anomalies over IO region in the previous month. In agreement with the findings in Section 3.3, year 2016 stands out as the most extreme one both in terms of SIE and moisture availability. Based on the stable regions identified in Figures 7a-d (marked by yellow boxes) we defined two indices: one for October IWV (IWV averaged over the yellow box in Figure 7a) and one for October T2m (T2m averaged over the yellow box in Figure 7c). For the in-phase stability maps (Figures 7b and 7d), the stable regions are very small and very regional and we did not consider them for further analysis. The correlation coefficient between November IO SIE and October IWV index is  $r = -0.62$  (99% significance level), while the correlation coefficient between November IO SIE index and October T2m index is  $r = -0.63$  (99% significance level).

The stability maps between December WS SIE and November/December IWV and T2m are shown in Figure 7a-d, respectively. In the case of December WS SIE, the stability maps show extended stable regions, having a dipole-like structure, both for November IWV and November T2m (marked by yellow and green boxes). Positive SIE anomalies over WS, in December, are associated with negative IWV and T2m anomalies over the WS region and positive IWV and T2m anomalies over RS, in the previous November. Based on the stability maps in Figure 8a-d, we have defined five indices (yellow and green boxes in Figure 8a, 8c and 8d). As in the case of November IO, the stable regions are more extended for 1-month lag analysis. The correlation coefficient between December WS SIE and November IWV1 index is  $r = -0.68$  (99% significance level) and the correlation between December WS SIE index and November T2m1 index is  $r = -0.60$  (99% significance level). The correlation coefficient between December WS SIE and November IWV2 (T2m2) index is  $r = 0.34$  (0.45), while the correlation coefficient between December WS SIE and December T2m index is  $r = -0.35$ . Negative SIE anomalies, over WS in December, are occurring in association with enhanced moisture and positive temperature anomalies over the WS and reduced moisture and negative temperature anomalies over RS, in the previous month.

The significant lagged relationship between the regional SIE and previous month IWV and T2m can be used as potential predictive information for the development of the upcoming SIE over particular regions. The same analysis can be performed for other regions or at pan-Antarctic level and by including other climate/oceanic variables. Since the focus of our paper was to see the influence of the moisture and temperature on the development of the Antarctic sea ice extreme event in the austral spring of 2016, here we focused just on IWV and T2m.

### 3.5 Daily evolution of the integrated water vapor transport in 2016

So far we have considered only monthly means, but a signal that is visible at monthly time scale has to have been predominant over a part of the month or extreme over particular days throughout the month (Schlosser et al., 2018). The later was the case for the moisture intrusions towards the Antarctic region, in October and November 2016, respectively. To emphasize the importance of these extreme daily moisture intrusions, based on the rank maps shown in Figure 4, we have defined two indices over the regions which rank as the moistest on record in October and November (black squares in Figure 5e and 5f). These indices have been computed by spatially averaging the daily vertical integral of water vapor over the months of October and November from 1979 until 2016. The two regions are defined over IO (Figure 9a) and WS (Figure 10a).

Over IO, there were two extreme events occurring in October 2016: one on the 3<sup>rd</sup> of October (Figure 9b) and the second one occurring on the 26<sup>th</sup> of October (Figure 9c). For these two extreme events the vertical integral of water vapor shows a band of enhanced moisture stretching from the IO towards the coastal eastern part of Antarctica (Figure 9b and 9c). The regions with the highest IWV are located over the IO (black squares in Figure 9b and 9c). Both events show clearly narrow bands, where the moisture fluxes are concentrated. These kind of events, also known as atmospheric rivers (ARs), have been associated with the occurrence of anomalous snow accumulation in east Antarctica (Gorodetskaya et al., 2014). In general, ARs transport large amounts of warm and humid air.

In November 2016, there were also two extreme events occurring (in terms of moisture transport): one on the 3<sup>rd</sup> of November (Figure 10a and 10b) and the second one on the 16<sup>th</sup> of November (Figure 10a and 10c). Although the IWT index is defined over a restricted area in the WS, when looking at the vertically integrated total moisture transport (vectors in Figure 9b and 9c) and the associated IWV values, a very particular picture emerges. During these two particular events, the WS, IO, WPO and ABS were under the influence of the advection of moist and warm air from the mid-latitudes. WS received enhanced moisture from the Tropical South Atlantic Ocean, IO received a band of enhanced moisture both from the Tropical South Atlantic Ocean as well as from the IO, and WPO received a lot of moisture from the IO. The combined effect of this enhanced moisture advection from the tropics, which happened simultaneously in WS, IO, WPO and ABS could, at least partly, explain the extremely low values of the daily SIE throughout the whole month of November 2016 and the beginning of December (Figure S2). Looking at the daily vertically integrated total moisture transport, we can observe that moisture sources are coming from the tropical parts of the Pacific Ocean (for ABS and RS), Atlantic Ocean (for WS and IO), and Indian Ocean (for IO and WPO). This is in agreement with a recent study of Drumond et al. (2016), who show that the most important moisture sources for the Antarctic ice cores are: the subtropical South Atlantic Ocean, Indian Ocean, and South Pacific Ocean.

### 4 Discussion and conclusions

An initial attribution of the Antarctic conditions throughout the 2016 austral spring indicates that the atmospheric circulation in the SH was very anomalous. The SAM was negative from October 2016 until December 2016, with top negative value of

-3.12 in November 2016 (the fifth lowest SAM since 1958). The persistence of the negative phase of SAM throughout these three months is associated with a weakening of the circumpolar westerlies and an overall surface warming of the coastal parts of the Antarctic continent, as well as large parts inside the continent. The overall warming accompanied by enhanced poleward advection of warm and moist air led to strong sea ice melting, especially in October and November.

5 Tietäväinen and Vihma (2008) have shown that poleward water vapor transport, especially over the RS, WS, and IO, is usually associated with the SAM wave number three. This is in good agreement with our findings, especially for the months of October and November 2016.

