We would like thank Reviewers for scrutinizing our manuscript and very valuable comments that helped us to rework our study and, hopefully, to improve both scientific content and presentation.

One of the major points raised by all reviewers was a problem of interpolation of model data on relatively coarse 2x2 grid. The reason to choose this grid was originally related to the inter-comparison with CMIP3 models that in general have a similar to 2x2 resolution. We agree that such a coarse grid can be a source of errors particularly for regional analysis. Moreover, 2x2 interpolation also distorts HadISST1 data that are originally on 1x1 grid.

Therefore, we have redone ALL figures and analyses after interpolating original data on 1x1 degree resolution that, for the majority of models, is better than or similar to the original model data. This is why the revision took us a longer time. While reducing the errors related to interpolation from finer grid to a coarser one, this also allowed us to compare the results for both interpolations and to estimate associated differences.

The major outcome of the comparison of the results based on 2x2 and 1x1 interpolation is that they are rather similar and do not qualitatively modify the originally made conclusions. This was, in particular, the case for the Barents Sea where a relatively coarse 2x2 resolution raised a concern about area-averaged data. SIC variability pattern also did not change much with somewhat sharper gradients around ice edge.
There are, however, noticeable (mainly) systematic differences. In March, Entire Arctic CMIP3 ensemble mean SIA systematically increases by about 0.5 mln.km2, whereas CMIP5 results remain basically unchanged. In Central Arctic, SIA becomes about 0.4 mln.km2 larger in both ensembles. Interestingly, Barents Sea SIA (ensemble mean) is only slightly affected by new interpolation. Ensemble mean Entire Arctic SIA also shifts up in September by about 0.3-0.4 mln.km2 with major portion of these changes accounted for Central Arctic. Barents Sea results are, again, only slightly modified.
Systematic shifts also affect SAT-SIA regression figures but the regression slopes remain basically unchanged.
For the seasonal cycle amplitude, the new interpolation impacted more HadISST1 data than CMIP models with similar relative changes as for 2x2 interpolation.

While recalculating the figures, we found a principle mistake in the script used for plotting figure 9. It is now totally different and leads to different conclusions.

Due to consistent and reasonable critics of all Reviewers related to AMOC analysis, we fully removed this sub-section. It was indeed very loose and ambiguous.

Another common comment was related to statistical significance of the correlations in figs.10-13 (original figs.10-11 related to AMOC are deleted now). Significance level (90%) is now indicated. The significance level was adjusted to effective sample size computed based on lag-1 autocorrelation (e.g., as in Stroeve et al. 2012).

The Reviewers also consistently pointed out the absence of discussion of empirical data uncertainty. We now included it in the Data and methods section. We do realize that HadISST1 dataset (mainly based on NASA Team algorithm) may not be the best representation of reality concerning sea ice concentration. However, it has been widely used to represent historical SIC changes in many studies including IPCC AR5. Also,

these data were used as boundary conditions in ERA-40 and ERA Interim reanalyses, and similar data (Reynolds OI) were used in NCEP reanalysis.

As proposed by Reviewers, we tried to shortened the text.

Below, we respond to the comments of each Reviewer in a point-by-point manner.
Our replies are in bold text.

Anonymous Referee #1

Authors compare different characteristics of Arctic sea ice concentration and area in CMIP3 and CMIP5 simulations for the Entire Arctic Ocean, central Arctic and Barents Sea. Paper also explore connections between sea ice area variability in this simulations and different climate indexes, such as Northern Hemisphere average temperature, AMOC, NAO, SLPG.

##General comments
Sea ice results of CMIP3 and CMIP5 experiments were already investigated and compared in several studies. Authors try to distinguish from them by using mainly sea ice area instead of concentration, by looking at some regional aspects of sea ice variability in projections and by comparing observed and projected sea ice variability to different climate indexes. I think if done properly it could be an interesting exercise that enhance our understanding of sea ice variability mechanisms in CMIP projections. However I find the paper purely descriptive. Authors make some attempts to explain what they observe, but all of them are speculative, and not supported by any additional analysis. Moreover I find several serious flaws in the methodology.
I do not recommend to publish the paper in the present from in "The Cryosphere".

We have substantially revised the manuscript aiming to address all concerns, see the introductory part for major revisions.

##Specific comments

Authors were not able to properly explain advantages, or any additional benefits of using SIA instead of SIC for this kind of analysis. On contrary, I believe that for the Entire Arctic model/data intercomparison use of SIA is a disadvantage, since there are no proper observations of SIA around the North Pole, and we can't make assumptions, that are valid in case of SIE in this region.

We agree that interpreting empirical estimates of SIA in Central Arctic should be done with keeping in mind the outlined problems. This is now discussed.
We believe, however, that both SIE and SIA are equally interesting parameters. In many papers, in particular those dealing with uncertainty of satellite data (e.g., in the most recent ones by Notz 2014 and Ivanova et al. 2014) both characteristics are discussed.
We agree that using SIE helps to reduce the uncertainty and thus represents a convenient parameter for inter-comparison. But this is done at the expense of loosing information, since below (and above) threshold values are assigned to the same SIA.
The atmosphere sees sea ice area, not extent. Regional SIC difference even in 20% range (say, from 40% to 60%) may results in principally different atmospheric circulation

response as was shown, e.g., by Petoukhov and Semenov (2010) by analyzing AGCM simulations, or, as previously shown, some 7% change in SIC modifies regional SAT by 6K (Parkinson et al. 2001). We may also cite Notz (2014): "SIA is more relevant for air-sea interaction processes. Important physical quantities such as Arctic wide average albedo, open-water fraction and thus ocean–atmosphere heat exchange depend therefore much more directly on sea-ice area than on the non-linear measure sea-ice extent."
Furthermore, the CMIP models do not have problems with data gaps or, e.g., interpreting ponds (though there may be problems with representing them). Why not use the full data information provided by the models? The main goal of our study is to illustrate how SIA characteristics evolved with development of the new generation of climate models.
Finally, not to forget that a usage of SIE has historical roots. In the era of pre-satellite and regular airborne measurements, this was a parameter derived from visual reports. It is an advantage nowadays that we may observe SIC and SIA from above.
Therefore looking at SIA characteristics does not seem to us to be a disadvantage, and the existence of 600 or 300 km (depending on satellite) data gap around the North Pole is not a reason to avoid SIA analysis.

Decisions about choice of the data sets or specific scenarios to include or exclude from the analysis are not justified and look almost as made randomly, or by just choosing ones that are most convenient for authors or show better results. Most importantly I question choice of HadlSST sea ice data set as source of information about sea ice area in the Entire Arctic. I also believe, that errors introduced by data interpolation to the 2x2 degree grid have to be discussed.

RCP8.5 is "business as usual" scenario that is often used to for analyzing climate change under aggressive anthropogenic forcing. RCP4.5 is chosen as it is another popular (for analysis) scenario and SRES A1B scenario lays in between of those two.
We agree that 2x2 interpolation is outdated for analyzing CMIP5 models. The data are interpolated on 1x1 grid that is similar to the resolution in most of CMIP5 models and higher than the resolution of the majority of CMIP3 models.

Analysis of SIA relation to AMOC, NAO and other indices rely on correlations that do not have information about their statistical significance. Most of the correlations are small, and taking in to account shortness of the time series and applied smoothing (running mean) I suspect that only very few correlations are actually statistically significant. Moreover there are no clear conclusions made from described relations.

