The authors would like to thank the two anonymous reviewers who have made thoughtful and insightful comments on this paper. Below, we provide a comment-by-comment response to each reviewer.

Reviewer 1

P1L15: I am unconvinced that the ocean is a dominant driver of retreat variability, and this paper shows atmospheric influences on retreat variability that are at least as important as those on advance.

Response – The sentence in the abstract has been revised to remove the reference to the ocean being a dominant driver during retreat.

From: Atmospheric influence on sea ice is known to be strongest during its advance, with the ocean emerging as a dominant driver of sea ice retreat; therefore, while it appears that models are able to capture the dominance of the atmosphere during advance, simulations of ocean-atmosphere-sea ice interactions during retreat require further investigation.

To: Atmospheric influence on sea ice is known to be strongest during its advance, and it appears that models are able to capture the dominance of the atmosphere during advance. Simulations of ocean-atmosphere-sea ice interactions during retreat, however, require further investigation.

P1L19: the simulations only have an amplified SAM in terms of fraction of variability contained; the SAMs in the models could be of accurate absolute magnitude relative to observations??

Response – The word ‘amplified’ has been removed to avoid confusion; the absolute magnitude of the models relative to the observations is now discussed in the results section.

P3L1: ‘divergent’ implied ice divergence to me

Response – ‘divergent’ has been replaced with ‘contrasting’.

From: The divergent sea ice trends of the Amundsen/Bellingshausen and Ross Seas are associated with the deepening of the ASL in recent decades (Turner et al., 2013b).

To: The contrasting sea ice trends of the Amundsen/Bellingshausen and Ross Seas are associated with the deepening of the ASL in recent decades (Turner et al., 2013b).

P3: There is a GRL paper in press by Kwok et al. “Linked trends in the South Pacific sea ice edge and Southern Oscillation Index” that suggests a link between SOI and the winter ice edge in the south Pacific.

Response – reference has been included in the paper:

The high-latitude atmospheric response to ENSO is linked to sea ice anomalies in the Amundsen, Bellingshausen, Ross and Weddell Seas (Karoly, 1989; Harangozo, 2000; Kwok and Comiso, 2002; Yuan, 2004; Stammerjohn et al., 2008; Bernades Pezza et al., 2012), with recent work indicating that trends in the south Pacific ice edge during winter can be explained by changes to ice drift and surface winds resulting from a positive trend in the Southern Oscillation Index (Kwok et al., 2016).

P4L5: and other places: What happened to September?

Response – According to the calculations of Raphael & Hobbs (2014), sea ice in the different sectors around Antarctic stops advancing during August, instead maintaining the winter maximum throughout September before beginning its retreat in October. The only exception was the King Hakon VII sector which reached its maximum later than the others and began its retreat one month later; however, to compare like with like, we used the majority advance period for all sectors in this study. None of the sectors had an extended minimum, which is why the end of retreat and start of advance do not have a gap.

P4L20: When this sentence says total ice area, it sounds like the definition of ice area (the area integral of ice concentration), not ice extent (the total area of ocean with ice concentration 15% or above). Which do the authors mean?

Response – We mean sea ice extent here; as stated in the manuscript, we use the 15% sea ice concentration isoline. "Area" has been replaced in the text by "cover" to avoid confusion.

From: From the regridded data, sea ice extent (SIE) was calculated from the total ice area for each degree of longitude, bounded by the coast, and the 15% sea-ice concentration isoline.

To: From the regridded data, sea ice extent (SIE) was calculated from the total sea ice cover for each degree of longitude, bounded by the coast, and the 15% sea ice concentration isoline.

Section 3: I found this section very hard to follow. When I read section 4 and saw the plots, a lot of the details became clear, but only then, and I spent a lot of time trying to ingest section 3 before I moved on. For example, it was frequently unclear whether time series were being detrended for each grid cell or for some sort of sector-wide timeseries, or whether a correlation was between a sector timeseries and a map of timeseries or another sector timeseries, etc. My suggested solution would be to only present the very basics of what data are being used in the methods section, and then to more fully explain the method underlying each figure in the results section 4.

Response – The method section has been substantially revised to more clearly explain the steps taken for each part of the analysis in order to reduce confusion.

P5L10: significance

Response – This has been updated in the manuscript.

P5L26: Why a square root cosine weighting on a grid with uniform latitude spacing?

Response – As stated in the manuscript, cosine weighting is used to account for the change of longitude distance with latitude. The cosine weighting is essentially an areal weighting, thus each grid cell has equal influence in the EOF analysis.

P6L13: The EOFs from the different ensemble members are averaged together to be correlated with SIE. Which SIE? I would have thought that each ensemble member would have its own EOFs and its own SIE, so they can be directly correlated for each ensemble member?

Response – This is an error in the manuscript. The individual model plots in Figure S2 should show the individual ensemble member EOFS. The Taylor diagram does actually show the individual ensemble member EOF against the same ensemble member SIE, not the model average as written. The text has been changed to reflect this, and Figure S2 has also been updated.

P7L5: Is the difference in ASL-advance and SAM-retreat due to the position of the ice edge, further north at the start of retreat than it is at the start of advance?

Response – This is an interesting idea; probably only answerable by looking at extensively at patterns of sea ice concentration rather than extent. This is beyond the scope of this paper, but is worthy of further analysis.

P7L12 and others: The wording needs to be very precise. I think the finding is that the ASL is the dominant driver of *interannual variability* in sea ice advance in the A/B seas, not that it is the driver of ice advance per se. Please check this throughout the paper.

Response – The wording in the paragraph has been changed to reflect this, and it has been checked throughout the paper.

From: This indicates that the ASL is the dominant large-scale atmospheric driver for the Amundsen/Bellingshausen sector during the period of ice growth...

To: This indicates that the ASL is the dominant large-scale driver of interannual sea ice variability for the Amundsen/Bellingshausen sector during the period of ice advance...

P7L21: see above! The ice in this region is definitely subjected to large-scale atmos influence, though I agree that it appears that its interannual variability is not. . .

Response – The wording in the paragraph has been altered.

From: Rather, sea ice in this region during ice advance is more likely driven by alternative factors such as synoptic-scale weather systems, intrinsic variability, or the ocean. During retreat, the positive correlation pattern in the Weddell sector is similar to the pattern in the Ross/Amundsen sector during the same season, exhibiting an ASL component but not the zonally symmetric SAM component (Figure 1f).

To: Rather, the variability of sea ice in this region during ice advance is more likely driven by alternative factors such as synoptic-scale weather systems, intrinsic variability, or the ocean. During retreat, the positive correlation pattern between sea ice variability in the Weddell sector with atmospheric variability over the Amundsen and Bellingshausen Seas indicates the influence of the ASL (Figure 1f).

P7L23: I do not agree that the patterns are similar.

Response – The sentence has been revised to more accurately described the correlation pattern in the Weddell Sector.

From: During retreat, the positive correlation pattern in the Weddell sector is similar to the pattern in the Ross/Amundsen sector during the same season, exhibiting an ASL component but not the zonally symmetric SAM component (Figure 1f).

To: During retreat, the positive correlation pattern between sea ice variability in the Weddell sector with atmospheric variability over the Amundsen and Bellingshausen Seas indicates the influence of the ASL (Figure 1f). The inverse sign of the correlations compared with ASL influence in the Ross/Amundsen sector during the same season indicates that as the atmospheric circulation pattern deepens, sea ice extent in the Weddell Sea decreases.

P7L26: and SAM?

Response – The reference to SAM has been deleted.

From: This reflects the implied circulation of the ASL and SAM in this region, where stronger southerly winds over the Ross Sea result in the northward transport and reduced melt of sea ice in this region and stronger northerlies over the north of the Antarctic Peninsula confining ice in the Weddell Sea and increasing melt (Liu et al., 2004).

To: This reflects the implied circulation of the ASL in this region, where stronger southerly winds over the Ross Sea result in the northward transport and reduced melt of sea ice in this region and stronger northerlies over the north of the Antarctic Peninsula confining ice in the Weddell Sea and increasing melt (Liu et al., 2004).

P8L11: I do not see SAM-ice interactions for Hakon.

Response – The pattern reflects the non-annular component of the SAM, which is more commonly discussed as the ASL. The text has been updated to reflect this.

From: The King Hakon VII sector during advance (Figure 1g) shows a pattern that is weakly reminiscent of that observed in previous studies which have linked sea ice in this sector to the SAM (Turner et al., 2015a). However, during retreat the SAM-like pattern disappears (Figure 1h), indicating that the region becomes more sensitive to other factors such as weather and a small ENSO forcing as suggested by Matear et al. (2015).

To: The King Hakon VII sector during advance (Figure 1g) shows negative correlations over the Amundsen and Bellingshausen Seas, indicating the influence of the ASL on sea ice variability in this sector. However, during retreat the pattern disappears, with no large-scale atmospheric influence on sea ice variability visible (Figure 1h). This suggests that variability in retreating sea ice in this region is more sensitive to other factors such as weather and a small ENSO forcing as suggested by Matear et al. (2015).

From: In summary, large-scale atmospheric circulation patterns do not appear to be a dominant force in all sectors and seasons. The ASL is the dominant force in the Ross/Amundsen and Amundsen/Bellingshausen sectors during advance and the Weddell sector during retreat, while SAM-sea ice interactions occur in the King Hakon VII sector during advance and in the Ross/Amundsen sector during ice retreat. The PSA pattern occurs in the Amundsen/Bellingshausen sector and to a smaller extent in King Hakon VII during retreat.

In summary, large-scale atmospheric circulation patterns do not appear to be a dominant driver of sea ice variability in all sectors and seasons. The ASL is the dominant force in the Ross/Amundsen, Amundsen/Bellingshausen and King Hakon VII sectors during advance and the Weddell sector during retreat. SAM-sea ice interactions occur in the Ross/Amundsen sector during ice retreat.

P8L12: I do not see the PSA pattern in either sector during retreat.

Response – We've removed this sentence and now only refer to the ASL and SAM in this summary.

From: ... The ASL is the dominant force in the Ross/Amundsen and Amundsen/Bellingshausen sectors during advance and the Weddell sector during retreat, while SAM-sea ice interactions occur in the King Hakon VII sector during advance and in the Ross/Amundsen sector during ice retreat. The PSA pattern occurs in the Amundsen/Bellingshausen sector and to a smaller extent in King Hakon VII during retreat.

To: ... The ASL is the dominant force in the Ross/Amundsen, Amundsen/Bellingshausen and King Hakon VII sectors during advance and the Weddell sector during retreat. SAM-sea ice interactions occur in the Ross/Amundsen sector during ice retreat.

Figure 2: Caption mentions lines at r=+/- 0.4 which do not appear. It would be better to add lines showing r^2=+50% and r^2=+80%, as referred to in the text. I don't think negative values should be shown with dotted lines, since any negative correlation would be a very bad thing. Can the plot limits be set to +/-1? Can the dots be coloured like in Figure 3 so we can see which models are bad?

Response – Lines have been revised to show r = 0.7 and 0.8. Plot limits have been changed to +/-1.0. Dots have been coloured using the same colour scheme as in Figure 3.

P8L17: It might be worth clarifying that a high correlation shows that the regional patterns are similar, but the magnitude of the relationship can still be way off in the model?

Response – following sentence has been added to to this paragraph for clarification.