The results presented in our study can be regarded as an additional contribution regarding the drivers of the 2016 extremely low sea ice event over the Antarctic region. In previous studies regarding the 2016 event, Turner et al. (2017) related this low SIE to the warm air advection and the strong negative values of SAM in November and December. Schlosser et al. (2018) have shown that the rapid decrease in the sea ice area and extent were associated with atmospheric flow patterns reminiscent to a positive zonal wave number 3 (ZW3) index, which triggered accelerated sea ice decline, especially at the beginning of November. Stuecker et al. (2017) showed that the extreme low SIE in November-December 2016 was partially driven by the 2015/16 El-Niño event and the negative phase of SAM. In our study, we show that enhanced moisture and positive temperature anomalies over different parts of the Antarctic region (e.g., IO, WS, RS) have led to the extremely low SIE recorded throughout the austral spring 2016. In October and November 2016, when the lowest daily SIC anomalies were observed, repeated episodes of poleward advection of warm and moist air took place, with the most intense episodes occurring in October and November 2016. Moreover, October 2016 ranks as the moistest and warmest October over the last 39 years, over large areas in the IO, ABS and RS (Figure 5e and 5f), while November ranks as the moistest and warmest November over extended parts over WS, WP and WS (Figure 5h and 5i). In this study, we have shown that negative SIE anomalies at regional level (e.g. IO and WS) are preceded by enhanced moisture and positive temperature anomalies over these regions, one month ahead. The lagged relationship between the regional SIE anomalies and previous month IWV and T2m could be used to provide a potential predictive skill for the upcoming development of the regional sea ice extent anomalies.

25 Given the dramatic SAM anomalies in some months, we investigated also the long term relationships between regional SIE and the monthly SAM (Table 2). However, significant relationships were found only for three month-region combinations and thus consistent with previous studies (Stammerjohn et al., 2008; Lefebvre et al., 2004; Holland et al., 2017; Liu et al., 2004; Simpkins et al., 2012). In September, significant correlations between SAM and regional SIE are found just for WS ( $r = -0.37$ , 95% significance level), while for the other regions, the correlations are not significant. Throughout the month of October, no significant correlations are found between monthly SAM index and the regional Antarctic SIE, while for November significant correlations are found just between the SAM index and IO ( $r = 0.43$ , 99% significance level). In December, significant correlations are found between the SAM index and RS ( $r = 0.46$ , 99% significance level). Overall, positive SAM in September occurs in association with negative SIE anomalies over WS, while in November positive SAM tend to be associated with positive SIE over IO. In December, a positive SAM index is associated with positive SIE over RS.

Our analysis indicates that SAM's role in sea ice variability is rather complex and dependent of the region under consideration.

Although at Antarctic level no significant trends in the meridional moisture fluxes over the period 1979-2010 have been observed (Tsukernik et al., 2013), the austral spring 2016 stands out as very extreme in this respect, with 2016 ranking as the moistest (Figure S3a) and warmest austral spring on record (Figure S3b), over large areas covering Antarctica and the surrounding seas. The same holds for the Arctic region, boreal autumn 2016 ranking as the moistest and warmest autumn on record over almost the whole Arctic basin (Figure S3c and Figure S3d). Generally speaking, both austral spring and boreal autumn 2016 have been characterized by enhanced poleward advection of moist and warm air. This exceptional event, occurring simultaneously in both polar regions, might be a direct or indirect consequence of the combined effect of 2015/16 El Niño event (Stuecker et al., 2017) and the fact that 2016, as a whole, was the warmest year on record (NOAA, 2017). Together, these two exceptional events could have triggered the release of large amounts of moisture in the atmosphere and via particular large-scale atmospheric circulation patterns (e.g. Rossby waves, weaker jet stream) parts of this moisture have been carried out towards the poles.

In order to have a clear picture of the physical mechanisms which relates IWV and T2m to the variability of the Antarctic SIE complementary modelling simulations are needed. By using observational/reanalysis data alone it is difficult to disentangle which of the potential drivers (e.g., IWV and T2m) has a stronger impact on the sea ice variability. For the Arctic region, previous studies (Mortin et al., 2016; Kapsch et al., 2013; Park et al., 2015) suggested that the transport of heat and moisture into the Arctic during spring enhances the incoming surface longwave radiation, thereby controlling the initiation of the annual ice melt and setting the stage for the Arctic September ice minimum. Thus, our study can be used as an indicator that moisture transport should be considered in future studies as a potential driver of the Antarctic sea ice variability.

From the perspective of future climate projection, our results imply that a realistic simulation of the Antarctic SIE trend and variability requires also a proper simulation of both climate modes of variability (e.g., SAM) as well as extreme events (e.g., moisture intrusions, Rossby waves, atmospheric blocking). Concluding, the 2016 austral spring event demonstrates that the present-day climate of the Antarctic continent and the surrounding areas allow for extensive sea ice reduction to occur. If such events are going to occur more frequently in the future is uncertain, but it is essential to understand and highlight the mechanisms responsible for triggering such events.