AMOC section is removed. Significant correlations are indicated now. As in the answer to Reviewer 3, we note that our purpose was not to provide the insights to mechanisms of atmospheric circulation impact on SIA variability. We aim to assess whether or not CMIP3 and CMIP5 models are in principle capable to reproduce those two important links. If yes – which and how many models, and how this link gets modified in the warmer future in comparison to the present day climate.

##Detailed comments

###Abstract

The abstract is very long and do not really serve the purpose of giving short condense information about the paper. I suggest you rework it considerably.

The abstract is now shortened.

P 1078

5-6: ... to anthropogenic forcing, the models ... You don't need "the models" here

Deleted

7-12: this paragraph does not belong to the abstract

The paragraph is removed

17: ... termed Entire Arctic ... Remove

Removed

18-23: You can fit it in to one sentence, without mentioning every index you have investigated, since you not talking about results here anyway.

Done

P 1079

2: . . . response to anthropogenic forcing is different . . . I think "different" is too strong a word here, sounds like they are really very far apart, while in fact there are just some variations, but, say, the sign, or spatial pattern are not really changed.

This sentence is modified. While redoing the analysis with 1x1 interpolated data, we found an error in the variability analysis. The figure 9 looks different now and the conclusions are changed accordingly.

5-7: Opposite between September and March or between CMIP3 and CMIP5?

Following the suggestions of the Reviewer 3, we removed the whole section about AMOC. We agree that our analysis of AMOC at 30N and SIA is hard to interpret and it does not help to get physical insights.

###Introduction

Introduction is also very long. I suggest several cuts, but I think authors should put more effort to make it shorter and clearer.

We shorten the introduction further (after deletions suggested by all reviewers), although, to our opinion, a bit more-extensive-than-usual introduction could be useful for a non-expert reader.

16: Better cite the original paper where this is stated than IPCC report in general. Or at least give a chapter in the report.

Done

24-27: I think this kind of statements belong rather to popular literature than to technical scientific paper. Remove.

Removed

P 1080

1-2: Antarctic is not considered in the paper. Remove.

Removed

18-21: You do not discuss thickness in the rest of the paper. Here mentioning the thickness decrease might be appropriate if connected to SIE retreat. But I would just remove the whole paragraph.

Removed

23: You use the term “Entire Arctic” here, but define it only at the page 1082.

Changed to “whole Arctic” here

P 1081

7: replace sea ice extent with SIE.

Done

8: replace sea ice extent with SIE.

Done

18: may be? I guess it IS strongly influenced, as supported by the references you list afterwards.

Corrected

P 1083

20-22: Any references to support this statement?

There are misplaced citations. This statement is illustrated by Fig. 9.2 from IPCC AR5 (Flato et al., 2013). Whereas the next sentence should be followed by citing Chapter 12 (Collins et al., 2013), which is a basis for Fig. SPM.8 from Summary for Policymakers. Corrected.

###Data and methods

This section completely lacks discussion on data uncertainties. The fact that satellite data were not used directly is very unfortunate.

The data uncertainty is now discussed in Data and methods section.

P 1085

3-6: I would not call HadlSST1 data “observations”. They are reconstructions based on observations, but as you mentioned further, very sparse observations. Quality of pan Arctic estimates of the sea ice concentration obtained before “satellite era” is very questionable, and they are certainly hardly qualifies to be “observations”

“Observations” is changed to “Empirical reconstructions”

3-6: When using HadlSST data for similar study Stroeve et al. 2012, make an adjustment to reduce overestimated sea ice concentration. Why you do not do this?

Stroeve et al. required the adjustment procedure in order to expand the satellite-based estimates into the past with HadISST data. Since we employ HadISST data only in our study, we do not apply any adjustment. We note that HadISST data (as it is) several times used in IPCC AR5 for representing historical sea ice extent changes. We also note that a variety (11) of sea ice concentration algorithms results in very different sea ice area estimates (with more that 1 mln.km2 spread for annual mean values, Fig. 1 of Ivanova et al. 2014, IEEE). This indicates that satellite based estimates are also rather uncertain with not much notion about which one is closer to reality.

11: What is the end of the period?

Stated in the text now (2014). We also modified the beginning of the period from 1950 to 1960, since the data from 1960s are better correlated with Arctic average temperatures.

17-18: Why this size for the target grid is chosen? What method of interpolation was used? What are the errors introduced by this interpolation (e.g. compare SIE and SIA calculated on original grid and on coarse resolution grid)?

Standard bi-linear interpolation was applied. As it was stated above, we have redone all analysis after interpolating model data on 1x1 grid. This is the same resolution as HadISST data and better or similar to resolution used in the majority of CMIP5 models (oceanic grid). This is now explained in the text.

21-23: You also should mention, that in your “observations” missing measurements from the satellites around the North Pole (due to satellite inclination) are just replaced by 100% concentrations. This is relatively reasonable approach for sea ice extent calculations, although in recent years there are more and more events with < 15% SIC around the North Pole. However for sea ice area calculations this is not acceptable, and this is why most of the papers dealing with pan Arctic sea ice only consider sea ice extent.

It is mentioned now.

27-28: It would be actually very interesting to estimate how big the impact of this error can be for different resolutions.

Please see discussion in the introductory part of our response

###Results

Discussions on the figures are very long with a lot of unnecessary details. I would concentrate more on the interesting features, and their implications for the analysis rather than on lengthy descriptions of the things that the reader can see on the pictures by himself.

We tried to shortened it.

P 1086

15 Before showing variability, it would be nice to show at least the mean ice edge for models and HadlSST if not the mean distribution of SIC. You can put the ice edge line over the panels of Fig. 1.

The ice age position (15%) is now depicted in SIC variability figures (1-3).

P 1088

1: show instead of simulate

Corrected

11-13: That would be a very strange idea, indeed.

The last sentence of this paragraph is removed.

15: remove "in response to anthropogenic forcing" – change in temperature is a response to anthropogenic forcing, change in the sea ice is a consequence.

Removed

15: Are there really some SD differences in March around 60N in the Atlantic to the south of Island (Fig.2 b,d,f)? I can't see any values there on Fig 1 e, or Fig 2 a,c,e.
26-27: I would remove (mask) places where SIC is zero in the projections, because otherwise this negative differences in SD are confusing, especially in September (Fig. 3). We would like to see changes in the sea ice variability, not changes between sea ice variability and open water. In other words if there is no ice – there is nothing to compare with (now it seems like there is ice with 0 variability).

As suggested, we now masked regions where SIC variability is zero in projections in figs. 2 and 3.

P 1089

9-10: Why only this scenario? Please explain.

One motivation was to illustrate rather consequences of stronger than weaker forcing ("business as usual"). This is now indicated in the text. Another reason was related to a number of figures. A presentation of another scenario would mean at least 6 additional figures.

16: remove of

Done

24: You can only talk about improvement for the period where you have "observations", which is from 1950 to something like 2014 (you did not specify this exactly in your data description).

It is changed to "for the period of observations". This period is now specified in the Data and methods section.

25: decreases compared to what?

Compared to the end of the 20th century. It is specified now.

P 1090

20: You forgot to mention that you also consider different RCP scenarios.

Here, the differences are discussed for the observational period. It is now specified. If you mean the difference between scenarios from 2005 onwards, we believe that this does not impact the overall picture for 1960-2014.

21-23: Your results are also depends on the grid cell area (especially considering that you interpolate to the very low resolution grid) and include many cells with low concentrations. I guess you have to mention this as well, if you start to compare your methodology to the one from Strouve et al., 2007, 2012. And I should mention once again – there is a reason why models more often compared to SIE rather than to SIA, it is lack of sea ice observations around the North Pole.