'These comparisons only measure the extent to which the observed spatial pattern was replicated in the models, not whether the magnitude of the interactions in the models is similar to that of the observations.'

P8L25 and others, e.g page 10: I realise it is statistical convention, but the use of the word 'explained' is inappropriate here. This is just showing how well the models match the observations – the models are not explaining anything in this case.

Response – In this case, the 'explained' refers to the amount of variance in the data to which each pattern corresponds. The comparison between the models and the observation is only to show the difference between how much variance in one is 'explained' by a particular pattern compared to how much is 'explained' by another. However, this has been replaced in the text by the term 'accounted for' to try to avoid confusion.

P8L29: I think this should say 'advance' not 'retreat'

Response – Correct; this has now been updated in the text.

P9L16: I don't understand the 'either. . . or. . .' construction of this sentence. Is it supposed to say that there is no relationship between higher pattern correlation and veracity of model trends? Can this claim be made quantitative?

Response – The text has been updated to remove the ambiguity. The intention of the sentence was to explain that having a better representation of atmosphere-ice interactions does not necessarily mean the same model will also produce a sea ice trend closer to observed trends.

From: There does not appear to be a strong relationship between either higher pattern correlation values (indicating close agreement between the model correlation maps and that of the reanalysis), or the proximity of model SIE trends to observed SIE trends in each sector and season.

To: There does not appear to be a strong relationship between higher pattern correlation values (indicating close agreement between the model correlation maps and that of the reanalysis) and the proximity of model SIE trends to observed SIE trends in each sector and season.

P9L22: Is the implication that the model SLP trends must be wrong? Or perhaps the model SIE and SLP patterns are spatially correlated well, but with the wrong magnitude in the correlation?

Response – The intention of this sentence is merely to point out that if a model produces a reasonable representation of interannual variability in the relationship between SIE and SLP, it doesn't necessarily also produce a reasonable sea ice trend. The sentence has been replaced for clarification.

From: This suggests that the ability of the models to simulate correlations between SIE and SLP that reflect observed correlation patterns does not necessarily mean that models also produce SIE trends that reflect observed SIE trends.

To: These results suggest that a model with an interannual sea ice-atmosphere interaction pattern that closely represents the observed pattern will not necessarily also produce realistic sea ice trends.

P9L30: Taking the ensemble mean EOFs does indeed reveal the forced climate response – but doesn't this complicate the comparison with ERA-Interim? The real climate is a single ensemble member, not an ensemble mean, so shouldn't ERA-interim should be compared to the population of ensemble members, not its mean?

Response – This paragraph has been updated to more clearly state that the individual members are indeed used, not the ensemble mean.

From: The EOF analysis was then conducted on the historical ensembles of each model, revealing the forced climate response of the models.

To: The EOF analysis was then conducted on the individual ensemble members of each model, revealing the forced climate response of each model member.

P9L32: Similarly to the above relations between SLP and SIE, pattern correlations will reveal whether the models have a relatively strong SAM relative to the model PSA, for example, but will not detect if that SAM variability is far too weak or strong relative to the real observed SAM variability. I think this should be mentioned explicitly.

Response – We have examined the absolute variance of the principal component corresponding to each EOF (Figure 6). This shows that the model SAM and PSA variability is far too weak compared to observed variability. This has been added to the text.

Figure 4: EOF1 explains exactly 36% of the variance in (a)?

Response – We have rounded the variance-explained to 2 significant figures. Since this is a gross empirical metric, we believe that this is a suitable level of precision to report.

Figure 5: I wondered if there is a concrete rationale for these being quarter-circle Taylor plots rather than just two-axis square plots like in figures 2 and 3?

Response – Originally, two-axis plots were used to show both these metrics; however, it was not easy to see the spread among the model ensemble members in both directions using this type of plot. The authors decided instead to use a Taylor diagram, which is a clearer method of comparing the outcome of multiple ensemble members at once using the two different metrics.

P10L20: The different ensemble members' PSAs show different pattern correlations to the ERA-Interim PSA. Could this be a real result, in the sense that not just the variability but also the different modes of variability can differ between ensemble members as a result of internal variability? If so, does it make sense to judge the models too harshly against the observed PSA pattern, since that is after all just one ensemble member? If not, how does this happen in the models and not in reality?

Response – The differences between the spatial representation of the PSA modes in the difference ensemble members suggest that they may change upon multidecadal timescales. We have updated the text here to include this caveat.

Figure6: Could reduce the y-limits from +/- 1.2?

Response – Limits have been reduced to +/- 1.0.

P11L5: I did not fully understand the argument in this paragraph. The observed relationships in Figure 6 all fit within the envelope defined by the simulations, so my default interpretation of the plot is that reality is indeed one member of the ensemble defined by CMIP5. I think the argument is that there are good physical reasons why the (singlemember) observed relationships have the spatial distribution that they do (?), and this is independent of internal variability (?), so we should expect most of the simulated relationships to follow this spatial distribution (?), or perhaps at least the multi-model mean relationship should follow it (?). Also, the figure shows the envelope and mean from the simulations, but not the standard deviation, which I think is what we need to assess whether the models are wrong.

Response – We have added lines depicting the 1.96 standard deviation (equivalent to the 95% confidence interval for a Normally distributed ensemble for infinite degrees of freedom.

Note that given: a) the strength of the observed correlation pattern (which is large compared to the standard deviation), b) its acknowledged importance in the literature, and c) the length of correlation period (approximately 3 decades), it is highly unlikely that the differences between ensemble members could be explained by internal variability alone.

P11L8: This paragraph seemed very unclear to me and I think needs rewriting and breaking into two paragraphs. 1) The first half of the paragraph says that the models have accurate SLP-SIE relationships during advance but do not capture the observed trends during advance, but this is not explored further until a few comments at the end of the paragraph. It seems to me that this paradox could be due to either the magnitude of the SLP-SIE relation being wrong in the models (it is only a pattern correlation that is good) or the model SLP trends being wrong. The latter would be unsurprising given the poor state of the model SLP EOFs 2&3. 2) The second half of the paragraph appears to argue that in the real world the importance of atmospheric variability is diminished during retreat, but it is not (figure 1). It is the veracity of the models in reproducing atmospheric-driven ice variations that is diminished during retreat (figure 2). This could be due to model errors in any of the mechanisms mentioned, but the paragraph seems to be suggesting that the mechanisms per se reduce the effect of atmospheric variability, which is not the case. In any case, only the atmosphere-induced fraction of the variability is under consideration in this paper, not the entire variability. It may be the case that ice-climate feedbacks have an important role here. During retreat, any variability in ice cover due to winds will be amplified by melting feedbacks (e.g. albedo causes low ice to melt faster, causing lower ice). I would speculate that it is hard for models to accurately represent such feedbacks, and as a result their SLP-SIE relationships are less reliable during retreat than advance.

Response – The paragraph has been broken into two sections as suggested, with the advance sea ice-atmosphere interactions discussed first and then retreat separately to avoid confusion. It is true that complex ice-ocean feedbacks are probably difficult for models to represent; however, those ice-ocean feedbacks are equally complex (if not more so than) during advance (for example, the entrainment of sub-mixed layer into the mixed layer from brine rejection). Although incredibly important, those feedbacks don't therefore explain why advance should necessarily be better represented than retreat in the models.

P12L2: I think the models underestimate the role of PSA (figure 5) in atmospheric variability?? And I am not convinced about the modelled role of PSA (figure 6).

Response – The sentence has been updated to reflect the underestimation of the PSA.

From: However, during retreat, historical simulations overestimated the relative importance of the SAM and PSA in terms of atmospheric variability as well as the relative influence of these modes on SIE.

To: However, during both sea ice advance and retreat, the majority of historical simulations overestimated the relative importance of the SAM and underestimated that of the PSA.

P12L13: This sentence is worded in a very complex way and would probably be better placed in the paragraph discussed above in comment P11L8.

Response – This sentence has been reworded to reduce its complexity.

<u>Reviewer 2 – Variability</u>

p.1, ll.12+: In the abstract and the conclusion section the authors state that their paper investigates the relationship between sea ice variability and atmospheric variability. Especially in the results section however, the authors do not mention variability, but e.g. talk about "the relationship between sea ice and atmospheric conditions during the seasons of ice advance and retreat“ (p.6, ll.20+). This is confusing. I am finally not sure, whether the paper really investigates the atmosphere-ice interactions in terms of variability. I encourage the authors to consistently check whether they say what they intend to say.

Response – Through addressing the comments of Reviewer 1, the text throughout the results has been revised to more specifically discuss interannual variability, and this hopefully reduces the confusion in the rest of the paper. The revised results and discussion are quite clear that the paper is discussing variability rather than trends.

p.1, l.15: This study does not show the ocean to be a dominant driver of sea ice retreat. The statement is hypothetical and need to be changed or removed. I like the phrasing in the final sentence of the abstract.

Response – The sentence in the abstract has been revised to remove the reference to the ocean being a dominant driver during retreat.

From: Atmospheric influence on sea ice is known to be strongest during its advance, with the ocean emerging as a dominant driver of sea ice retreat; therefore, while it appears that models are able to capture the dominance of the atmosphere during advance, simulations of ocean-atmosphere-sea ice interactions during retreat require further investigation.

To: Atmospheric influence on sea ice is known to be strongest during its advance, and it appears that models are able to capture the dominance of the atmosphere during advance. Simulations of ocean-atmosphere-sea ice interactions during retreat, however, require further investigation.

p.4, l.5: Is there a reason why September is not considered?

Response – According to the calculations of Raphael & Hobbs (2014), sea ice in the different sectors around Antarctic stops advancing during August, instead maintaining the winter maximum throughout September before beginning its retreat in October. The only exception was the King Hakon VII sector which reached its maximum later than the others and began its retreat one month later; however, to compare like with like, we used the majority advance period for all sectors in this study. None of the sectors had an extended minimum, which is why the end of retreat and start of advance do not have a gap.

p.4, ll.29+: The authors mention the use of monthly reanalysis data, but they never specify the time resolution of the CMIP5 model output used. I assume this is also monthly. Please specify this here. Further the authors use reanalysis data from 1979 to 2014 but historical model output only until 2005. Why don’t the authors prolong the historical simulations

until 2014? At least I would like to know whether the results remain qualitatively the same when prolonging the simulations by the last 10 years, i.e. with RCP4.5.

Response – The method section has been updated to clearly state that CMIP5 monthly historical data is used. Cross-correlations between ERA-Interim reanalysis SLP and NSIDC sea ice extent have been run also for the period January 1979-December 2005, and have yielded largely the same results (now attached as Figure S1). There is no substantial difference between the shorter and longer timeseries in the observations. Therefore, we decided not to lengthen the historical ensembles, given the significant extra work required to concatenate RCP4.5 onto 73 historical ensembles.

p.5, ll.6+: It is not clear to me how the authors detrend the reanalysis data and the piControl simulations. Did they use linear detrending for both? If so, is this appropriate for the reanalysis data? The authors should explain more specifically the methods they use.