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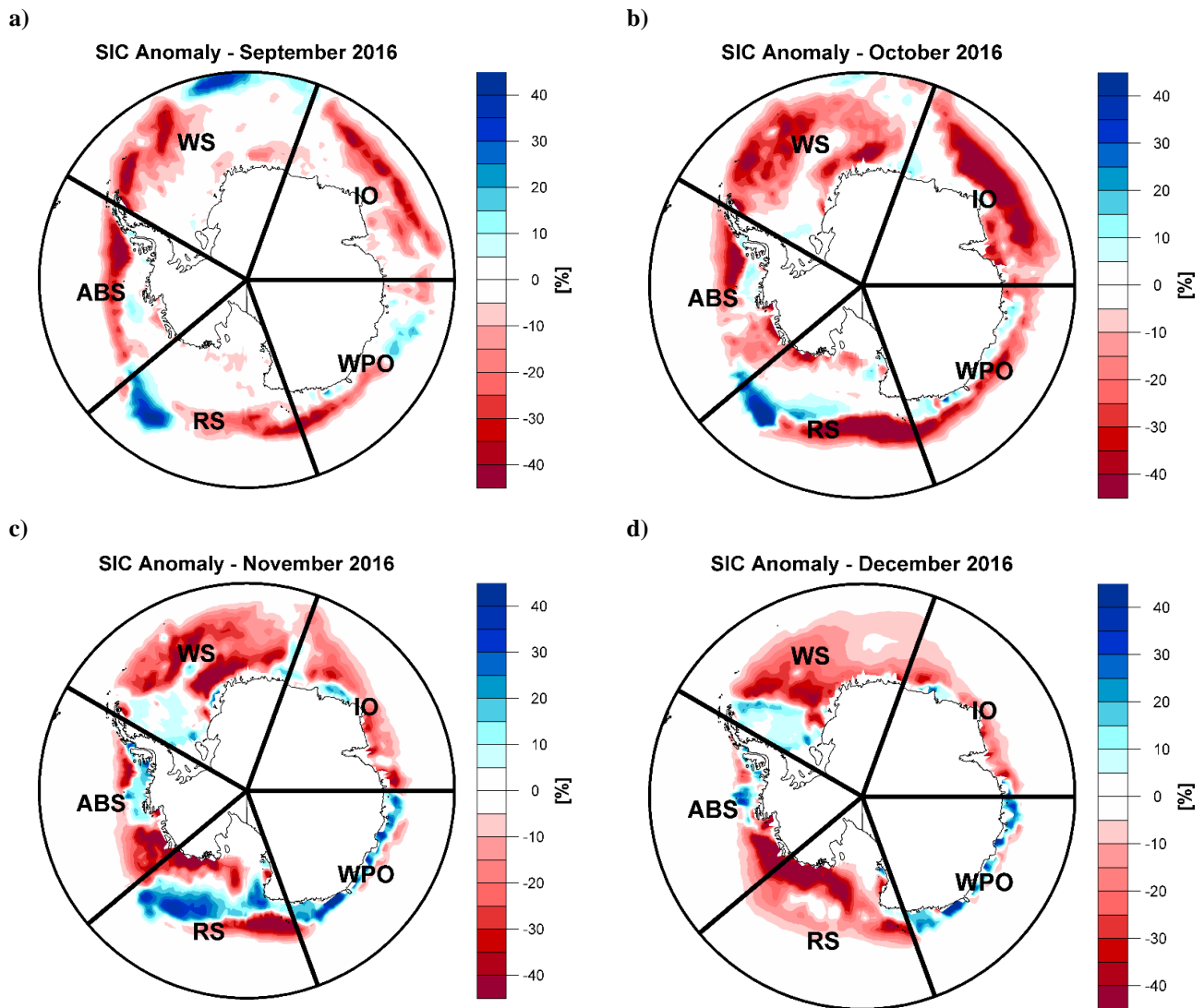
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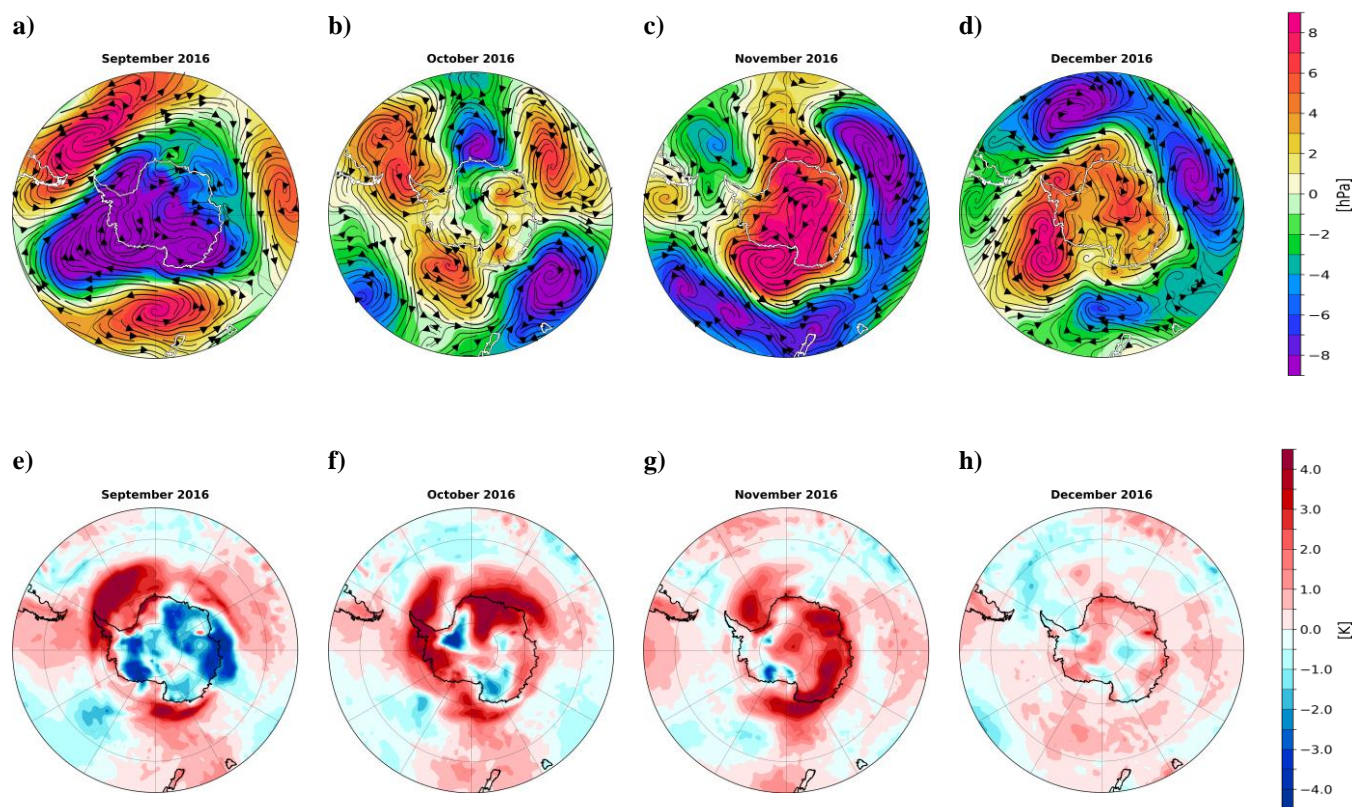
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**Figure 1.** Sea ice concentration (SIC) anomalies 2016 for: a) September; b) October; c) November and d) December. The anomalies are computed relative to the reference period 1979 – 2010. WS = Weddell Sea; IO = Indian Ocean; WPO = Western Pacific Ocean; RS = Ross Sea; ABS = Amundsen - Bellingshausen Sea.