The whole sentence is removed. It is ambiguous.
See above our discussion about SIA and SIE.

23-24: Why it is better to keep outliers? This requires an explanation.

We did not say and do not mean that keeping outliers is a better approach than sorting them out. We just mentioned that as a possible source of the disagreement between our results and those of Strove et al. (2012). Both approaches, to our opinion, can be justified.

28: Decrease compared to what?

Specified now. Compared to the end of the 20th century.

P 1091

3-5: Or this indicates, that your “observations” overestimate sea ice in central Arctic. For example here is comparison of September SIC for HadlSST , NASA team algorithm (http://nsidc.org/data/nsidc-0051) and OSI SAF reprocessed data set (http://osisaf.met.no/p/ice/) (Fig.1). One can see that NASA team algorithm show lower concentrations in the central Arctic. It might not be true, of course, in reality (and “more advanced” OSI SAF seems to confirm higher concentrations), but this possibility should be discussed and possible errors should be evaluated.

We agree that the uncertainty of empirical data is high in Central Arctic in summer (both in HadISST1 and various satellite algorithms), and therefore conclusions about model performance should be made with caution. This is now indicated in the text. “Observed” is also changed to “HadISST1” in order to be more specific.

7-8: The 3 decades from present day is 2045, and your mean still show about 1x10ˆ6. Some models show sea ice removal, but it’s not a majority.

“majority” is changed to “part”

P 1092

4: It is not really clear to me what sharp decrease you talking about. It is for March or September? In the model data or in the HadlSST?

It is the observed accelerated sea ice loss in March. It is now clarified.

25: Why you all over sudden switch to Summer/Winter analysis, while before only use September and March? How we can relate results obtained in this section to your previous analysis?

When representing seasonality of sea ice variations, March and September values are usually used instead of seasonal means. Among the reasons is the interest to the highest and lowest sea ice extent, important from practical point of view. Another one is a problem with averaging over possible “open water” and “ice” conditions. However, we all know that March and September anomalies well represent winter and summer anomalies respectively. As to the temperature, multi-monthly values are usually considered in order to smooth differences in monthly fluctuations. Furthermore, temperature and sea ice variations are lagged. We thought that having both SIA and T averaged for the same seasons would be more consistent than regressing, say, March SIA on JFM or March temperature.

28: Why you didn’t include RCP 4.5 results on Fig. 6 and 7?

Only in order not to overload the figures. Doubled number of symbols make it hard to distinguish with model belongs to what ensemble cloud. The RCP4.5 results, however, are presented in the Table 3.

P 1093

24: Do you mean SIA instead of SIC?

SIA. Thank you for noticing!

26: Which century?

21st. Specified now.

28: Do you mean 2070-2100? If not please elaborate.

We meant here that given the majority of models with summer ice free conditions, the difference between present day (1970-2000) and future (2070-2100) values would only depend on present day values.

29: Once again – why you did not plot RCP 4.5 data?

Just for sake of clearer illustration (see comment above)

P 1095

23: “may be” instead of “may are”

Corrected

P 1098

10: With such a low number of points is it really meaningful to talk about correlation? Are you correlation values statistically significant?

Since we indeed can hardly draw any solid conclusions from AMOC analysis (we agree with Reviewer 3), AMOC section and figures 10 and 11 are removed.

20: Can you support this statement with a reference?

Not fully. Such a link was found by Semenov (2008) in MPI-OM model. However, other models show no such a link, as correctly noticed the Reviewer 2. We agree with that and, also following reasonable critics of the Reviewer 3, removed the ANOC section completely.

24: You have to provide information about statistical significance of your correlations. I guess with 9 year running mean and a lot of very small correlations that you show, only few (if any) models will pass.

Correlation significance level is now indicated in the figures (for NAO and SLPG). Figures 10 and 11 are removed.

26: Why 9 year running mean?

Since we focused on decadal to inter-decadal variations, 9-yr running mean seemed to be a reasonable smoothing to filter out inter-annual to intra-decadal variability. Again, Figures 10 and 11 are removed.

P 1100

14: Why in this case you use running mean with 5 year window? It is not consistent with your previous 9 year window for AMOC.

Alone with inter-annual variability, Arctic sea ice and ocean is dominated by decadal and multi-decadal variability (e.g., Polyakov and Johnson, 2000, GRL) that is presumably internally generated. We cannot estimate multi-decadal variability with 70-yr time slices. Therefore we focus on interannual and decadal variability. The latter is reasonably well filtered by 5-yr running means.

20: I don't really see the point of showing correlations that are not statistically significant.

Now, we show significant correlation levels. Since, e.g., negative correlation between Barents SIA and SLPG has a physical background, we believe that showing that the majority (or all) models demonstrate negative correlation may be a useful information.

21: Here is the only time you mention statistical significance of your correlations. However you have to do it for all your correlations. Below you discuss results for the data that were smoothed by 5 year running mean (Fig. 12 b,d), making the R that is needed to pass %5 about 0.54. For your Fig. 11 it is 0.71 (taking in to account 9 year window for running mean, so you reduce degrees of freedom considerably). Hardly any model on this figures pass this tests.

Significance is now indicated in the figures.

###Figures

Figure 4. It is better to have same 10^6 for y axis on every panel, otherwise it is hard to compare.

We thought we redid the figure as was requested but did not modify the script. We discovered it in the last moment and will correct it later leaving it as it is for a moment.

Figure 5. Same as for Fig. 4.

Same here

Figure 8. Please provide names of the scenarios.

Done

Figure 9. Is in really a "change", or just SD values?

These are SD values, not changes. Thank you!

Anonymous Referee #2

General: The article "Arctic sea ice area in CMIP3 and CMIP5 climate model ensembles – variability and change" by Semenov, Martin, Behrens and Latif analyzes seasonal and interannual sea ice area variations in three different Arctic regions in the 20th and 21st century in CMIP3 and CMIP5 models. The study shows that CMIP5 models simulate in general a somewhat more realistic Arctic sea ice area and variation compared to the CMIP3 for September. However, particularly in winter, biases are larger in CMIP5 than CMIP3. The CMIP5 models sea ice area seems to be more sensitive to greenhouse gas forcing compared to the CMIP3 ensemble. Uncertainties and errors in CMIP5 and CMIP3 are large. Links of the sea ice area to NAO and AMOC have been investigated. Many processes stay similar in the 20th and 21st century until most sea ice has disappeared in the respective region. The article is interesting and well written and structured. To my knowledge, it is the first study comparing sea ice area reductions and variations in CMIP3 and CMIP5 in more detail; most exiting studies focus on total Arctic extent only. The article is therefore of interest for the scientific community and I suggest accepting the article after responding to the mainly minor points below.