Response – We use the same linear detrending method for all datasets, including the reanalysis dataset, as it has been used widely both for ERA-Interim and other datasets, for example:

- Bracegirdle, T. J.: Climatology and recent increase of westerly winds over the Amundsen Sea derived from six reanalyses, International Journal of Climatology, 33, 843-851, 2013.
- Bromwich, D. H., Nicolas, J. P., Monaghan, A. J., Lazzara, M. A., Keller, L. M., Weidner, G. A., and Wilson, A. B.: Central West Antarctica among the most rapidly warming regions on Earth, Nature Geoscience, 6, 139-145, 2013.

p.5, ll.10-11: Related to 4) I wonder whether monthly data is sufficient to detect autocorrelation in the SLP and SIE data.

Response – We're only interested in autocorrelation in this case insofar as it affects statistical significance tests. As we are using monthly data in the study, it is only appropriate to consider the autocorrelation at monthly timescales.

The authors mention the similarity of their approach to that of Raphael and Hobbs (2014) in the method section and the similarity of theirs results to those from Raphael and Hobbs (2014) in the results section. I roughly know the study by Raphael and Hobbs (2014). However, from the present study it is not clear to me which scientific insights go beyond those from Raphael and Hobbs (2014). This needs to be pointed out more clearly. I appreciate that the authors try this distinction especially on p.4, ll.1- 15, but I feel that at least its role as a predecessor study is not sufficiently accounted for.

Response – We have updated the text to clearly refer to the Raphael and Hobbs (2014) study in the Introductory section, Method section and Discussion so as to most clearly differentiate between the predecessor study and this one.

p.6, ll.2-4: I am not convinced that ensemble averaging for the historical model output is a good solution when correlating to the reanalysis. The reanalysis (and also reality) is a

single realization and thus cannot be expected to be related to the ensemble average of a model.

Response – This is an error in the manuscript. The individual model plots in Figure S2 should show the individual ensemble member EOFS. The Taylor diagram does actually show the individual ensemble member EOF against the same ensemble member SIE, not the model average as written. The text has been changed to reflect this, and Figure S2 has also been updated.

p.6, section 4.1: I have some difficulties with the description of the results presented in Fig.1.
p.7, l.14: Please mention that the correlation pattern during retreat (Fig. 1d) is much weaker than during advance (Fig.1c).

Response – The text has been updated to include the weakening of the pattern.

From: During the retreat season, the correlation pattern remains in a similar area but contracts northwards and towards the Ross Sea (Figure 1d).

To: During the retreat season, the correlation pattern remains in a similar area but weakens, contracting northwards and towards the Ross Sea (Figure 1d).

p.7, ll.23+: I do not see a pattern similarity between Fig.1b and Fig.1f, even not of inverse sign. Please check again whether the interpretation is really supported by the results shown in Fig.1.

Response – As described in the text, the correlation pattern for Figure 1f shows the non-annular component of the SAM, the ASL, but not the annular component of the ASL. The ASL pattern is inverse to that of the non-annular component of the SAM pattern in the Ross/Amundsen sector during the same sector. Physically, this is well known, as the implied circulation of the ASL results in increased southerly winds over the Ross Sea and northerly winds over the Antarctic Peninsula and Weddell Sea (e.g. Turner et al. 2015).

p.8, l.2: Why not a new paragraph for East Antarctica here?

Response – A separate paragraph has been inserted here for East Antarctica.

p.8, l.31-32: Are the numbers 12 for East Antarctica and 4 for King Hakon VII correct? According to Fig. 2d for King Hakon, there are more than 4 models situated above 0.5 for the advance season.

Response – We have double checked this, and altered the Figure to make the results clearer as a result of comments from Reviewer 1. These numbers are indeed correct; in order for the model to obtain an r^2 score of 50%, it needs to have a pattern correlation of 0.7 or higher, not 0.5 (which would only obtain an r^2 score of 25%). Dotted lines at 0.7 and 0.8 have been added at the urging of Reviewer 1 in order to make this clearer, and we hope this assists with the comments of Reviewer 2 as well.

p.9, l.33: The second metric is clear, but what is the first metric? This becomes not very clear by structure. Try to use the expression "the first metric“ before "a second metric“.

Response – The text has been updated here to avoid confusion.

From: Correlation values close to 1 indicate good representation of the spatial pattern of the observation-based atmospheric mode in the models, while values near 0 indicate little resemblance between them. A second metric was created by dividing the amount of atmospheric variance explained by the model EOF by the amount of variance explained by the observation-based pattern, creating a ratio of the percentage of variance explained.

To: The results are explained using two metrics. The first metric, correlation values, is used to indicate the strength of the simulated representation of the spatial pattern seen in the reanalysis. A correlation value close to 1 indicates good representation of the pattern, while values near 0 indicate little resemblance between the two. A second metric was created by dividing the amount of atmospheric variance explained by the model EOF by the amount of variance explained by the observation-based pattern, creating a ratio of the percentage of variance explained.

p.11, l.15: The start of the sentence is misleading because to me it sounds like a definition of the advance season. I would suggest to start with: "In the advance season the modeled sea ice trends diverge ...“

Response – The text has been updated as suggested.

From: The advance season is when the CMIP5 models sea ice trends diverge most significantly from observed trends, particularly in the Ross/Amundsen and Amundsen/Bellingshausen sectors where the highest-magnitude change is also observed (Hobbs et al., 2015; Hobbs et al., 2016).

To: In the advance season, the modelled sea ice trends diverge most significantly from observed trends, particularly in the Ross/Amundsen and Amundsen/Bellingshausen sectors where the highest-magnitude change is also observed (Hobbs et al., 2015; Hobbs et al., 2016).

In contrast to the rest of the manuscript, I find the conclusion section a bit weak. I think it hides some major findings that are more clearly stated in the results section. I would also love to see that the last sentence/paragraph contains the major conclusion(s) of or the overall benefit from the present paper, rather than an outlook as it is currently done. To me, this leaves the impression the results of this paper are not important which is not true.

Response – The conclusion section has been reorganised and rewritten in parts to more clearly state the conclusions and their importance in context of other academic literature.

Fig.1 and Fig.S1 (captions): I would prefer red dotted/blue "contours“ or "isolines“ instead of just "lines“.

Response – This has been updated as suggested.

Fig.2 (caption): The authors mention dotted lines at 0.4 and -0.4. I cannot find them in the figure.

Response – Figure 2 has been updated to show dotted lines at 0.7 (r^2=50%) and 0.9 (r^2=80%) for ease of interpretation. At the advice of Reviewer 1, the dotted lines have not been extended to negative correlations.

Fig.5: It would be very helpful for the reader if the authors would use the same color for each model as in Fig.3. I cannot see a reason for not doing so.

Response – The colour scheme here has been updated to match the other coloured plots.

Technical comments: p.2, l.19: "i“ is missing in comparatively p.3, l.33: remove one "boundaries“ p.5, l.10: significance instead of "significant“ Fig.6 (caption): a dot is missing after "retreat“

Response – All these technical comments have been implemented in the text.

Interactions between Antarctic sea ice and large-scale atmospheric modes in CMIP5 models.

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Abstract

The response of Antarctic sea ice to large-scale patterns of atmospheric variability varies according to sea ice sector and season. In this study, interannual atmosphere-sea ice interactions were explored using observations and reanalysis data, and compared with simulated interactions by models in the Coupled Model Intercomparison Project Phase 5. Simulated relationships between atmospheric variability and sea ice variability generally reproduced the observed relationships, though more closely during the season of sea ice advance than the season of sea ice retreat. Atmospheric influence on sea ice is known to be strongest during advance, and it appears that models are able to capture the dominance of the atmosphere during advance. Simulations of ocean-atmosphere-sea ice interactions during retreat, however, require further investigation.

A large proportion of model ensemble members overestimated the relative importance of the Southern Annular Mode compared with other modes of high southern latitude climate, while the influence of tropical forcing was underestimated. This result emerged particularly strongly during the season of sea ice retreat. The zonal patterns of the Southern Annular Mode in many models and its exaggerated influence on sea ice overwhelm the comparatively underestimated meridional influence, suggesting that simulated sea ice variability would become more zonally symmetric as a result. Across the seasons of sea ice advance and retreat, 3 of the 5 sectors did not reveal a strong relationship with a pattern of large-scale atmospheric variability in one or both seasons, indicating that sea ice in these sectors may be influenced more strongly by atmospheric variability unexplained by the major atmospheric modes, or by heat exchange in the ocean.

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1. Introduction

Antarctic sea ice extent has increased by approximately 1.5% per decade since satellite observations began in 1979 (Parkinson and Cavalieri, 2012; Turner et al., 2015a). The small overall increase masks higher-magnitude regional and seasonal trends around the continent, most notably an increase of 3.9% per decade in the Ross Sea peaking during spring, and a decrease of -

3.4% per decade in the Amundsen and Bellingshausen Seas peaking during autumn (Turner et al., 2015a). By contrast, models in the Coupled Model Intercomparison Project Phase 5 (CMIP5) exhibit decreasing sea ice trends in all months (Turner et al., 2013a). The reasons for the disparity between observed and modelled trends are not yet well understood (Bindoff et al., 2013; Hobbs et al., 2016). A large proportion of the observed trends are thought to be driven by interactions between Antarctic sea ice and atmospheric processes such as wind (Liu et al., 2004; Raphael, 2007; Lefebvre and Goosse, 2008; Massom et al., 2008; Yuan and Li, 2008; Holland and Kwok, 2012; Matear et al., 2015), and it has been suggested that deficiencies in the model representation of atmospheric circulation may account for at least part of this disparity (Hosking et al., 2013; Mahlstein et al., 2013). The response of Antarctic sea ice to atmospheric forcing incorporates complex feedbacks and interactions between the atmosphere, sea ice and ocean (Lefebvre and Goosse, 2008; Raphael and Hobbs, 2014; Matear et al., 2015), and measuring the extent to which these feedbacks and interactions are represented in global climate simulations could provide insight into the representation of sea ice trends and variability.

The Southern Annular Mode (SAM) is the dominant mode of atmospheric variability in the Southern Hemisphere (Gong and Wang, 1999; Limpasuvan and Hartmann, 1999; Thompson and Wallace, 2000; Marshall, 2003). It is a zonally symmetric atmospheric structure with pressure anomalies of opposing signs vacillating between the polar- and mid-latitudes of the Southern Hemisphere (SH) (Karoly, 1990; Gong and Wang, 1999; Thompson and Wallace, 2000). The positive phase of SAM is characterised by a poleward shift and intensification of westerly circumpolar winds (Thompson et al., 2000; Marshall, 2003) which has previously been thought to increase the northward expansion (and greater areal coverage) of sea ice through Ekman transport (Hall and Visbeck, 2002; Sen Gupta and England, 2006), while simultaneously pushing warmer oceanic air masses from the north over the comparatively cold land of the Antarctic Peninsula (Thompson and Wallace, 2000; Marshall et al., 2006; van Lipzig et al., 2008). A trend has been observed of the SAM moving towards its high-index (positive) polarity, with negative pressure anomalies over the Antarctic continent and positive anomalies in the mid-latitudes (Thompson et al., 2000; Thompson and Solomon, 2002; Marshall, 2003; Fogt et al., 2009). This trend is associated with stratospheric ozone depletion and forcing by greenhouse gases (Gillett and Thompson, 2003; Thompson et al., 2011; Ferreira et al., 2015). However, it has been recently suggested that the response of the Southern Ocean surface to a sustained SAM trend is more complex than the interannual Ekman response, whereby an initial sea ice expansion is followed by warming over the longer term caused by upwelling of relatively warm, mixed-layer ocean water (Marshall et al., 2014; Ferreira et al., 2015; Armour et al., 2016).