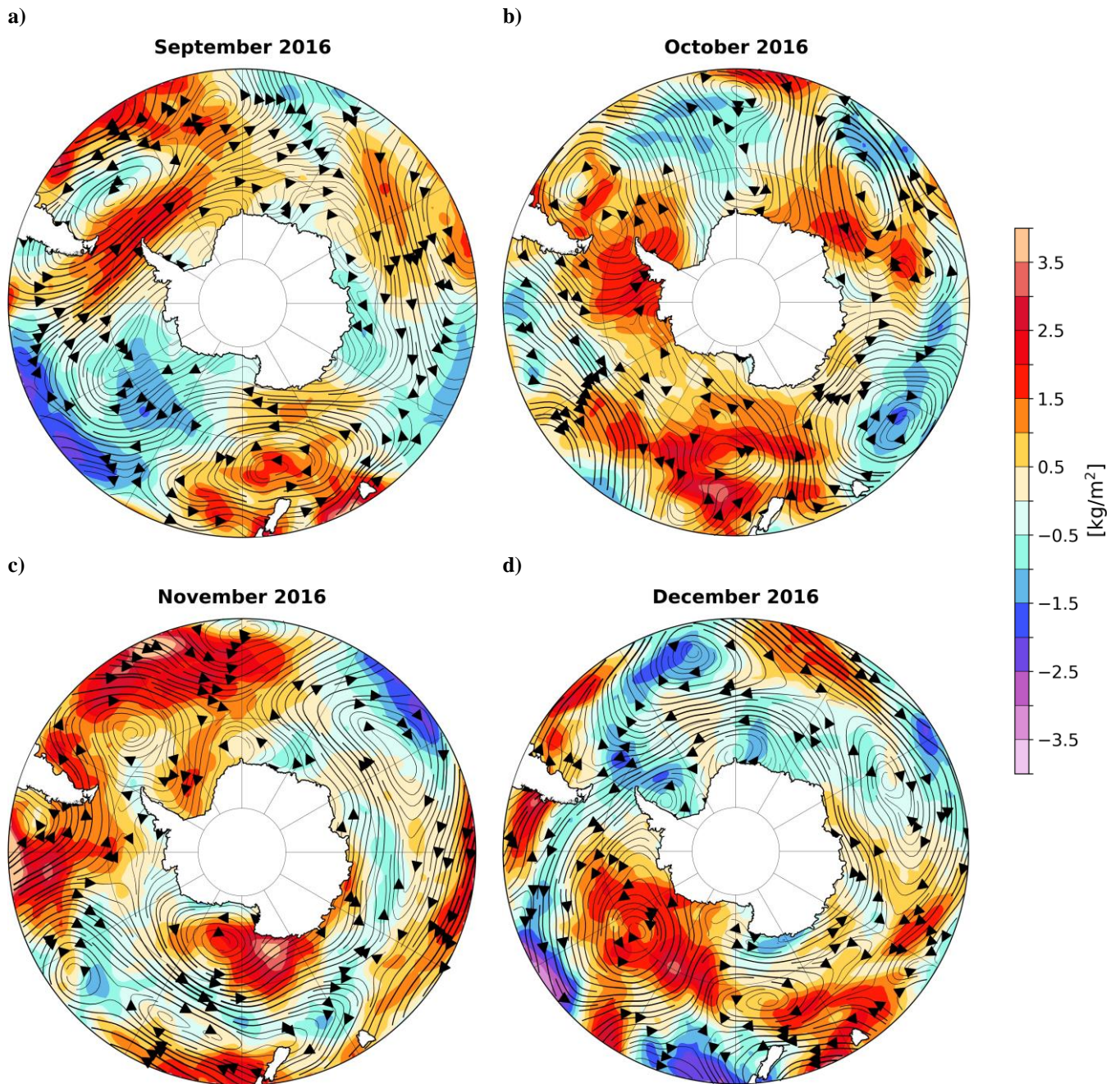


**Figure 2.** Sea level pressure (SLP) anomalies and the associated wind streamlines (upper panels) and 2m air temperature (T2m) anomalies (lower panels) from September until December 2016. The anomalies are computed relative to the reference period 1979 – 2010.