Main points:
1. One general problem with comparing sea ice variation fields averaged over the variations of the individual models is the spread in the position of the ice edge in the individual models. The sea ice concentration variations are normally largest near the ice edge. Thus, if a few models have e.g. very little sea ice during summer, the ice edge is situated far to the north in the Central Arctic. These models will then show high ice variations in the Central Arctic. As a consequence, also the ensemble mean shows too high ice variations in the Central Arctic compared to observed values and too little ice variations in the area where observations show the largest variability. The overestimated ice variations in the Central Arctic and underestimations along the observed ice edges in CMIP models are thus probably at least partly due to the spread in the models. It is thus problematic to draw from the ensemble mean the general conclusion that CMIP models overestimate sea ice variations in the Central Arctic and underestimate sea ice variations along the observed ice edges as done by the authors (e.g. Page 1087, lines 7/8 and in the summary-section). To validate this conclusion it is necessary to compare the variations at the respective ice edges of the individual models with the variations at the ice edge in observations. This would generate insight if models generally underestimate variations along their ice edge. Since it is difficult to show all CMIP3 and CMIP5 models in the figures, I would suggest showing a few "representative single models", e.g. (one with very low ice extent, one with average and one with high ice extent) or extract the area with largest variations in each individual model and showing time periods. Similar, even the comparison between CMIP3 and CMIP5 might suffer from the fact that CMIP5 consists of about twice as many models than CMIP3, thus the likelihood for extreme positions of the ice area is larger and we could expect a more smoothed variation pattern in CMIP5.

We plotted examples for maximal and minimal sea ice edges in Fig. 1 now. It is discussed in the text.

2. AMOC and SST-gradient between Scandinavia and Svalbard are used in this article mainly as index for the ocean heat transport. I have problems with this for the following reasons: AMOC (section Pages 1097 and 1098): I agree, the AMOC is highly related to heat transport at 30N and also up to 50N (or maybe even 60N). But the northern tip of the AMOC normally ends in the area of the convection regions in the North Atlantic and ocean heat fluxes north of this into the Arctic Ocean is not necessarily very good correlated to the AMOC. Processes in the northern North Atlantic, e.g. in the sub-polar gyre and atmospheric circulation (e.g. Karcher et al. 2003; Sandö et al. 2010) in these area strongly affect the heat transport into the Barents Sea as well. Koenigk and Brodeau (2014) found e.g. no significant correlation between the AMOC and the ocean heat transport into the Barents Sea on decadal time scales

in their model. This is obvious different in different models (e.g. in ECHAM5-MPIOM, Semenov 2008), however, indicates that the relation between AMOC and ocean heat transport into the Arctic is not as clear as formulated here. Furthermore, the statement “reduced AMOC implies reduced ocean heat transport into the Arctic” in the future is neither supported by models or recent observations. AMOC might already (there are no consistent observations) or is at least expected to weaken in future while ocean heat transport into the Barents Sea is according to observations (e.g. Skagseth et al. 2008) showing positive trends in the last decades and model simulations tend to project increase for the future, mainly due to increased ocean temperatures. This clearly indicates that the assumption made by many : “larger AMOC = more heat transport into the Arctic” is too easy. The AMOC is further very difficult to measure in real world; it is much easier to measure the ocean heat transport into the Barents Sea directly. This makes the AMOC in the real world to an index, which is very difficult to use for e.g. prediction of sea ice variations. SLP-gradient (Figure 13/ section 3.7.2): Although this SLP-gradient is important for the oceanic inflow into Barents Sea, it is likely also important for the atmospheric heat inflow. Further, a stronger gradient and thus stronger winds will transport the ice to the northeast, which would also reduce the SIA in Barents Sea. Thus, this gradient is not only reflecting the ocean heat inflow into the Arctic but a combined effect of ocean and atmosphere. If the main goal with both AMOC and SLP-gradient is, as it appears to me from the manuscript, to represent the ocean heat flux into the Arctic, it would be much better to directly use the ocean heat flux as index. I am aware that this would mean handling of a lot of data and a lot work to calculate the ocean heat fluxes from all CMIP models. Therefore, if the authors decide to keep AMOC and SLP-gradient as index, they should discuss the points mentioned above and should avoid the impression that these indexes excellently represent the ocean heat transport into the Arctic. Also interpretation of the correlations found should be made with care.

We fully agree with this comment. AMOC section is indeed ambiguous and loose. This is also indicated by two other Reviewers. Therefore, we removed this section.
We also agree that atmosphere not only drives oceanic inflow to the Barents Sea but directly impacts the sea ice dynamically and thermodynamically. We modified the text according to the reviewer’s comments.

3. In some parts, particularly in the introduction, the article would profit from some shortening.

We agree. We tried to shorten the text.

Minor points:
1. Page 1079, line 5: what is meant with “worse results for winter SIA characteristics”?

Worse agreement with observations. This part is rewritten now to make it clearer.

2. Page 1080, line 10/11: what is meant here: that recent winter SIE decline is similar to ETCW or that winter SIE decline was smaller than summer decline in the ETCW as well?

Recent winter SIE decline can be comparable to negative winter SIE anomaly during ETCW. The sentence is rewritten now to avoid misunderstanding.

3. Page 1081, lines 1-3 and following lines are a bit contradicting each other. First, it is stated that global models reproduce the decline, then it is argued that they are noticeably underestimating the decline. Maybe rephrase to make clear.

This part is modified to make is clearer.

4. Page 1081, line 12. Please mention that this is only valid under the assumption of a high emission scenario. For A1B or B1/B2, the ensemble mean does not project a total September SIE loss until 2100.

This is true. We removed the part about total loss until 2100 and specified scenario now.

5. Page 1082, line 3: although Wang and Overland (2009) is a very nice paper, it does not really fit here in my eyes since it does not compare CMIP5 and CMIP3. It could be cited in the section before where CMIP3 model results are discussed.

WO2009 citation is removed from this place. It was already cited two paragraphs above.

6. Page 1085, line 5/6: The use of sea ice concentration poleward of the marginal ice area before the satellite-era is problematic since observations are extremely scarce. This is why many ice data sets (e.g. the Walsh data) use ice concentrations of 1 in these areas before 1978. Although HadISST made corrections to this (if I am right), the ice concentrations in the Central Arctic and especially the ice concentration variability is very uncertain before 1978 (even after 1950). I thus would suggest to use as comparison for SIC (figure 1) 1979-2005 (or 1979-2010 using e.g. RCP4.5 or A1B after 2005) and not 1950-2000. Of course the time period is shorter but ice concentrations away from the ice edges are not sufficient reliable to be used as reference “observations”.

We agree with. The figure is now remade for 1970-2000. It is not exactly satellite era period, but we would like to have at least 30 years sample.

7. Page 1087, line 22: I am not entirely convinced we could conclude from larger variations in the Central Arctic that CMIP5 models are generally more sensitive to heat balance variations. I would think, the main reason is generally thinner ice in CMIP5 compared to CMIP3. And thinner ice is more sensitive to variations of heat fluxes than thicker ice (as correctly stated on page 1088, line 19/20). Thus the same ice thickness anomalies in CMIP5 lead to larger affect on the sea ice concentration than in CMIP3.

We agree. It is now indicated in the text that increased sensitivity comes from thinner ice in CMIP5 models.

8. Page 1088, line 23-25: Again, I feel it is not straight away to draw this conclusion just from looking at the ensemble mean. Although it is not unlikely that CMIP5 models are more sensitive to heat anomalies due to the fact that more ice models in CMIP5 use e.g. multiple ice categories, melt ponds or improved rheologies compared to CMIP3, more detailed analyses of single models is needed. I agree that RCP4.5 and A1B look relatively similar despite the fact that A1B is a stronger emission scenario (best comparable to RCP6.0). But as discussed before, this could also be due to the fact that historical simulations in CMIP3 have thicker ice, which is less sensitive to heat anomalies.

We agree and indicated this in the text now.