The Amundsen, Bellingshausen, Ross and Weddell Seas fall within a zone of orography that is non-axisymmetric, and experiences the highest mean sea level pressure variability in the SH (Lachlan-Cope et al., 2001). A climatological low-pressure centre within the circumpolar atmospheric trough south of 60°S, known as the Amundsen Sea Low (ASL), plays a significant role in driving the advance and retreat of sea ice in this region (Hosking et al., 2013; Turner et al., 2013b; Fogt and Wovrosh, 2015; Raphael et al., 2015; Turner et al., 2015b). The depth and longitudinal location of the ASL, which influence sea ice, are in turn influenced by tropical forcing (Yuan and Martinson, 2001; Ding et al., 2011; Schneider et al., 2011; Fogt and Wovrosh, 2015; Raphael et al., 2015), radiative forcing (Fogt and Wovrosh, 2015; Raphael et al., 2015) and the phase of the SAM (Lefebvre et al., 2004; Turner et al., 2013b). The contrasting sea ice trends of the Amundsen/Bellingshausen and Ross Seas are associated with the deepening of the ASL in recent decades (Turner et al., 2013b). Recent studies have suggested that trends in the ASL and associated winds affecting sea ice in these regions are within the bounds of modelled intrinsic variability (Turner et al., 2015a; Turner et al., 2015b).

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The other major modes of climate variability are the two Pacific South American modes (PSA1 and PSA2), which are associated with the high-latitude atmospheric response to ENSO (Karoly, 1989; Mo, 2000; Mo and Paegle, 2001). ENSO is teleconnected to the southern polar latitudes through meridional circulation anomalies (Harangozo, 2000), and is known to impact Antarctic sea ice (Simmonds and Jacka, 1995; Kwok and Comiso, 2002; Turner, 2004; Yuan, 2004; Simpkins et al., 2012). However, evidence suggests that ENSO is only able to strongly influence the Antarctic climate during periods where SAM is relatively weak, or an in-phase relationship exists between the PSA modes and the SAM, such as when the warm (cold) ENSO phase coincides with a negative (positive) SAM (Fogt and Bromwich, 2006; Stammerjohn et al., 2008; Fogt et al., 2010). This enables the ENSO to project onto the SAM and the two act synergistically to enhance pressure anomalies that influence Antarctic sea ice (Karoly, 1989; Fogt and Bromwich, 2006; Stammerjohn et al., 2008; Bernades Pezza et al., 2012). The high-latitude atmospheric response to ENSO is linked to sea ice anomalies in the Amundsen, Bellingshausen, Ross and Weddell Seas (Karoly, 1989; Harangozo, 2000; Kwok and Comiso, 2002; Yuan, 2004; Stammerjohn et al., 2008; Bernades Pezza et al., 2012), with recent work indicating that trends in the south Pacific ice edge during winter can be explained by changes to ice drift and surface winds resulting from a positive trend in the Southern Oscillation Index (Kwok et al., 2016).

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While these large-scale atmospheric modes are clearly a strong influence on the observed variability of Antarctic sea ice, whether the representation of atmospheric modes in CMIP5 models can explain the disparity between observed and modelled sea ice trends remains uncertain. Some observational studies have concluded that the dominant modes, SAM and ENSO, cannot account for regional Antarctic sea ice trends, and that lesser-understood large-scale modes or local processes should be investigated as alternative drivers (Liu et al., 2004; Yu et al., 2011; Hobbs et al., 2016). Other recent studies have shown that sea ice around Antarctica, except in the Amundsen, Bellingshausen and Ross Seas regions, is not in fact influenced to a great extent by large-scale atmospheric modes, but is most impacted by synoptic weather (Matear et al., 2015; Kohyama and Hartmann, 2016). It is also unlikely that a single climate process or driver can explain all regional and seasonal sea ice trends (Lefebvre and Goosse, 2008; Holland, 2014; Raphael and Hobbs, 2014). Exploring the simulated interactions between atmospheric variability and Antarctic sea ice variability can provide further clarification as to which sectors of sea ice are most strongly influenced by large-scale atmospheric modes, and whether the strength of representation of these interactions leads to more accurate simulations of Antarctic sea ice trends.

This study explores the extent to which global climate models reproduce large-scale patterns of atmospheric variability as well as the influence of these patterns on Antarctic sea ice variability. Previous analyses of Antarctic sea ice have generally delineated sea ice sectors by oceanographic and meteorological boundaries (Zwally et al., 1983, Figures 2-3; Parkinson and Cavalieri, 2012, Figure 2). However, Raphael and Hobbs (2014) used spatial autocorrelation to calculate boundaries for independent sectors of Antarctic sea ice variability to define sectors where the sea ice is strongly correlated with neighbouring sea ice, indicating distinct sea ice regimes. The same study also calculated the average annual cycles of sea ice in each sector, revealing regionally distinct climatologies which, when aggregated to monthly intervals, produced seasons of sea ice advance (March – August) and retreat (October – February). Sea ice advance and retreat have been shown to be the key periods during which sea ice interacts with the atmosphere, and are more suitable for atmosphere-sea ice analysis than the traditional atmospheric seasons used in many studies (Stammerjohn et al., 2008; Renwick et al., 2012). Indeed, recent studies of change in Antarctic sea ice seasonality have concentrated on the seasons of annual advance, retreat and duration of sea ice coverage, with the annual sea ice season calculated between the sea ice minimum of one year to the next (February to February) (Stammerjohn et al., 2012; Massom et al., 2013). This study extends the results of Raphael and Hobbs (2014), based on observed interactions between large-scale atmospheric circulation and different sectors of Antarctic sea ice during the seasons of sea ice advance and retreat, by comparing these with simulated interactions in CMIP5 climate models in the same sectors and during the same seasons. Establishing the extent to which the CMIP5 models produce simulated atmosphere-sea ice interactions that closely reflect observed interactions provides insight into whether large-scale patterns of variability are responsible for driving regional sea ice trends around Antarctica.

2. Data

Monthly Goddard-merged sea ice concentration data on a 25km x 25km grid were obtained from the National Snow and Ice Data Center for the period March 1979-February 2014 (Meier, 2015). These sea-ice data were then interpolated from their native grid onto a grid of 0.5° of longitude by 0.25° of latitude, equating to approximately 25km^2 at 60°S. From the regridded data, sea ice extent (SIE) was calculated from the total sea ice cover for each degree of longitude, bounded by the coast, and the 15% sea ice concentration isoline. Monthly mean sea level pressure (SLP) data from the ERA-Interim global atmospheric reanalysis from March 1979-February 2014 were obtained from the European Centre for Medium-Range Weather Forecasts (available at http://apps.ecmwf.int/). ERA-Interim was chosen from the range of global atmospheric reanalysis products due to the consistency of its surface air temperature and surface temperature trend patterns with sea ice trends (Bromwich et al., 2011; Hobbs et al., 2016). ERA-Interim reanalysis assimilates observed data sequentially in 12-hour cycles, combining new data in each cycle with a forecast model estimate of the global atmosphere and surface based on calculations from data in the previous cycle (Dee et al., 2011).

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Monthly model SIE and SLP data from the Coupled Model Intercomparison Project Phase 5 (CMIP5) (Taylor et al., 2009; Taylor et al., 2012) were obtained from the CMIP5 multi-model ensemble archive at the Program for Climate Model Diagnosis and Intercomparison (PCMDI). The full names and modelling institutions for the models used in this study are shown in Table 1. Output from both the pre-industrial control (piControl) and 20th century (historical) experiments were used. The piControl experiment, run for at least 500 years after the 'spin-up' period in which model conditions are stabilised, applies a prescribed pre-industrial atmosphere that does not evolve over time, enabling examination of internal variability within the models (Taylor et al., 2009). The historical experiment runs from 1850 to at least 2005, and applies evolving climate forcings including aerosol emissions, changes to atmospheric composition from greenhouse gases and solar forcing.

3. Methods

ERA-Interim reanalysis SLP data (south of 50°S) and observed SIE data for each year between 1979-2014 were sliced into the seasons of sea ice advance (March-August) and retreat (October-February) based on the analysis of Raphael and Hobbs (2014), and weighted according to the length of each month during the season. The SIE season data was then integrated to produce the five sectors of Raphael and Hobbs (2014): East Antarctica (71°E - 163°E, Ross/Amundsen (163°E - 250°E), Amundsen/Bellingshausen (250°E - 293°E), Weddell (293°E – 346°E) and King Hakon VII (346°E-71°E). Both datasets were then detrended, and a cosine latitude weighting applied to the SLP data to compensate for the convergence of meridians. The same method was followed for the model SLP and SIE data from piControl experiments (of various lengths). The piControl experiment was chosen to isolate the unforced variability in the models. A two-sided t-test was used to determine statistical significance in the reanalysis correlations, after which any data that were not significant at the 0.05 confidence level were masked out. Autocorrelation in climate data can lead to an overestimate of statistical significance (e.g. Zwiers and von Storch, 1995); however, the data were tested for autocorrelation and at the timescales used in this analysis no autocorrelation was found. Sector-integrated SIE was then correlated with SLP for each season in both reanalysis and model datasets, producing maps of correlations. This approach was based on that used by Raphael and Hobbs (2014) but expands upon it by also incorporating the masking of insignificant values, weighted seasonal averaging, and the use of SLP instead of geopotential height. This produces a proxy for the observed and simulated relationship between SIE in each sector with large-scale atmospheric variability. The simulated correlation maps were then pattern-correlated with the observed map to obtain a single metric for how closely the models reproduce observed interactions between SLP and SIE.

CMIP5 historical SIE data were averaged to create an ensemble mean SIE for each model, and sliced into the sea ice sectors described above. An ordinary least squares regression was then calculated for each sea ice sector between January 1979-December 2005. The ensemble mean SIE sector trend for each model was plotted against the pattern correlation value of the same model to compare SIE trends to representation of the modelled SIE-atmosphere interactions.

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The monthly climatology was removed from SLP data for both ERA-Interim and model data from the historical experiment, which were then sliced into the seasons of sea ice advance and retreat for each year (1979-2014 for ERA-Interim, 1979-2005 for the models) as above. The seasonal data were detrended, and a square root cosine weighting applied. An empirical orthogonal function (EOF) analysis was then conducted on the data to produce the three leading eigenvectors and their associated principal component time series of atmospheric variability in the high southern latitudes during the seasons of sea ice advance and retreat. The same calculations were conducted upon a reanalysis timeseries between 1979-2005 to investigate whether the a qualitative difference was noticed between a shorter and longer timespan, but the results remained largely the same (Figure S1), indicating that the shorter model timespan would not impact substantially on the comparison between simulated and reanalysis eigenvectors. The leading eigenvectors display the spatial patterns of the SAM and the two PSA modes. As the two PSA modes both depict aspects of tropical teleconnections to the high latitudes, these modes were added together to create a single mode that describes the influence of tropical forcing on the Antarctic climate. The results are thus presented as from two modes: the first mode (SAM) and the combined second and third modes (PSA). Individual model ensemble member EOFs were then pattern-correlated with the corresponding EOFs of the reanalysis. The resulting correlation value for each model ensemble member indicated the extent to which the simulated pattern reflected the observed pattern for each of the eigenvectors. The percentage of variance explained by the simulated pattern was compared to the percentage of variance explained by the reanalysis. A 1:1 ratio indicated good agreement between the ensemble and the reanalysis, with a higher or lower ratio indicating an overestimation or underestimation of the importance of that eigenvector in the model. The variance of each principal component timeseries of both ERA-Interim and the CMIP5 ensemble members was recorded and plotted for comparison.