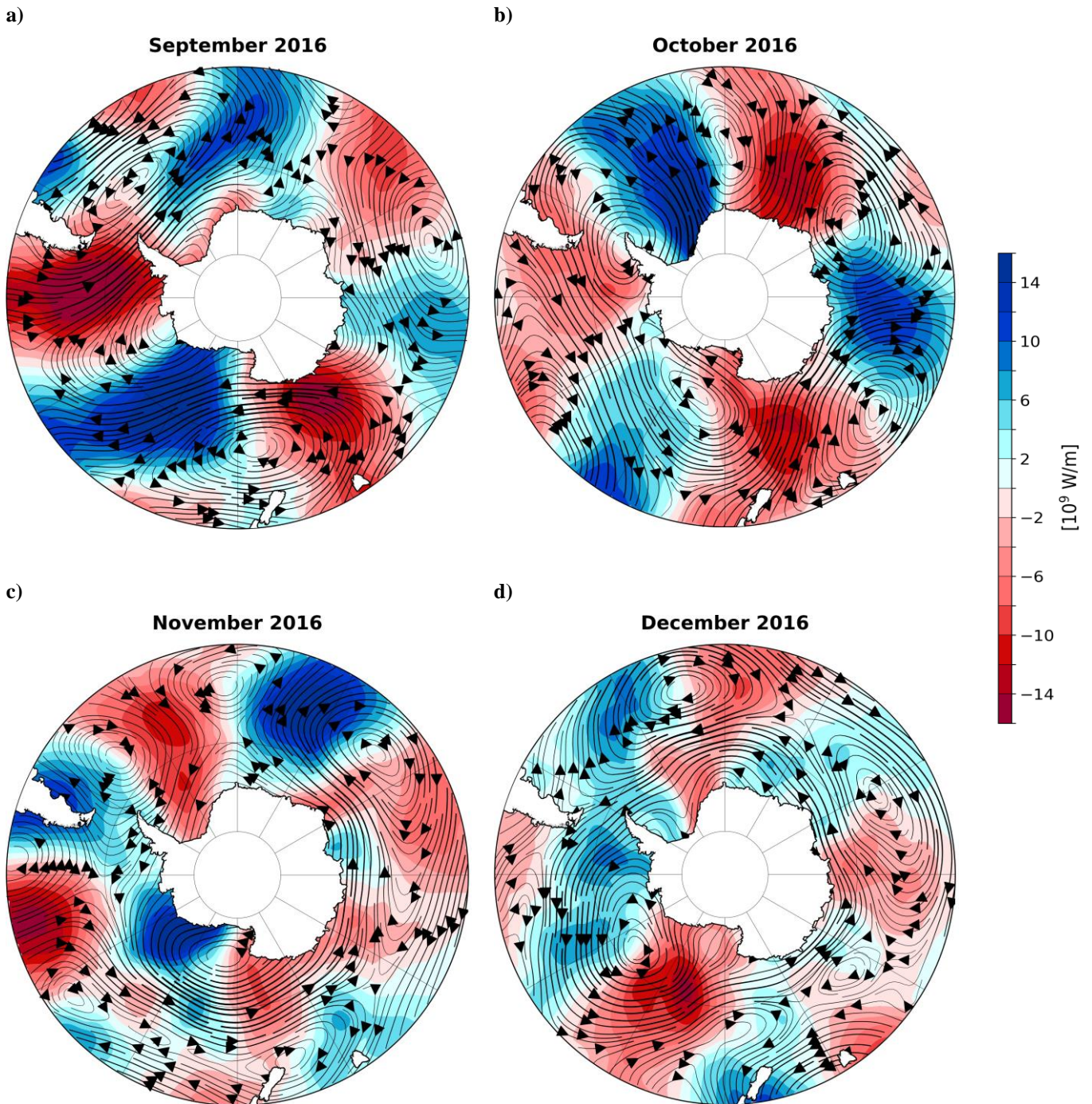
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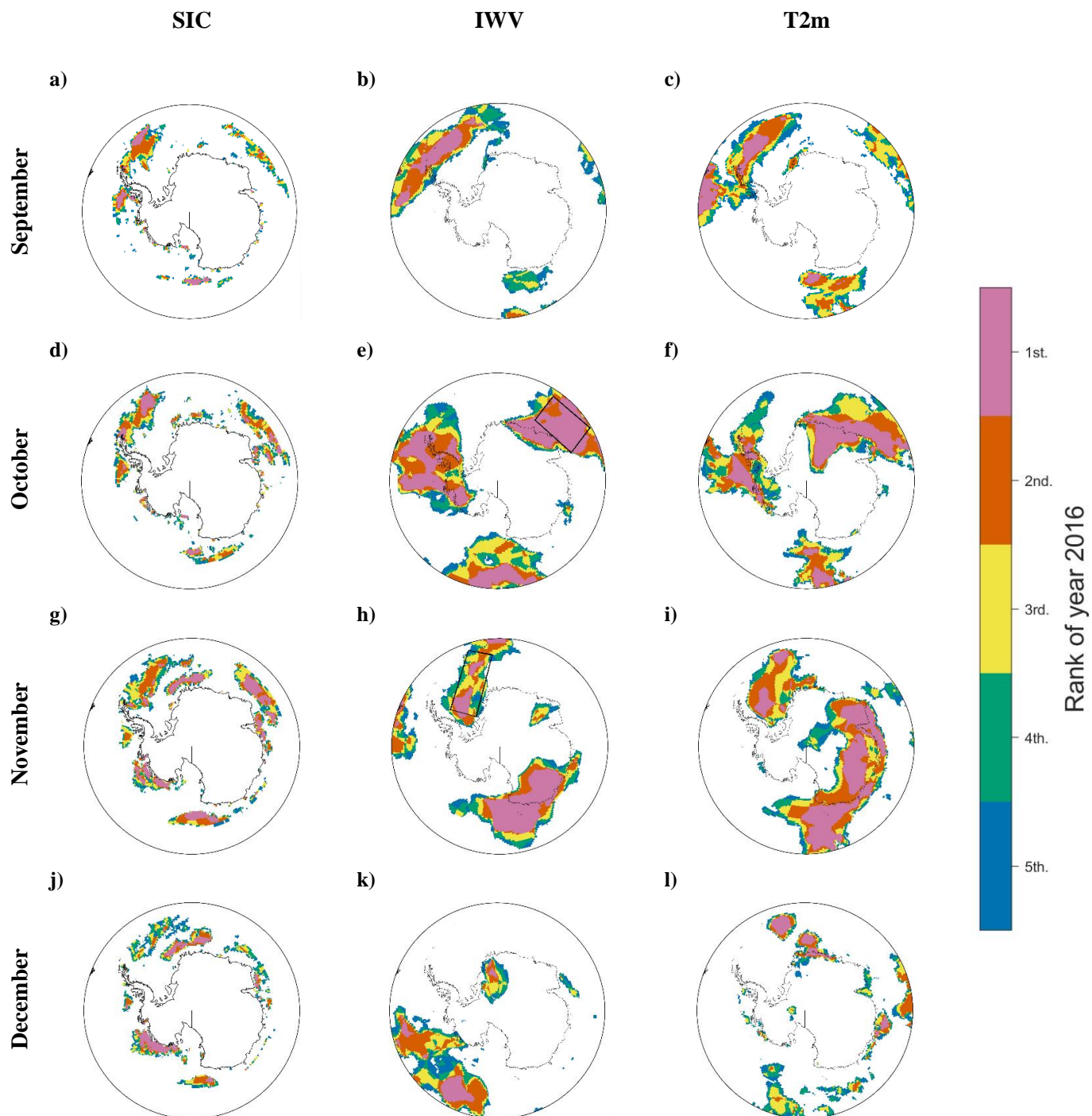
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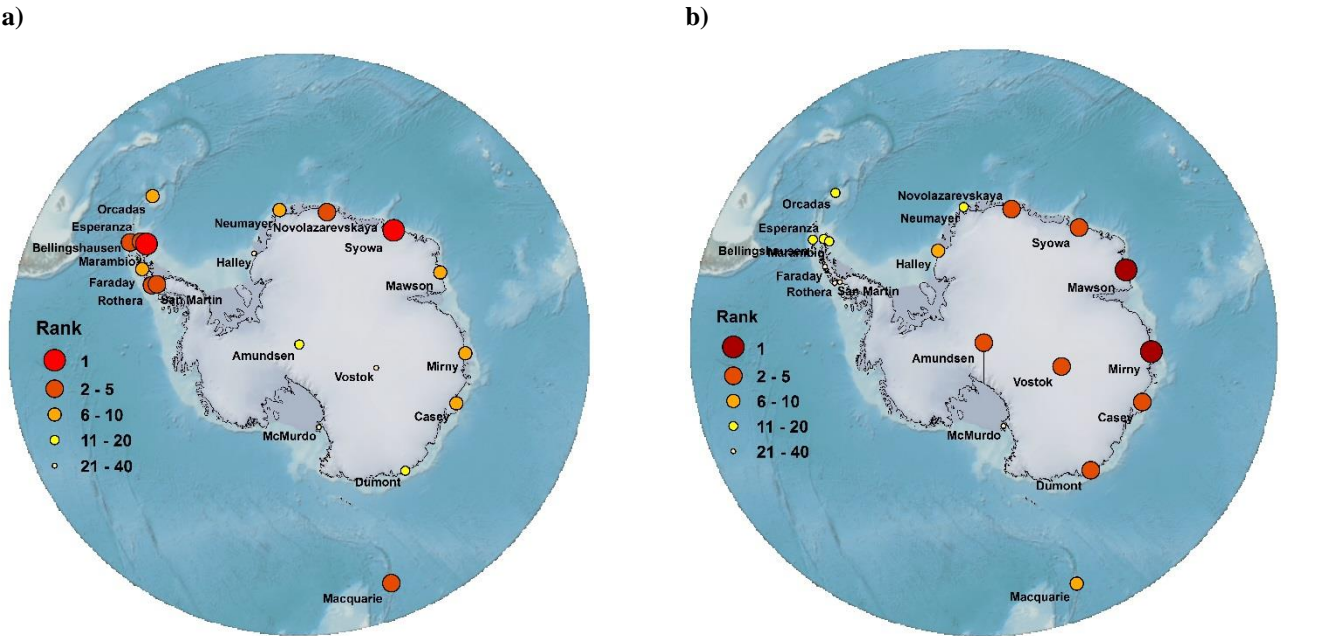
**Figure 3.** The vertical integral of water vapor anomalies (IWV, shaded areas) and the vertically integrated water vapor transport (WVT, streamlines) from September until December 2016. The anomalies are computed relative to the reference period 1979 – 2010.