9. Page 1090, lines 11/12: Given the two last summers with some recovery of the ice extent and almost return to the linear trend of the last 2-3 decades, an ice-free Arctic around 2020

seems to be relatively unlikely. I would also suggest replacing “very recent observed accelerated Arctic sea ice loss” by “ the accelerated Arctic sea ice loss in the last decade.“

Corrected as suggested

10. Page 1093, lines 17/18: Is there any speculation why the spread in the Barents Sea is so much larger in CMIP5 compared to CMIP3. Is there a stronger mixing of sophisticated and more basic ice models in CMIP5 while in CMIP3 almost all models overestimated the ice in Barents Sea (because all CMIP3 ice models were still quite simple)?

Thank you for the suggestion. It looks indeed (fig. 4 and 5 e,f) that there is a larger portion of CMIP5 models that simulate Barents SIA reasonably well in both in Mach and September, whereas the majority of CMIP3 distinctly show a highly overestimated Barents SIA. Almost all CMIP3 models have much lower oceanic resolution than CMIP5 models. We discuss it now in the text.

11. Figure 8: I am surprised by the small seasonal cycle of the observed NH ice area. If I understood correctly this should be the ice area difference between March and September. Sea ice area variations from e.g.
http://arctic.atmos.uiuc.edu/cryosphere/IMAGES/seaice.recent.arctic.png
suggest for the entire Arctic something like 9x10**6 km2 (and from Figures 4 and 5 I would extract about 8x10**6 km2) but the observed values in Figure 8 seem to suggest only 4-5 mill km2. Please check the results in Figure 8 (and in case something went wrong in Fig. 8 also the conclusions in section 3.4) or specify more detailed how you defined seasonal cycle if it is not March – September ice area.

This is just a misunderstanding. By “amplitude” we mean “peak amplitude”, not “peak to peak amplitude”, that the values in figure 8 should be multiplied by 2 for comparison with maximum seasonal SIA spread. This is now indicated in the caption. We note that since the amplitude is estimated from harmonic analysis, it doubled value does not exactly correspond to March to September SIA difference. This is discussed in the text.

12. Page 1095, line 5: what is meant with “most probable trend”? Please define.

Here, we meant that the ensemble mean was not within the most dense cloud of trends, statistically speaking, not close to the mode of the trend distribution implying high skewness or bi-modality. This is now specified in the text.

13. Page 1096/1097: “Holland and Stroeve . . ..because a shift in the surface pressure (SLP) anomalies.” This sentence does not make much sense as it is now. Please clarify. Compared to what is the SLP shifted? March? Future and PD?

This is a rather irrelevant sentence indeed. We removed it.

14. Figures 10 d) shows a strongly positive correlation between AMOC and sea ice reduction: This is interpreted as: “ models with strong sea ice reduction also simulate strong AMOC reduction”. I am unsure if you would like to state that the processes are not related for summer and a third process affects both AMOC and summer ice or do you want to state that a positive AMOC leads to more sea ice during summer? In winter a much weaker negative correlation (how large is this correlation and is it significant?) is interpreted as: AMOC slowing and associated reduction in oceanic poleward heat transport plays a more important

role for . . .” . I have problems finding an explanation: If a strong AMOC reduce winter ice by melting of ice, it is very surprising that the summer sea ice area should be larger in the following summer. Is there any speculation about the physical process behind? Did you also calculated lag-correlations, AMOC leading the ice? I would expect that the ocean heat would need a few years from 30N to the Arctic (if it reaches at all the Arctic).

We agree that all AMOC-related analysis is vague. Simply comparing AMOC at 30N and sea ice variability does not bring much. We deleted this section as was also suggested by Reviewers 3.

15. Figure 11: Please indicate if the correlations are significant. Using 9-year running means and probably quite a high auto-correlation do not leave many degrees of freedom for one single model for 70-year periods. I would assume that quite a number of the correlations are not significant.

The correlations are insignificant. The section is deleted.

16. Figure 12: From the figure, it looks like a number models do not show significant correlations (below r= -0.24); in the text it is stated that many exceed -0.24. Please mark in the figure the 95% significance level (e.g. by a line at -0.24). However, even if correlations in many models really is just above -0.24, it should be stated that correlations are generally small (particular for annual values in a) and b)), hardly any correlation exceeds -0.5, many are between 0 and -0.3/ -0.4, which means that NAO is not explaining more than 10-15% of sea ice variance in the Barents Sea in most models.

Significance level is marked now and a small portion of explained variance is discussed now.

17. Page 1102, line 21/22: I do not understand the sentence: “Regional SEA changes are characterized by much stronger uncertainties that changes in the Entire Arctic”. Please rephrase to make clear what is meant.

There is a misprint: “than”, not “that”. We wanted to say that simulated SIA in the Barents Sea is characterized by stronger relative bias and higher uncertainties of future projections in comparison to the Entire Arctic. The sentence is reformulated.

18. Page 1103 line 13: It is not entirely clear what is the hen and the egg. Warmer SAT will lead to more SIA reduction but on the other hand SIA-reduction, which could e.g. be due to increased oceanic or atmospheric heat fluxes, will also strongly increase SAT in the Arctic , reflected in increased NH-SAT. Thus, I would suggest replacing “dependence “by “relationship” or similar.

Replaced by “link”.

Typings etc.

General: I would suggest to introduce the abbreviations only the first time the term is mentioned or to not use the abbreviation at all. E.g. SLP and SIA are introduced several times throughout the script.

Corrected

Page 1078, line 17: delete: “termed Entire Arctic”, not necessary in the Abstract.

Done

Page 1078Line 18-23: long and complicated sentence, I would suggest splitting into two sentences.

The sentence is shortened.

Page 1082, line 24: The author is called: “Massonnet “

Corrected

Page 1085 line 20: it should probably be: “.. sea ice extent (SIE)” or “.. sea ice concentration (SIC)”?

(SIE). Corrected

Page 1087, line 10: in the Barents Sea.

Corrected

Page 1089, line 16: “The CMIP5 ensemble mean SIA of is. . .” something is missing or “of” needs to be deleted.

Done

Page 1095 line 23: “may be” instead “may are”

Corrected

Page 1102. Line 14: delete one “the”

Done

Anonymous Referee #3

The authors discuss the variability and change of Arctic sea ice area (SIA) in the 20th and 21st centuries as simulated by the CMIP3 and the CMIP5 ensembles. They discuss the relation between projected changes in SIA and changes in Northern Hemisphere surface air temperature (SAT) and Atlantic Meridional Overturnung Circulation at 30N (AMOC). Lastly, they discuss the relation between natural variability of the North Atlantic Oscillation index (NAO) and sea ice in the Barents Sea.
They find that some observed aspects of the SIA are better represented in CMIP5 than they were in CMIP3, while others are worse. As expected, there seems to be a robust correlation between an increase in SAT and a decrease in SIA across the CMIP ensembles. The links in

the CMIP ensembles between changes and variability of SIA and changes and variability of AMOC and NAO remain unclear.

General comments:

I would like to make three distinct points, each relating to different parts of the manuscript.
1) Large parts of the manuscript are a purely descriptive discussion of SIA in the CMIP3 and CMIP5 ensembles (Sections 3.1, 3.2, 3.4, 3.5) and thus are hardly original. Nevertheless, this description goes into more detail than previous publications, and therefore these parts could be useful to the community provided that the methodological flaws described in the specific comments are addressed.