Lastly, the long-term climatological mean was removed from NSIDC SIE data to reveal SIE anomalies by longitude. These SIE anomalies were then cross-correlated with each reanalysis EOF principal component time series to show the relationship between changes to the amplitude of each atmospheric mode and anomalies of SIE in the advance or retreat seasons when the atmospheric influence of sea ice is known to be most important. The same analysis was conducted on model historical SIE data, where the SLP EOF for each model ensemble member (calculated above) was correlated with the SIE anomalies for the same ensemble member. The result from the reanalysis was compared to the results from the ensemble member correlations to determine whether the simulated influence of the leading atmospheric modes on SIE reflects the reanalysis.

4. Results

4.1 Observed Atmosphere-Sea Ice Interactions

In this section, the relationship between Antarctic sea ice and atmospheric conditions during the seasons of ice advance and retreat were examined. As previously discussed, interactions during the seasons of ice advance and retreat are the key focus of this study, as it is during these periods that the link between Antarctic sea ice to atmospheric forcing is strongest (Stammerjohn

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et al., 2008; Renwick et al., 2012). Figure 1 shows the zero-lag correlation of sector-integrated SIE with SLP, following Raphael and Hobbs (2014). Sea ice in individual sectors responds to different atmospheric patterns, and the response also varies between the seasons of ice advance and retreat. Many of these response patterns are similar to those found by Raphael and Hobbs (2014) upon whose approach this method is based; however, the use of seasonal weighting in this analysis (which was not included in the previous study) yielded different patterns for some sectors and seasons.

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During ice advance, SIE in the Ross/Amundsen sector is negatively correlated with SLP over West Antarctica (Figure 1a). The negative correlation here indicates that increasing SIE in this sector is associated with a deepening of the atmospheric pattern shown. This negative correlation pattern persists into the retreat season (Figure 1b), but shifts towards the Ross Sea and expands to incorporate a circumpolar component. The shape and location of the correlation pattern is indicative of an ASL component, which in its mean position is centred close to 110°W, while the circumpolar, zonally symmetric component reflects a SAM-like "see-saw" of pressure anomalies between the high- and mid-latitudes (Karoly, 1990; Gong and Wang, 1999; Thompson and Wallace, 2000; Marshall, 2003). The longitudinal position of the ASL, which shifts towards the west during the winter and towards the east in summer (Turner et al., 2013b), is strongly influenced by the polarity of SAM and is itself a strong influence on the climate of West Antarctica (Hosking et al., 2013). Raphael et al. (2015) demonstrated the link between large-scale atmospheric circulation changes, particularly their effect on geostrophic flow, and the climatic influence of the meridional and zonal location of the ASL. The correlations in Figures 1a and 1b indicate that sea ice in the Ross/Amundsen sector responds to surface air flow changes brought about by the ASL during the period of advance, and that the SAM dominates the sector during the period of retreat.

Correlations between SIE and SLP in the Amundsen/Bellingshausen sector during advance are almost the inverse of those in the Ross/Amundsen sector during the same season, with positive correlations centred over the Amundsen Sea and extending from the Ross Sea towards the Bellingshausen Sea (Figure 1c). This indicates that the ASL is the dominant large-scale atmospheric driver of interannual sea ice variability for the Amundsen/Bellingshausen sector during the period of ice advance, and is consistent with previous analysis showing the influence of the ASL on the meridional wind field in the West Antarctic region (Hosking et al., 2013). During the retreat season, the correlation pattern remains in a similar area but weakens, contracting northwards and towards the Ross Sea (Figure 1d). This does not follow the longitudinal shift of the ASL described above, but rather reflects the spatial pattern of the PSA (Mo and Paegle, 2001). This atmospheric pattern is generally taken to reflect the relationship between ENSO and the high latitudes, and indicates the influence of tropical forcing on sea ice in the Amundsen/Bellingshausen sector during ice retreat, in agreement with Raphael and Hobbs (2014).

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In the Weddell sector during ice advance, there is no significant correlation between SIE and SLP (Figure 1e), indicating that there is no distinct large-scale atmospheric influence on the interannual variability of sea ice in this sector and season. Rather, the variability of sea ice in this region during ice advance is more likely driven by alternative factors such as synoptic-scale weather systems, intrinsic variability, or the ocean. During retreat, the positive correlation pattern between sea ice variability in the Weddell sector with atmospheric variability over the Amundsen and Bellingshausen Seas indicates the influence of the ASL (Figure 1f). The inverse sign of the correlations compared with ASL influence in the Ross/Amundsen sector during the same season indicates that as the atmospheric circulation pattern deepens, sea ice extent in the Weddell Sea decreases. This reflects the implied circulation of the ASL in this region, where stronger southerly winds over the Ross Sea result in the northward transport and reduced melt of sea ice in this region and stronger northerlies over the north of the Antarctic Peninsula confining ice in the Weddell Sea and increasing melt (Liu et al., 2004). The apparently differing drivers affecting ice advance and retreat in the Weddell sector agrees with recent findings by Matear et al. (2015) that sea ice variability in the West Atlantic region is likely driven by combined wind variability from synoptic and large-scale atmospheric patterns.

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The King Hakon VII sector during advance (Figure 1g) shows negative correlations over the Amundsen and Bellingshausen Seas, indicating the influence of the ASL on sea ice variability in this sector. However, during retreat the pattern disappears, with no large-scale atmospheric influence on sea ice variability visible (Figure 1h). This suggests that variability in retreating sea ice in this region is more sensitive to other factors such as weather and a small ENSO forcing as suggested by Matear et al. (2015).

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Correlations in the East Antarctica sector do not reveal the SAM-like patterns found by Raphael and Hobbs (2014) during either advance or retreat (Figures 1i and j), but rather SIE is negatively correlated to SLP over the eastern Ross and Amundsen Seas and positively correlated to the South Atlantic during advance. During retreat, the negative correlations shift to an area between 130°E-180°E and are stronger, while the positive correlations in the South Atlantic become negative. This agrees with previous studies showing that annual SIE in roughly this same region is influenced more by cyclonic activity around the West Pacific Ocean rather than a large-scale atmospheric pattern (Matear et al., 2015; Turner et al., 2015a).

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In summary, large-scale atmospheric circulation patterns do not appear to be a dominant driver of sea ice variability in all sectors and seasons. The ASL is the dominant force in the Ross/Amundsen, Amundsen/Bellingshausen and King Hakon VII sectors during advance and the Weddell sector during retreat. SAM-sea ice interactions occur in the Ross/Amundsen sector during ice retreat.

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4.2 Simulated Atmosphere-Sea Ice Interactions

The analysis presented for the observations in Figure 1 was repeated for each piControl simulation for the CMIP5 models. The correlations for each model were compared to the observed correlations in each sector and season to determine how closely the models represent the observed pattern of atmosphere-sea ice interactions (Figure 2). A high pattern correlation value indicates that the simulated interactions closely reflected the observed interactions, while a value near zero indicates that the two were substantially different. A high negative correlation value means that the pattern was similar, but the correlation was

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the inverse sign to the observations. These comparisons only measure the extent to which the observed spatial pattern was replicated in the models, not whether the magnitude of the interactions in the models is similar to that of the observations. The correlation between simulated patterns and observed patterns during advance is plotted horizontally, while the correlations during retreat are plotted vertically for each sector. (Correlation maps for individual models can be seen in Figure S2).

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Simulated SIE and SLP correlation patterns most closely reflect observed patterns during the season of advance. The percentage of variance in the observed pattern that can be accounted for by each simulated pattern can be obtained by calculating the coefficient of determination, r^2, which is the square of the pattern correlation value. During advance, 5 of the 16 models simulate a correlation pattern in the Ross/Amundsen sector that can account for at least 80% of the spatial variance in the observed pattern, while 12 of the 16 models simulate a pattern that can account for over 50% of the observed pattern. Correlations are even stronger in the Amundsen/Bellingshausen sector during advance, with 7 of the 16 models simulating a correlation pattern with an r^2 value of at least 80% of the observed pattern, and 13 of the 16 producing a pattern with an r^2 value of over 50% of the observed pattern. For East Antarctica and King Hakon VII, the number of model simulations with patterns that can account for at least 50% of the observed pattern is 12 and 4 respectively.

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However, during the retreat season, the simulated patterns are less consistent with the observed patterns. Only in the Weddell sector do more simulations produce patterns that can account for over 50% of the variance in the observed pattern during retreat (5) than in advance (0). In the Ross/Amundsen sector, simulations during ice retreat continue to reflect the observations reasonably well, though not as strongly as in advance. In the remaining sectors, especially East Antarctica and the Amundsen/Bellingshausen, the simulations largely do not capture the observed SIE and SLP correlations during retreat.

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These results have shown that the models have varying levels of success in representing the atmosphere's impact on sea ice variability. It is particularly interesting that the models reproduce these atmosphere-sea ice interactions more strongly during the period of advance than during retreat, especially given the strong representations in the Ross/Amundsen and Amundsen/Bellingshausen sectors, and that ice advance is the period during which model trends of SIE in these sectors deviate most significantly from the observed trends (Hobbs et al., 2015; Hobbs et al., 2016). Given the discrepancy between simulated and observed SIE trends, it is pertinent to consider whether the extent to which models represent observed atmospheric variability also impacts upon their representation of sea ice trends. To examine this issue, the same pattern correlation values discussed above are plotted for each model against that model's SIE trend for that sector and season, which is calculated using the ensemble average of the model's historical simulation (Figure 3). The observed trend for each sector and season is plotted as a red dotted line. There does not appear to be a strong relationship between higher pattern correlation values (indicating close agreement between the model correlation maps and that of the reanalysis) and the proximity of model SIE trends to observed SIE trends in each sector and season. This is most clearly noticeable in the Ross/Amundsen, the Amundsen/Bellingshausen and East Antarctica, particularly during advance (Figures 3a, 3c, and 3i). In these sectors, although

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the representation of the reanalysis correlations is generally strong, a wide spread in trend values is also evident. These results suggest that a model with an interannual sea ice-atmosphere interaction pattern that closely represents the observed pattern will not necessarily also produce realistic sea ice trends.

4.3 Model representation of large-scale atmospheric modes

The leading atmospheric mode produced by the EOF analysis of ERA-Interim SLP data clearly displays the spatial pattern of the circumpolar SAM and the associated ASL, explaining 36% of the variance in SLP during advance and 40% during retreat (Figure 4a and 4b). The second and third eigenvectors illustrate the spatial pattern of the PSA (Mo and Ghil, 1987). These two PSA modes were added together to produce a single mode representing the influence of tropical forcing on the high southern latitudes, in order to compare observation-based and simulated tropical impacts on sea ice (Figure 4c and 4d). The combined PSA EOF accounts for 27% of the variance in SLP during advance and 21% during retreat. The EOF analysis was then conducted on the individual ensemble members of each model, revealing the forced climate response of each model member. Individual ensemble member EOFs can be seen in Figure S3. These were then correlated with the EOFs from ERA-Interim (Figure 5).