**Figure 4.** The vertical integral of northward heat flux (shaded areas) and the vertically integrated heat transport (streamlines) (lower panels) from September until December 2016. The anomalies are computed relative to the reference period 1979 – 2010. In a) – d) positive anomalies indicate northward advection and negative indicates southward advection.



**Figure 5.** Ranking of 2016 monthly: Sea ice concentration (SIC - first column, '1' means lowest SIC over the analyzed period), the vertical integral of water vapor (IWV – second column, '1' means the moistest month over the analyzed period); 2m air temperature (T2m – third column, '1' means the warmest month over the analyzed period). Analyzed period: 1979–2016. Rankings below 5 appear white.

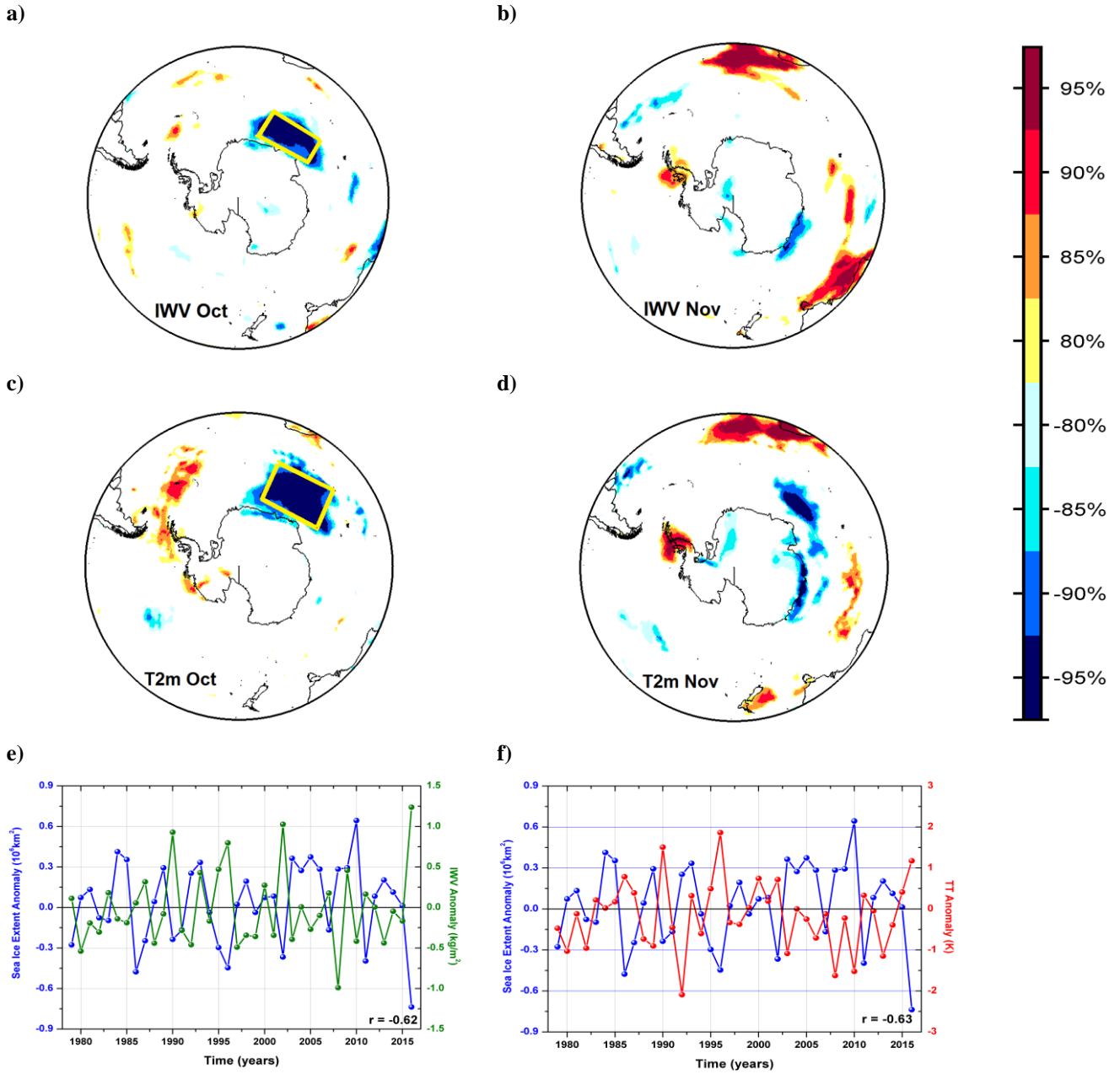


**Figure 6.** Ranking of the monthly mean temperature at observation stations: a) October 2016 and b) November 2016. Number “1” means the warmest month since 1981, number “2” signifies the second warmest, etc. Analyzed period: 1981–2016.