We agree that our study is basically a descriptive one. We do not address processes and mechanisms rather providing information about models' performance. Sea ice in CMIP3 and CMIP5 models has already been analyzed in several studies. However, our paper presents inter-comparison of CMIP3 and CMIP5 performance for several important SIA characteristics (area, variability, seasonal cycle, sensitivity to SAT, some dynamical links). We believe that having all this information in one paper could be useful.

2) The relation between changes in SIA and SAT (Section 3.3) has been documented many times in the literature (e.g. Li et al. 2013 (their Fig. 5), West et al. 2013 (their Fig. 3b), Ridley et al. 2012 (their Fig. 2)). It is therefore to be expected and of little novelty. Still, as in the comment above, it could be worth to document this relationship specifically for the CMIP ensembles.

We note that the figures in the mentioned papers and corresponding analyses address totally different questions (reversibility of sea ice changes and possible negative feedbacks) and are based on one model each.
Here is the description of the cited figures.

Li et al., 2013: September and March SIE vs Annual SAT in ECHAM5/MPI-OM model
West et al., 2013: September SIE vs Annual SAT in HadGEM1model
Ridley et al., 2012: Annual mean SIA vs Annual SAT in HadCM3 model

We study the *intra-ensemble* relationship between SIA and SAT changes in CMIP3 and CMIP5 ensembles what is principally different to the mentioned studies. This allows one estimating how much the differences among CMIP model in simulated SAT and SIA changes are related. This is a totally different issue than what is studied in the suggested papers.

3) The most questionable part of the paper lies in Sections 3.6 and 3.7 corresponding to Figures 10-13. Here, both the statistical inference and the physical interpretations are unsound, and I would reject any conclusions drawn here.

We agree that the section related to AMOC at 30N and sea ice is vague and confusing. A connection between AMOC, wind driven, therohaline circulation and Arctic heat and mass balance is indeed a too complication story to be discussed in light of simple regression analysis of AMOC and SIA changes. This section t is deleted.
As to the link to NAO and SLPG, these are robust factors impacting Arctic sea ice, in particular in the Barents Sea. It has been established (based on both empirical data and

some model simulations, e.g., Dickson et al., 2000, Semenov, 2008, Smedsrud et al., 2013 for review) that NAO is linked to Barents SIA. Oceanic inflow to the Barents Sea is primarily wind driven and SLPG may serve as a feasible index of the inflow (Bengtsson et al., 2004 and refs. therein). The link between the inflow and SIA in the Barents Sea may constitute an important positive feedback that may enhance Arctic climate variation and potentially even result in the inflow shutdown (Bengtsson et al., 2004, Semenov et al., 2009, Smedsrud et al., 2013).
We note that our purpose was not to provide the insights to mechanisms of atmospheric circulation impact on SIA variability. We aim to assess whether or not CMIP3 and CMIP5 models are in principle capable to reproduce those two important links. If yes – which and how many models, and how this link gets modified in the warmer future in comparison to the present day climate.

In summary, I would only recommended publication of this manuscript if the authors completely re-invent or delete the fatally flawed Sections 3.6 and 3.7, and address substantial flaws in Sections 3.1 - 3.5, as detailed in the specific comments below.

Specific comments:

1) The observational uncertainty of SIA is not discussed at all, yet it is used as the truth to evaluate all model results. In the pre-satellite era until 1979, SIA observations are highly uncertain throughout. In the satellite era from 1979 on, there is still a sizable gap in the observations around the north pole, where different assumptions about filling this gap can lead to differences in SIA. Thirdly, as discussed by Notz et al. (2014), there are substantial differences in SIA between different retrieval algorithms and satellites (their Figures 2 and 3). These observational uncertainties of SIA need to be integral part of an evaluation of modelling uncertainties of SIA.

We fully agree. This was a serious gap in the original manuscript and we tried to fill it now. Recent studies by Notz 2014 and Ivanova et al. 2014 nicely illustrate the uncertainty of satellite retrieval algorithms. The uncertainty of empirical data is now discussed in "Data and methods" section. We also note that HadISST1 data were often used to represent "observations", in particular in the mentioned West et al. 2012 paper. HadISST1 is also widely used in IPCC AR5 as state of the art dataset for illustrating historical Arctic sea ice variations. In Figure 4.5 (IPCC AR5) HadISST SIE is compared to different satellite retrieval algorithms and it is well within the uncertainty range. Given that SIA estimates results in almost twice higher uncertainty among the algorithms (Ivanova et al. 2014), we may conclude than HadISST1 SIC analysis is a rather good reference dataset to represent observed variations for the historical period.

2) The interpolation of model and observational data to a 2x2 degree grid is not appropriate for analysing SIA in the Barents Sea. The meridional extent of this region is then resolved by only 5 (five) grid cells. Large interpolation errors are to be expected that might dominate a regional comparison between different models. Given that most models in the CMIP5 ensembles (certainly in the ocean component) will have a higher resolution, I request re-doing all the analysis on a 1x1 degree grid or finer to lend credibility to regional assessments.

As stated in the introductory part of our response, all analyses are now performed with model data interpolated on 1x1 grid.

3) pp. 1097f. and Fig. 10: The physical mechanism that links the AMOC at 30N and SIA in the Arctic is not established. Furthermore, the correlations are weak at best. For this part to be acceptable, two things need to happen: (i) a clear physical pathway needs to be suggested how AMOC changes are related to SIA changes (aided by some appropriate analysis), and (ii) rigorous significance testing against the null hypothesis of zero correlation between AMOC and SIA changes needs to be performed, to demonstrate that there is actually a signal.

The AMOC section is deleted.

4) pp. 1098f. and Fig. 11: The same criticism as in my previous comment applies. It needs to be established which correlations in Fig. 11 are actually significant at all (NB reduction of degrees of freedom by 9 year running means), and which of the correlation changes are significant.

The AMOC section is deleted.

5) pp. 1099-1101 and Figs. 12-13: The same criticism as in my previous comment applies. Additionally, there is doubt about the reliability of the Barents Sea SIA values given the 2x2 degree interpolation. I agree with the authors (ll. 27f. on p. 1099) that there is a physical mechanism how the NAO has an impact on SIA in the Barents Sea. This is supported by a more consistent model ensemble than for the AMOC: simulated correlation coefficients are mostly between 0 and 0.6 in Fig. 12. However, it is quite a stretch to call this a "strong" impact, and some discussion is necessary as to why the models simulate quite different correlations. I appreciate the idea of the authors to look at the sea level pressure difference Scandinavia-Svalbard. If the hypothesis of winddriven SIA changes in the Barents Sea was correct, Fig. 13 should depict negative correlations that are strong and consistent between the models. However, there is a large model spread, which needs to be discussed. Diagnosing the ocean heat transport through the Barents Sea Opening might help to understand what is going on here.

The analysis performed now on 1x1 interpolated data. Significance levels are indicated, large model spread and generally low correlations are discussed.

References:

Li, Chao, Dirk Notz, Steffen Tietsche, and Jochem Marotzke. 2013. “The Transient versus the Equilibrium Response of Sea Ice to Global Warming.” Journal of Climate 26 (February): 5624–36. doi:10.1175/JCLI-D-12-00492.1. http://journals.ametsoc.org/doi/abs/10.1175/JCLI-D-12-00492.1.

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Ridley, J. K., J. A. Lowe, and H. T. Hewitt. 2012. “How Reversible Is Sea Ice Loss?” The Cryosphere 6 (1). Copernicus GmbH: 193–98. doi:10.5194/tc-6-193-2012. http://www.the-cryosphere.net/6/193/2012/tc-6-193-2012.html.