The results are explained using two metrics. The first metric, correlation values, is used to indicate the strength of the simulated representation of the spatial pattern seen in the reanalysis. A correlation value close to 1 indicates good representation of the pattern, while values near 0 indicate little resemblance between the two. A second metric was created by dividing the amount of atmospheric variance explained by the model EOF by the amount of variance explained by the observation-based pattern, creating a ratio of the percentage of variance explained. A ratio of 1:1, which would appear on the dotted curved reference line, would indicate that the amount of variance explained by the pattern in the models is the same as the amount explained in the observation-based pattern, while a higher or lower ratio, appearing above or below the dotted reference line, would indicate whether the model is over-representing or under-representing the influence of this atmospheric pattern.

The first EOF shows loose clustering across the ensemble members, indicating general agreement within individual models in their representation of the spatial pattern of the SAM during both ice advance and ice retreat (Figures 5a and 5b). Of the 73 individual ensemble members used in the study, 68 during advance and 45 during retreat produced a reasonable spatial pattern of the SAM as evidenced by correlation values greater than 0.7. No ensembles during either advance or retreat obtained correlation values of 0.5 or less. In terms of the percentage of atmospheric variance explained by the simulated patterns compared with that of the observation-based pattern, the patterns of 45 ensemble members during advance and 60 during retreat account for a ratio of variance higher than the 1:1 ratio that indicates agreement with the variance explained by the reanalysis. This shows that the relative influence of SAM is overestimated in a large proportion of models, particularly during the season of ice retreat, consistent with Haumann et al. (2014). The response of sea ice to SAM is stronger during retreat than

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during advance, so the amplification of the simulated influence of SAM occurs most strongly when the SAM matters most to simulated SIE.

The combined second and third EOFs show a large spread of correlations across the ensemble members during both ice advance and ice retreat (Figures 5c and 5d). The spread occurs across the ensemble members generally, and also across the ensemble members of individual models. An implicit assumption in this comparison is that the PSA observed during the period 1979-2014 is a stable mode over longer timescales than are observed; a caveat could be that the PSA may change over long timescales, and differences between the spatial representation of PSA in different ensemble members may represent the influence of multidecadal variability.

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During advance, 32 ensemble members produce a PSA pattern with a correlation greater than 0.7, while during retreat only 21 ensemble members achieve this. Meanwhile, 29 ensembles during advance and 60 during retreat produce patterns that have correlations with the reanalysis of less than 0.5. This indicates that a substantial proportion of ensemble members – indeed, the majority of ensemble members during retreat – do not produce a reasonable representation of tropical teleconnection in the high southern latitudes. Furthermore, the PSA patterns for 54 of the ensemble members during advance and 51 during retreat explain a lower percentage of atmospheric variance than the reanalysis. The overarching implication here is that for most ensembles, the SAM mode dominates atmospheric variability, creating a stronger zonal pattern than is seen in the reanalysis. The variance explained by the tropical mode is comparatively weak in these ensembles as a result, and the simulated patterns of the PSA are generally weak representations of the observation-based PSA pattern. This is perhaps unsurprising, given that even basic ENSO characteristics are known to be weakly represented in the CMIP5 models (Guilyardi et al., 2012; Bellenger et al., 2014), and therefore the high-latitude teleconnections would be expected to be likewise underestimated.

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These metrics test the strength of SAM relative to the PSA in each model, but do not indicate the amount of variability of each mode in the models compared with observed variability. To test this, the variance of each ensemble member principal component timeseries corresponding to each of the three EOFs was compared to the variance of the same principal component timeseries in the reanalysis data during the seasons of sea ice advance and retreat (Figure 6). The results show that the absolute variance of both SAM and PSA is substantially less than observed variability in these modes across both seasons, despite the models overestimating the percentage of variance in the data explained by the SAM. The close clustering of the ensemble members relative to the reanalysis indicates that these ensemble members generally underestimate variability in large-scale atmospheric modes. However, though simulated large-scale atmospheric variability appears to be underestimated, it is well known that sea ice variability in the Southern Hemisphere is generally too high in the models (Zunz et al., 2013).

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The relative influence of the SAM and PSA on SIE in the historical ensembles as compared to ERA-Interim is shown in Figure 7. Correlations of the EOFs and SIE using piControl ensembles (not shown here) were consistent with the correlations using historical ensembles for both advance and retreat, as the detrending of historical ensembles reveals interannual variability rather than the forced response of the historical members. Observed correlations between SAM and SIE, shown by the dark blue line, indicate the strong regional heterogeneity in this relationship in several sectors around Antarctica during both seasons (Hosking et al., 2013; Turner et al., 2013b; Fogt and Wovrosh, 2015; Raphael et al., 2015; Turner et al., 2015b). However, modelled interactions between SAM and SIE, shown by the grey lines, indicate no clear regional discrimination, particularly during retreat when the strong correlation over the Ross/Amundsen Seas sector falls outside of the 1.96 standard deviation (as shown by the black line towards the top of the grey lines). The multi-model mean (shown in red) shows an overall zonal pattern with weak correlations between SAM and SIE that are largely consistent across the range of longitudes, while the +/- 1.96 standard deviation indicates a similarly zonal pattern. The correlations of simulated PSA and SIE in historical ensembles (Figure 6c and 6d) likewise lack regional distinction, with a largely zonally-symmetric pattern during retreat and a similar zonal pattern during advance that has a slight increase in strength around the Amundsen/Bellingshausen sectors. Once again, the multi-model mean of historical ensembles is zonal with very weak correlations and the +/- 1.96 standard deviation indicate that the models do not represent the spatial variability of this mode and its interaction with sea ice that are known to be important in the observational record (Simmonds and Jacka, 1995; Kwok and Comiso, 2002; Turner, 2004; Yuan, 2004; Simpkins et al., 2012).

Discussion and Conclusions

By expanding upon the approach of Raphael and Hobbs (2014), this study has provided insight into the representation of interannual sea ice-atmosphere interactions in CMIP5 models. The metrics used in this study showed that piControl simulations had surprisingly good skill in representing the observed atmosphere-sea ice interactions in several sectors. Interestingly, the representation of these interactions more closely reflected observations during the season of sea ice advance than during retreat. The results from Section 4.2 provide evidence that during advance, the models largely capture the response of sea ice to atmospheric drivers. In the advance season, the modelled sea ice trends diverge most significantly from observed trends, particularly in the Ross/Amundsen and Amundsen/Bellingshausen sectors where the highest-magnitude trends are also observed (Hobbs et al., 2015; Hobbs et al., 2016). Simulated representations of atmosphere-sea ice interactions during advance which more closely reflect observed interactions do not appear to lead to an improved representation of sea ice trends. It has been shown that sea ice trends in some sectors during advance are driven by changes in the previous retreat season (Holland, 2014). If observed and modelled sea ice trends during advance are sensitive to changes in interactions between sea ice and the atmosphere during retreat, this could explain why simulated sea ice trends in some sectors are most significantly different from the observations during advance despite the close representation of observed interannual atmosphere-ice interactions during this season.

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It has previously been established that the observed influence of SAM and ENSO on high southern latitude climate is strongest during the late southern winter and spring (Jin and Kirtman, 2010; Simpkins et al., 2012). However, during both sea ice advance and retreat, the majority of historical simulations overestimated the relative importance of the SAM and underestimated that of the PSA. The amount of variance in the models explained by the PSA is generally weak compared with the representation of SAM, which is also much more zonal than observed. The interannual relationship between SAM and sea ice also lacks regional variation, which is known to be substantial particularly in the Ross, Amundsen, Bellingshausen and Weddell Seas. The relationship between the PSA and sea ice likewise does not show strong regional variation. If the simulated zonal atmospheric influence overwhelms meridional influence, it follows that simulated sea ice variability would become more zonally symmetric as a result. However, the absolute magnitude of large-scale atmospheric variability being generally very low in the models compared with observations, while simulated sea ice variability is known to be generally too high, suggests that large-scale atmospheric modes in the models may explain less of the discrepancy between modelled and observed sea ice trends than previously thought.

The absence of a strong observed influence of large-scale atmospheric modes in several sectors indicates that while large-scale atmospheric variability is a strong and important influence on sea ice in some sectors, it may not be the dominant driver of sea ice change around all of Antarctica. Other possible drivers for some sectors include sub-synoptic scale wind forcing (such as the variability of the Ross Sea Polyna driven by katabatic surges, drainage and barrier winds over the Ross Sea (Bromwich et al., 1998), atmospheric variance not explained by the major modes, or the ocean.

Acknowledgements

The authors thank Dr Marilyn Raphael, Dr Rob Massom, and two anonymous reviewers for their helpful comments in the preparation of this manuscript. SS was supported by an Australian Government Research Training Program Scholarship through the University of Tasmania/CSIRO Quantitative Marine Science Programme, and CMIP5 data management was supported by the Australian Research Council Centre of Excellence for Climate System Science. Data analysis and visualisation was performed using NCL (http://dx.doi.org/10.5065/D6WD3XH5). We acknowledge the World Climate

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Research Programme's Working Group on Coupled Modeling, which is responsible for CMIP, and we thank the climate modelling groups (listed in Table 1) for producing and making available their model output. For CMIP the U.S. Department of Energy's Program for Climate Model Diagnosis and Intercomparison provides coordinating support and led development of software infrastructure in partnership with the Global Organization for Earth System Science Portals. This work was supported by the Australian Government’s Cooperative Research Centres Programme through the Antarctic Climate and Ecosystems Cooperative Research Center (ACE CRC), and contributes to AAS Project 4116.

Table 1: Summary of models from the Coupled Model Intercomparison Project Phase 5 (CMIP5) used in the study, showing the Institution/Modelling Centre and official model name

Modelling Centre/Group	Model Name
Commonwealth Scientific and Industrial Research Organization (CSIRO) and Bureau of Meteorology (BOM), Australia	ACCESS1.0 (Bi et al., 2013)
CSIRO and BOM, Australia	ACCESS1.3 (Bi et al., 2013)
Beijing Climate Center, China Meteorological Administration	BCC-CSM1.1 (Xiao-Ge et al., 2013)
Canadian Centre for Climate Modelling and Analysis	CanESM2 (Arora et al., 2011)
National Center for Atmospheric Research	CCSM4 (Gent et al., 2011)
Community Earth System Model Contributors	CESM1-CAM5 (Neale, 2010)
Centre National de Recherches Météorologiques / Centre Européen de Recherche et Formation Avancée en Calcul Scientifique	CNRM-CM5 (Voldoire et al., 2013)
LASG, Institute of Atmospheric Physics, Chinese Academy of Sciences and CESS, Tsinghua University	FGOALS-g2 (Li et al., 2013)
NOAA Geophysical Fluid Dynamics Laboratory	GFDL-CM3 (Griffies et al., 2011)
Institut Pierre-Simon Laplace	IPSL-CM5A-LR (Mignot and Bony, 2013)
Institut Pierre-Simon Laplace	IPSL-CM5A-MR (Mignot and Bony, 2013)
Atmosphere and Ocean Research Institute (The University of Tokyo), National Institute for Environmental Studies, and Japan Agency for Marine-Earth Science and Technology	MIROC5 (Watanabe et al., 2010)
Max-Planck-Institut für Meteorologie (Max Planck Institute for Meteorology)	MPI-ESM-LR (Jungclaus et al., 2013)
Max-Planck-Institut für Meteorologie (Max Planck Institute for Meteorology)	MPI-ESM-MR (Jungclaus et al., 2013)
Meteorological Research Institute	MRI-CGCM3 (Yukimoto et al., 2012)
Norwegian Climate Centre	NorESM1-M (Bentsen et al., 2012)

Figure 1: Cross-correlations (significant at 95%) of observed SIE with ERA-Interim SLP from 1979-2014 during advance (a,c,e,g,i) and retreat (b,d,f,h,j). Red dotted contours indicate negative correlations, where a decrease in sea level pressure is associated with an increase in sea ice extent; blue contours indicate positive correlations, where a decrease in sea level pressure is associated with a decrease in sea ice extent. Black lines show sector boundaries.