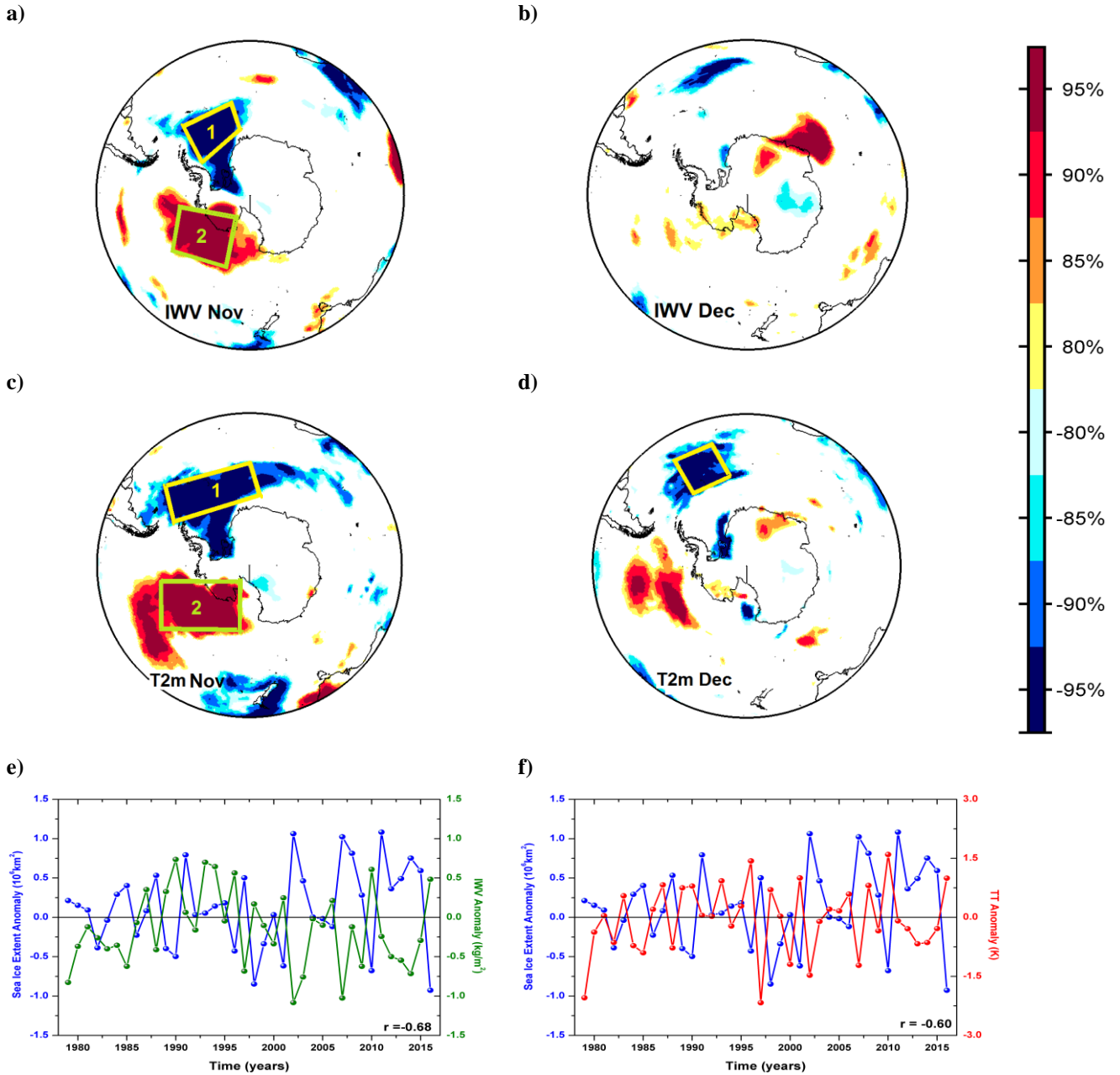
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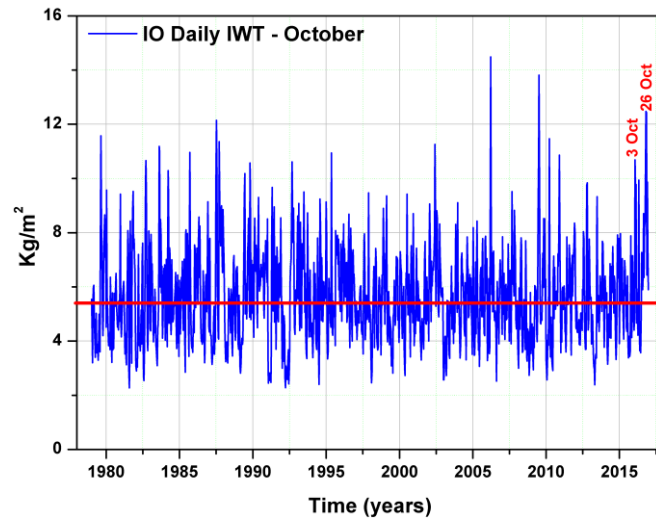


**Figure 7.** The stability maps between November Indian Ocean (IO) sea ice extent and a) October IOW; b) November IOW; c) October T2m; d) November T2m; e) The time series of November IO SIE (blue line) and the time series of October IOW (green line) averaged over the yellow box in a); f) The time series of November IO SIE (blue line) and the time series of October T2m (red line) averaged over the yellow box in c). The regions where the correlation is positive and stable are represented as dark red (95% significance level), red (90% significance level), orange (85% significance level) and yellow (80% significance level) and the regions where the correlation between the regional SIE index and the gridded data is stable and negative will be represented as dark blue (95% significance level), blue (90% significance level), green (85% significance level) and light green (80% significance level) on the stability maps.

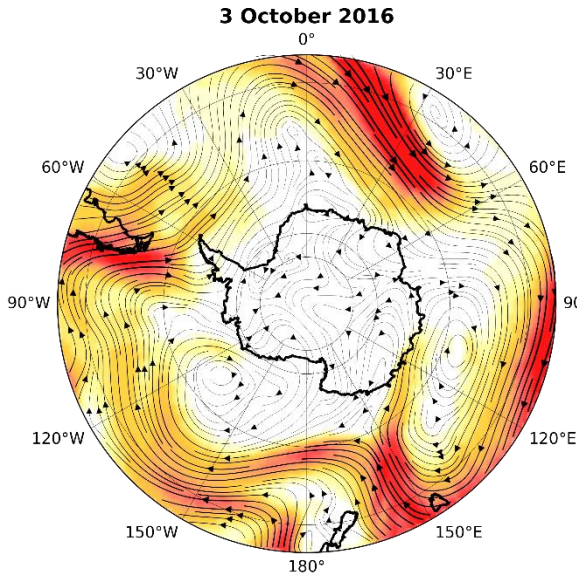


**Figure 8.** The stability maps between December Weddell Sea (WS) sea ice extent and a) November I WV; b) November T2m; d) December T2m; e) The time series of December WS SIE (blue line) and the time series of November I WV1 (green line) averaged over the yellow box in a); f) The time series of December WS SIE (blue line) and the time series of November T2m1 (red line) averaged over the yellow box in b). The regions where the correlation is positive and stable are represented as dark red (95% significance level), red (90% significance level), orange (85% significance level) and yellow (80% significance level) and the regions where the correlation between the regional SIE index and the gridded data is stable and negative will be represented as dark blue (95% significance level), blue (90% significance level), green (85% significance level) and light green (80% significance level) on the stability maps.