West, A. E., A. B. Keen, and H. T. Hewitt. 2013. "Mechanisms Causing Reduced Arctic Sea Ice Loss in a Coupled Climate Model." The Cryosphere 7 (2): 555–67. doi:10.5194/tc-7-555-2013. http://www.the-cryosphere.net/7/555/2013/.

Arctic Sea Ice Area in CMIP3 and CMIP5 Climate Model Ensembles – Variability and Change

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Abstract

The shrinking Arctic sea ice cover observed during the last decades is probably the clearest manifestation of ongoing climate change. While climate models in general reproduce the sea ice retreat in the Arctic during the 20th century and simulate further sea ice area loss during the 21st century in response to anthropogenic forcing, the models suffer from large biases and the ~~model~~ results exhibit considerable spread. ~~The last generation of climate models from World Climate Research Programme Coupled Model Intercomparison Project Phase 5 (CMIP5), when compared to the previous CMIP3 model ensemble and considering the whole Arctic, were found to be more consistent with the observed changes in sea ice extent during the recent decades. Some CMIP5 models project strongly accelerated (non-linear) sea ice loss during the first half of the 21st century.~~

Here, ~~complementary to previous studies,~~ we compare results from the two last generations of climate models, CMIP3 and CMIP5, with respect to total and regional Arctic sea ice change. Different characteristics of ~~We focus on September and March sea ice. S~~sea ice area (SIA) ~~variability~~in March and September~~,~~ ~~sea ice concentration (SIC) variability, and characteristics of the SIA seasonal cycle and interannual variability~~ have been analysed for the ~~whole~~ Entire Arctic, ~~termed Entire Arctic,~~ Central Arctic and Barents Sea. Further, the sensitivity of SIA ~~changes~~ to changes in Northern Hemisphere (NH) ~~averaged~~ temperature is investigated and ~~several important~~ dynamical links between SIA and some ~~natural climate variability~~atmospheric variability modes ~~involving the Atlantic Meridional Overturning Circulation (AMOC), North Atlantic Oscillation (NAO) and sea level pressure gradient (SLPG) in the western Barents Sea opening serving as an index of oceanic inflow to the Barents Sea~~ are ~~studied~~assessed.

~~The~~ CMIP3 (SRES A1B) and CMIP5 (RCP8.5) models not only simulate a coherent decline of the Arctic SIA but also depict consistent changes in the SIA seasonal cycle ~~and in the aforementioned dynamical links~~. The spatial patterns of SIC variability improve in ~~the~~ CMIP5 ensemble, ~~particularly~~ most noticeably in summer when compared to HadISST1 data. A better simulation of summer SIA in the Entire Arctic by CMIP5 models is accompanied by a slightly increased bias for winter season in comparison to CMIP3 ensemble. SIA in the Barents Sea is strongly overestimated by the majority of CMIP3 and CMIP5 models, and projected SIA changes are characterized by a high uncertainty. Both CMIP ensembles depict a significant link between the SIA and NH temperature changes indicating that a part of

inter-ensemble SIA spread comes from different temperature sensitivity to anthropogenic forcing. ~~Our~~ The ~~analysis~~results ~~suggests~~ suggest that, ~~on average~~in general, ~~the~~ a sensitivity of SIA to external forcing is enhanced in ~~the~~ CMIP5 models. Arctic SIA interannual variability in the end of the 20th century is on average well simulated by both ensembles. To the end of the 21st century, September ~~The Arctic SIA~~ variability ~~response to anthropogenic forcing is different in CMIP3 and CMIP5. While the CMIP3 models simulate increased variability in March and September, the CMIP5 ensemble shows the opposite tendency.~~ is strongly reduced in CMIP5 models under RCP8.5 scenario, whereas variability changes in CMIP3 and in both ensembles in March are relatively small. The majority of models in ~~A noticeable improvement in the simulation of summer SIA by the CMIP5 models is often accompanied by worse results for winter SIA characteristics. The relation between SIA and mean AMOC changes is opposite in September and March, with March SIA changes being positively correlated with AMOC slowing. Finally, b~~both CMIP ensembles demonstrate an ability to capture~~, at least qualitatively,~~ a ~~important dynamical links~~negative correlation of interannual SIA variations in the Barents Sea ~~of SIA to decadal variability of the~~with ~~AMOC,~~ North Atlantic Oscillation~~NAO~~ and~~and~~ sea level pressure gradient in the western Barents Sea opening serving as an index of oceanic inflow to the Sea~~SLPG~~. ~~SIA in the Barents Sea is strongly overestimated by the majority of the CMIP3 and CMIP5 models, and projected SIA changes are characterized large spread giving rise to high uncertainty.~~

1 Introduction

The Northern High Latitudes exhibit the most visible signs of the climate change during the last decades. The surface warming in the Arctic has been at least twice as strong as the global average warming during recent decades (e.g., ~~IPCC AR5, 2013~~Bekryaev et al., 2010). ~~This~~ Mechanisms of Arctic amplification ~~and its mechanism is~~are under intense debate, with ~~variations~~ retreating of sea ice, increasing atmospheric and oceanic heat transport and positive radiative forcing feedbacks all having been suggested as possible mechanisms (Holland and Bitz,2003, Alexeev et al., 2005, Graversen et al., 2008, ~~Serreze et al., 2009,~~ Screen and Simmonds, 2010, Serreze and Barry, 2011, Walsh, 2014). The Arctic warming has been accompanied by a rapid summer sea ice extent (SIE) decline of the order of about 10% per decade since 1979 (the start of satellite observations) that has considerably, by a factor of two, accelerated in the 21st century (Stroeve et al., 2007, Stroeve et al., 2012). ~~This is probably the~~

~~most apparent, accurately observed and influential manifestation of regional climate change on the Earth. The complicated mechanisms involved in the Arctic sea ice loss and its dramatic consequences make it “a grand challenge of climate science” (Kattsov et al. 2010). On the contrary, Antarctic SIE depicted a slight increase during the satellite era (Cavalieri and Parkinson 2012), further demonstrating the complex physics operating in sea ice variability and change.~~

Reconstructions suggest that current summer Arctic sea ice retreat is likely to be unprecedented in the last millennium (Kinrad et al., 2011, Halfar et al., 2014), although a clear manifestation of strong multidecadal variability is indicated by observations and models (Polyakov et al., 2003, Divine and Dick, 2006, Semenov, 2008, Semenov and Latif, 2012, Day et al., 2012, Miles et al., 2014). For example, regional scale records, in particular in the eastern Arctic, also indicate considerable summer sea ice area (SIA) reduction during the Early Twentieth Century Warming (ETCW) (Polyakov et al., 2003, Alekseev et al., 2007, 2009). The winter sea ice cover reduction during the satellite era is considerably smaller than that in summer. T~~and t~~here are indications that the ongoing winter sea ice retreat~~it~~ may be comparable to that during the ETCW (Semenov and Latif, 2012). The winter sea ice retreat~~, however,~~ has a great potential to impact the large-scale atmospheric circulation by modulating the intense turbulent heat fluxes from the ocean surface to the atmosphere, which may force anomalous ~~and extreme~~ weather regimes (see Vihma, 2014, for a review).~~ Recently, a link between weather extremes and sea ice retreat has also been suggested for summer (Screen, 2013, Tang et al., 2013, Guo et al., 2013).~~

~~Arctic sea ice thickness has also experienced a dramatic decrease, by roughly a half, during the last three decades, as suggested by different observation methods (Vaughan et al., 2013). We note that the uncertainty of these estimates is much higher than that for the sea ice area (Johannessen et al., 2004, Schweiger et al., 2011).~~

The analyses of long-term historical sea ice cover variations in the ~~Entire~~ whole Arctic are restricted to the second half of the 20^{th} century and early 21^{st} century, ~~for which~~when sufficiently reliable gridded sea ice concentration data based on regular instrumental observations are available (Walsh and Johnson, 1979). Since 1979, passive microwave satellite data provide the most accurate estimates of the sea ice extent with high spatial and temporal resolution that, however, are dependent on the data retrieval algorithm (Andersen et al., 2007, Kattsov et al., 2010, Ivanova et al., 2014, Notz 2014).