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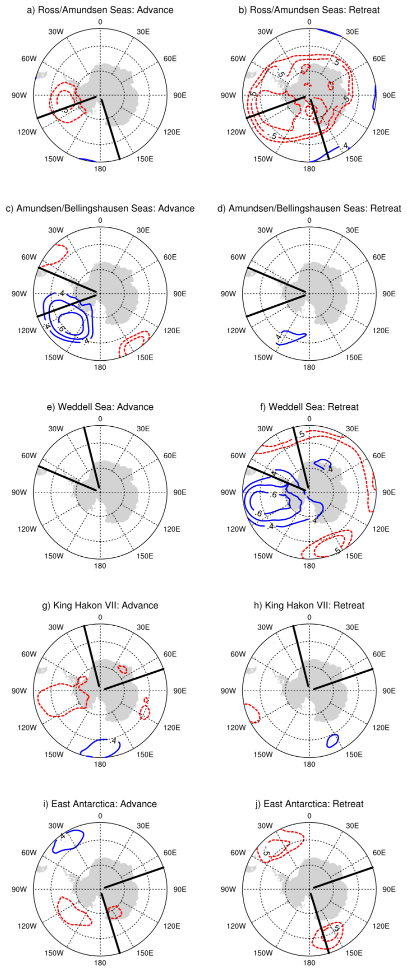

Figure 2: Pattern correlation values comparing observations and CMIP5 piControl ensemble correlation maps of SLP and SIE in the (a) Ross/Amundsen Seas; (b) Amundsen/Bellingshausen Seas; (c) Weddell Sea; (d) King Hakon VII; and (e) East Antarctica sectors. Dotted lines at 0.7 and 0.9 show the point at which the coefficient of determination, r^2, is equal to 50% or 80%, respectively. The diagonal line indicates where correlations for both seasons would be in agreement.

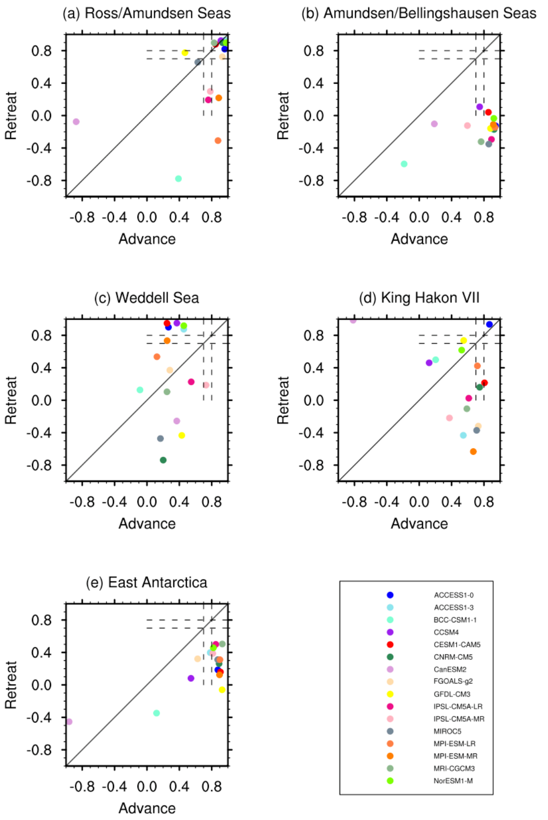

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Figure 3: Pattern correlation values comparing observations and CMIP5 model correlation maps of SLP and SIE against the model historical (1979-2005) SIE trends for: Ross/Amundsen Seas (RAS) during (a) advance and (b) retreat, Amundsen/Bellingshausen Seas (ABS) during (c) advance and (d) retreat, Weddell Sea (WS) during (e) advance and (f) retreat, King Hakon VII (KH) during (g) advance and (h) retreat, and East Antarctica (EA) during (i) advance and (j) retreat.

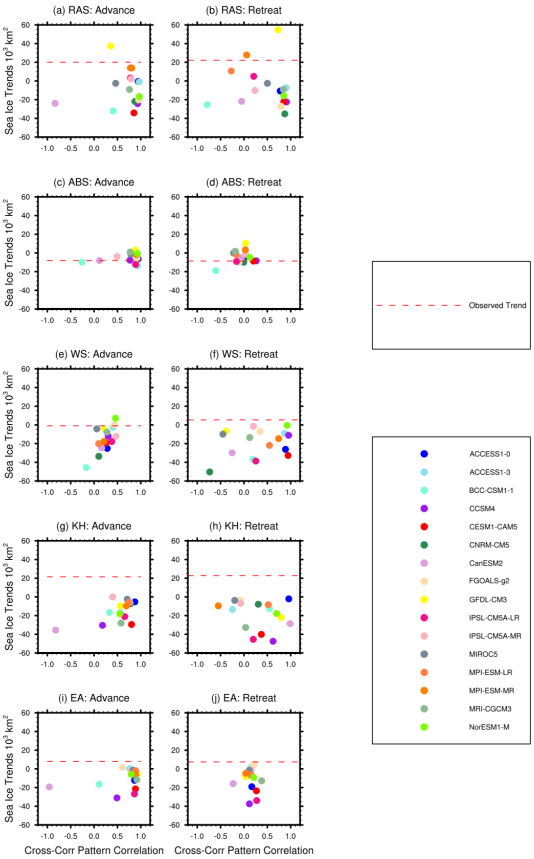
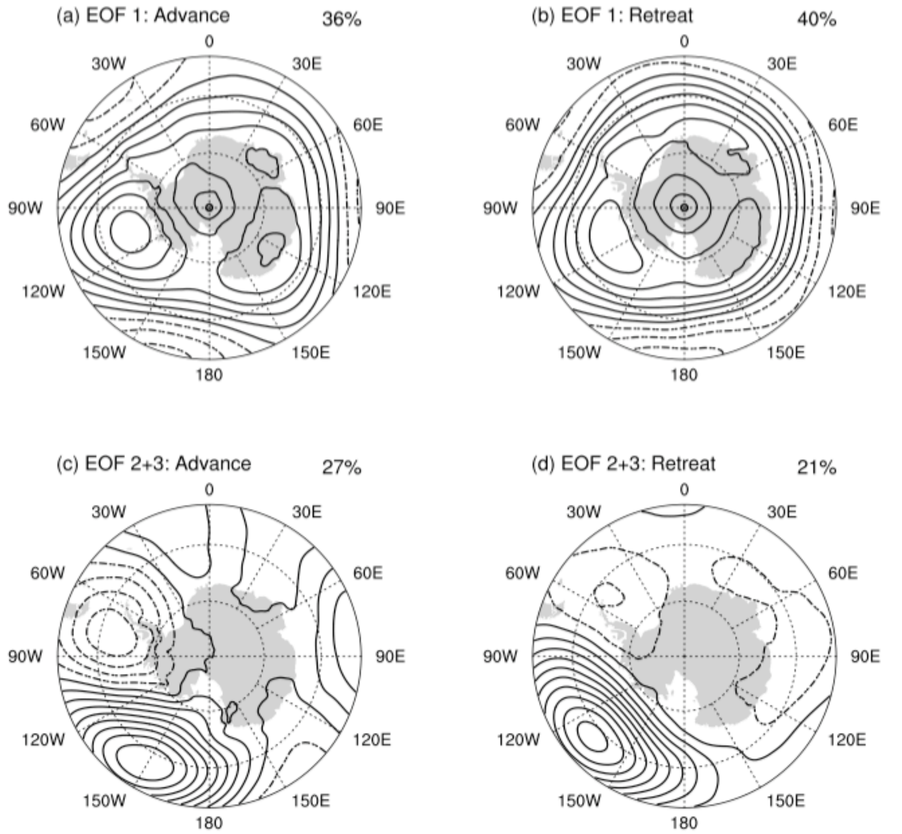


Figure 4: Eigenvectors of ERA-Interim SLP (1979-2014) in the Southern Ocean for advance (a,c) and retreat (b,d). Numbers at top right indicate the percentage of variance in the data explained by each pattern.



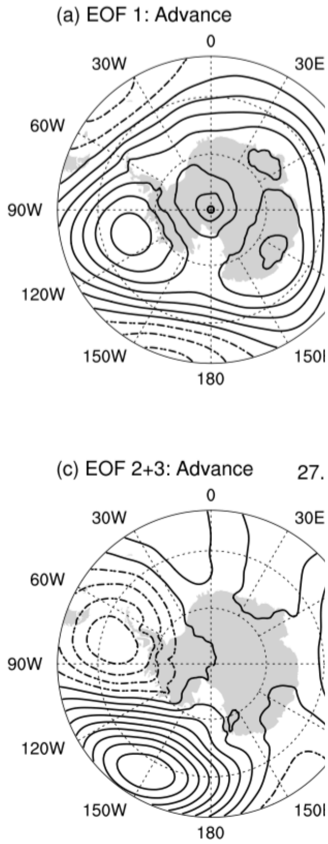


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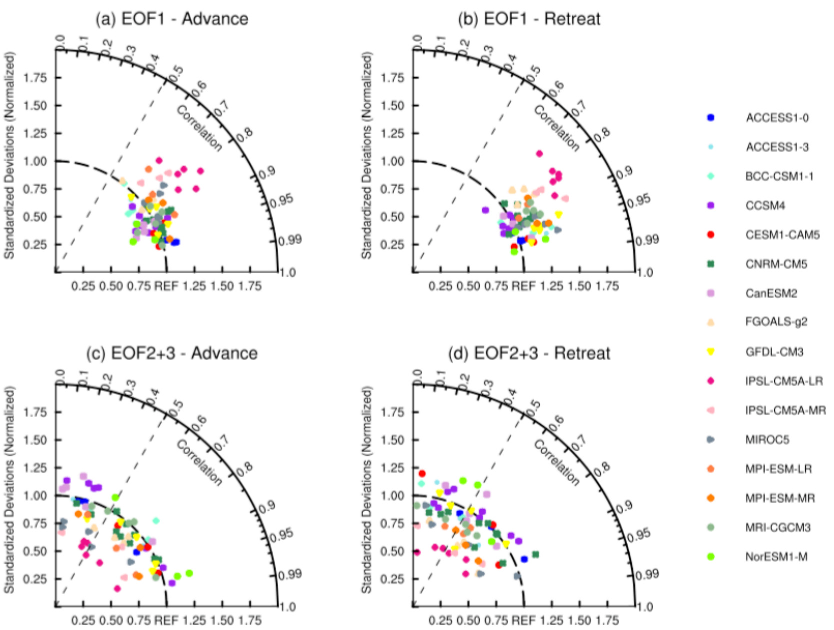
Figure 5: Taylor diagram showing the pattern correlation value (curved outer line) comparing historical CMIP5 ensemble and ERA-Interim SLP eigenvectors, and the percentage of variance explained by each pattern in the historical ensembles as a ratio of the observations for EOF 1 during advance (a) and retreat (b) and the combined EOFs 2 and 3 during advance (c) and retreat (d).