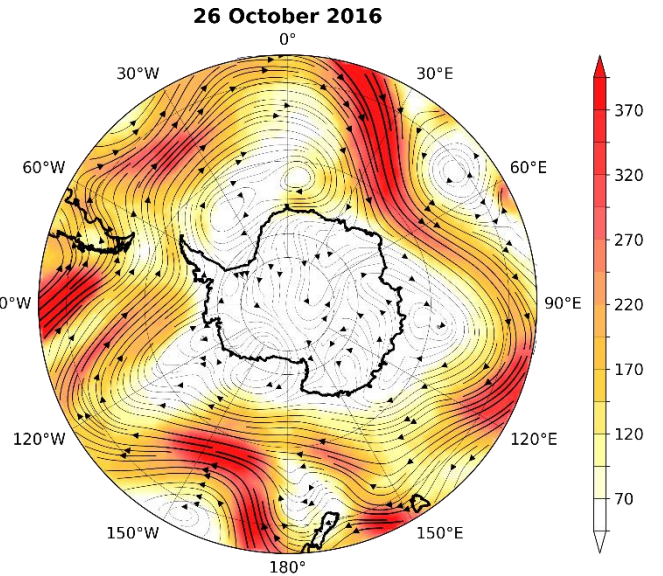
a)



b)

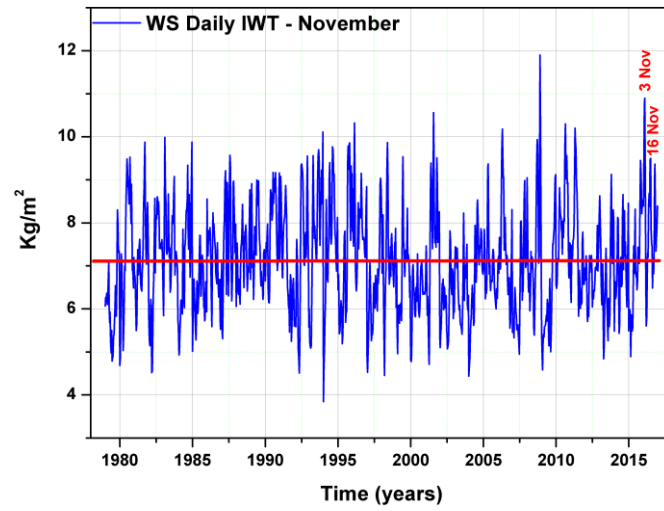


c)

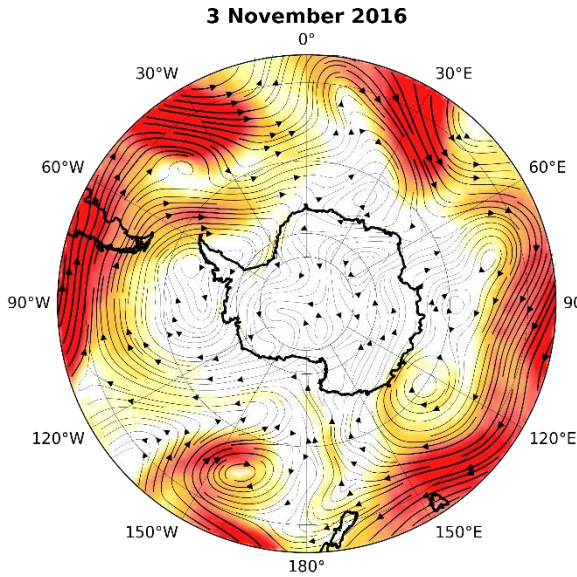


**Figure 9.** a) Daily IWT averaged over IO (black square in Figure 4e) over the period 1979 – 2016; b) The vertically integrated water vapor transport (WVT) on the 3<sup>rd</sup> October 2016 and c) as in b) but for the 26<sup>th</sup> October 2016. In b) and c) the color shaded areas indicated the magnitude of the moisture transport and the vectors the direction of the moisture transport.

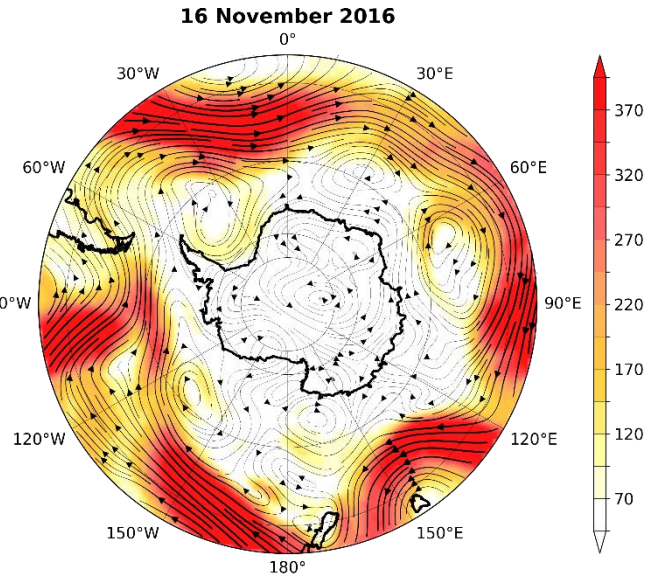
a)



b)



c)



**Figure 10.** a) Daily IWT averaged over WS (black square in Figure 4h) over the period 1979 – 2016; b) The vertically integrated water vapor transport (WVT) on the 3<sup>rd</sup> November 2016 and c) as in b) but for the 16<sup>th</sup> November 2016. In b) and c) the color shaded areas indicated the magnitude of the moisture transport and the vectors the direction of the moisture transport.

*Table 1.* Rank of regional Sea Ice Extent from September to December 2016.

	September	October	November	December
ABS	5	4	8	4
IO	2	2	1	2
RS	10	2	1	2
WP	15	11	1	22
WS	32	27	12	1
ANT	3	2	1	1

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**Table 2.** Correlation coefficients between regional sea ice extent (SIE) and monthly Southern Annular Mode (SAM)

	<b>September</b>	<b>October</b>	<b>November</b>	<b>December</b>
<b>ABS</b>	0.21	0.23	0.09	0.10
<b>IO</b>	0.07	0.17	<b>0.43**</b>	0.31
<b>RS</b>	-0.25	-0.03	0.05	<b>0.46**</b>
<b>WPO</b>	0.04	0.07	0.05	0.16
<b>WS</b>	<b>-0.37*</b>	-0.29	-0.13	0.20

\* 95% significance level

5 \*\* 99% significance level