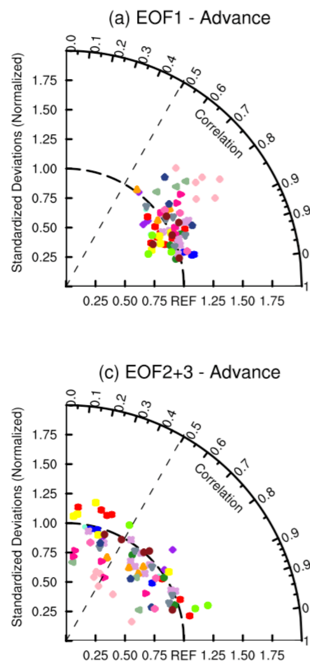


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Figure 6: Absolute variance during sea ice advance and retreat of the corresponding principal component time series for (a) SAM, (b) PSA1 and (c) PSA2. The black markers indicate CMIP5 ensemble members; the red marker indicates ERA-Interim reanalysis.

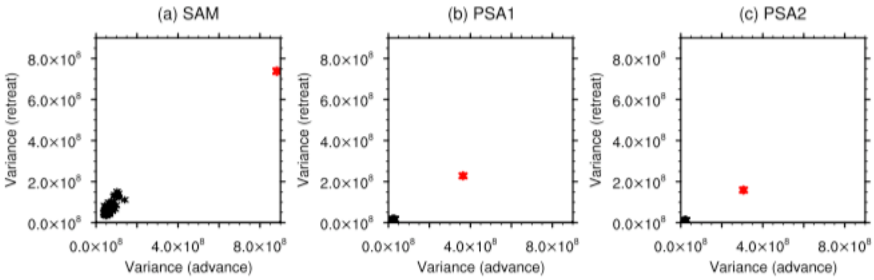

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Figure 7: Cross-correlation of SIE with historical (1979-2005) SAM during (a) advance and (b) retreat; with historical (1979-2005) PSA during (c) advance and (d) retreat. The blue line indicates observation-based correlations, with the light blue shading depicting the 95% confidence interval. The red dotted line shows the multi-model mean, and the pale grey lines show individual model correlations. The thin black lines at the edge of the grey lines shows the 1.96 standard deviation from the simulations at each longitude point, while the horizontal black line shows the zero line for reference.

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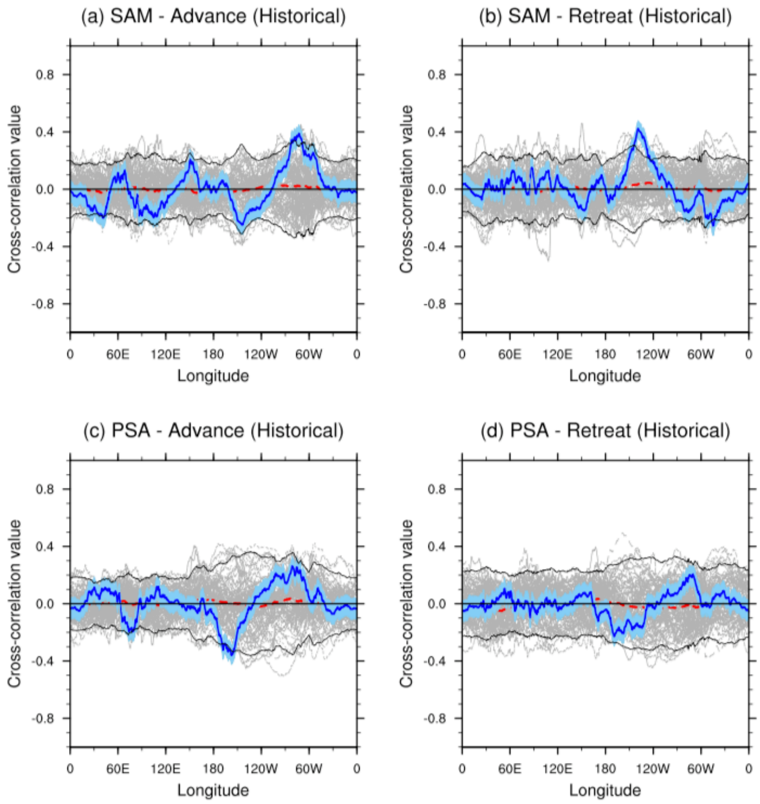

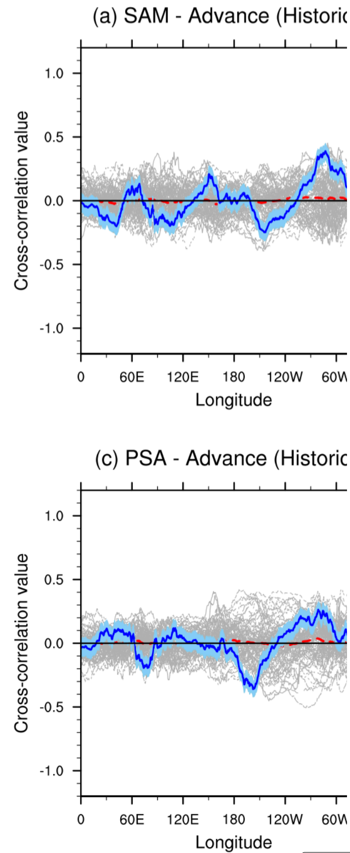

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Figure S1: As in Figure 4, eigenvectors of ERA-Interim SLP (1979-2005) in the Southern Ocean for advance (a,c) and retreat (b,d). Numbers at top right indicate the percentage of variance in the data explained by each pattern.

Figure S2: Cross-correlations (significant at 95%) of SIE with SLP for CMIP5 piControl members overlaid on observed cross-correlations during advance (a,c,e,g,i) and retreat (b,d,f,h,j). Black contours indicate observations; red dotted contours indicate negative model correlations; blue solid contours indicate positive model correlations. Black lines show sector boundaries.

Figure S3: Individual CMIP5 model historical ensemble member eigenvectors of SLP (1979-2014) in the Southern Ocean showing the SAM (EOF1) and the PSA (combined EOFs 2 and 3) for advance and retreat. Numbers at top right indicate the percentage of variance in the data explained by each historical ensemble member pattern.

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Model data from the piControl experiment were chosen for this analysis to isolate the unforced variability in the models. Sector boundaries for SIE were based on those of Raphael and Hobbs (2014): East Antarctica (71°E - 163°E, Ross/Amundsen (163°E - 250°E), Amundsen/Bellingshausen (250°E - 293°E), Weddell (293°E – 346°E) and King Hakon VII (346°E-71°E). As with the observations, sector-integrated model SIE for advance and retreat was correlated with model SLP for the same seasons, producing

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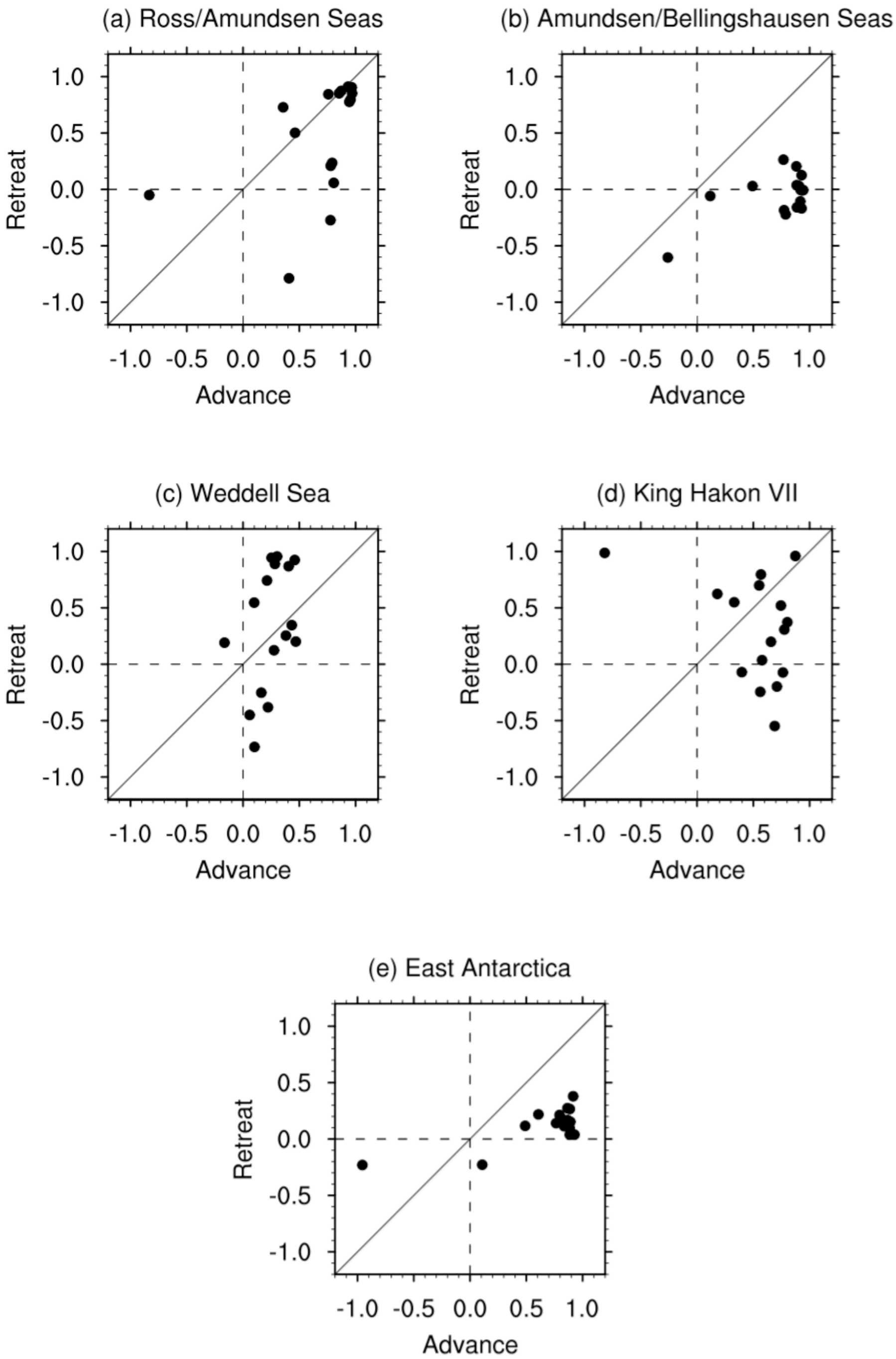
(a) Ross/Amundsen Seas
(b) Amundsen/Bellingshausen Seas
(c) Weddell Sea
(d) King Hakon VII
(e) East Antarctica
Retreat
Advance
1.0
0.5
0.0
-0.5
-1.0

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