Global climate models ~~reproduce~~ also simulate the Arctic sea ice area/extent decline during the recent ~~observational~~ historical period (from the mid-20th until beginning of the 21st century) when forced by estimates of historical anthropogenic and natural forcings. However~~Simulations with~~, climate models participating in the World Climate Research Programme (WCRP) Coupled Model Intercomparison Project Phase 3 (CMIP3) (Meehl et al., 2007) used in the Fourth Assessment Report of the IPCC (IPCC: Climate Change 2007) in general noticeably underestimate the observed September ~~sea ice extent~~SIE reduction. Based on CMIP3 models, only about 47% to 57% of the ~~sea ice extent~~SIE decrease over the satellite era can be attributed to anthropogenic forcing, leaving the rest either for natural variability, model or forcing errors (Stroeve et al., 2007). Several models, which compare well to observations, predicted a seasonally ice free Arctic already before 2040 under SRES A1B scenario (Wang and Overland, 2009)~~, with the ensemble mean reaching this level around 2080 (Alekseev et al., 2009).~~. However, the model results depict a very large spread (Stroeve et al., 2007, 2012, Alekseev et al., 2009). The important role of increasing greenhouse gas concentrations has also been suggested by solely empirical data analyses (Johannessen, 2004; Notz and Marotzke, 2012) that, however, presumably exclude the possibility of strong internal multidecadal fluctuations (Bengtsson et al., 2004, Wood et al., 2010).

~~Arctic sea ice may be strongly influenced by atmospheric and oceanic internal variability, including North Atlantic Oscillation (NAO), Atlantic Multidecadal Osillation (AMO) and Barents Sea inflow (BSI) variability (Dickson et al. 2000, Bengtsson et al. 2004, Semenov 2008, Day et al. 2012, Smedsrud et al. 2013, Miles et al., 2014). The links between natural forcing factors and Arctic sea ice, however, may be essentially non-stationary and non-linear (Semenov 2008, Smedsrud et al. 2013). Again, a relatively short observational record hinders a detailed analysis of the variability mechanisms, while climate models suffer from large biases, particularly on a regional scale.~~

A new generation of climate models included in ~~the~~ CMIP5 (Taylor et al., 2012) ensemble employed in IPCC AR5 (IPCC AR5, 2013) have demonstrated in general a better agreement with the observed September Arctic SIE trends, thus implying a larger (52% ~~–~~to 67%) contribution of the anthropogenic forcing (Stroeve et al., 2012). ~~The~~ CMIP5 models project a seasonally ice free Arctic sooner than ~~the~~ CMIP3 models (Stroeve et al., 2012~~; Wang and~~

~~Overland, 2009~~). Model spread and uncertainty of the 21st century projections in CMIP5, however, remained similar to those in CMIP3 (Stroeve et al., 2012). We note that the above assessments relate to September trends of the sea ice extent for the whole Arctic, termed Entire Arctic.

To better understand mechanisms underlying Arctic sea ice cover variations and to estimate uncertainties of projected future changes, the results of simulations with different model ensembles should be inter-compared and validated against ~~observations~~empirical data. One has to keep in mind that updated observations provide a reference line for climate models to match by tuning parameters within the range of uncertainty (Mauritsen et al., 2012). This is particularly the case with the Arctic ~~sea ice area~~SIA/SIE that exhibited about twice as strong decline during the early 21st century than during previous decades, thus having provided different perspectives for CMIP3 and CMIP5 modelers. Total Arctic ~~sea ice area~~SIA (and volume) is sensitive to parameters' choice in climate models, in particular poorly constrained ice albedo, and therefore can be easily tuned (Eisenman et al., 2007; Hodson et al., 2013). The reliability of model results can be better assessed by analyzing regional changes of sea ice and also investigating changes in its seasonal cycle, variability and links to atmospheric and oceanic dynamics in different generations of climate models. Here, we follow this strategy.

In contrast to majority of previous studies, we analyze SIA, not SIE. The latter parameter is often used as it can be more reliably observed from ships, airplanes and satellites than sea-ice area (Notz 2014) and reduces errors related to uncertainties in the original data. The advantages of using SIE are, however, accompanied by a loss of information about SIC beyond the chosen threshold. It is SIA that modulates heat fluxes at ocean-atmosphere interface and is directly related to surface albedo.

Further, most analyses of ~~the~~ CMIP3 and CMIP5 models have so far been performed for either of the ensembles and focused on the changes of sea ice cover in the Entire Arctic in September and (less so) in March (e.g., Stroeve et al., 2007; Stroeve et al., 2012; Alekseev et al., 2009; Kattsov et al., 2010; Massonnet~~e~~ et al., 2012). Here, we also present analyses of simulated ~~sea ice area~~SIA ~~(SIA)~~ variability in March and September and its sensitivity to global warming on a regional scale. Furthermore, the seasonal cycle amplitude is also investigated. A major focus of this study is on the intercomparison of ~~the~~ CMIP3 and CMIP5 model ensembles.

Past climate variations and projected changes in the Arctic differ considerably between individual regions (Overland et al., 1997; Venegas and Mysak, 2000; Semenov and Bengtsson, 2003; ~~Semenov, 2008; ~~Rogers et al., 2013). Some regions may be of particular importance for Arctic climate variability.~~,~~ This is the case for ~~example ~~the Barents Sea. Strong variability of oceanic inflow and atmospheric circulation, intense heat losses from the sea surface and positive feedbacks in the regional coupled atmosphere-sea ice-ocean system lead to enhanced variability in this region that affects the climate of the Entire Arctic (Bengtsson et al. 2004; Semenov and Bengtsson, 2003; Semenov, 2008; Semenov et al., 2009; Smedsrud et al., 2013). The sea ice conditions in the Barents Sea itself are directly impacted by the North Atlantic Oscillation (NAO) (Kwok, 2000), the leading mode of internal atmospheric variability in the Northern Extratropics during winter (van Loon and Rogers, 1978)~~ and by the Atlantic Multidecadal Oscillation (Semenov, 2008, Miles et al., 2014), the leading large-scale pattern of multidecadal variability in North Atlantic surface temperature~~. Additionally, the oceanic inflow into the Barents Sea is affected by the NAO (Dickson et al., 2000), and the link between all these processes may be non-stationary, as suggested by climate models and observations (Goosse and Holland, 2005; Semenov, 2008; Smedsrud et al., 2013). ~~Petoukhov and Semenov (2010) showed that reduced sea ice concentrations in the Barents-Kara Sea region may exert a strong effect on the European climate through changes in atmospheric circulation, leading to anomalously cold winters over Eurasia. ~~Furthermore, the Barents Sea is the region where climate models exhibit the strongest sea ice error and bias in simulating present day temperatures (Flato et al., 2013; IPCC, 2013). This is also the region where climate models project the strongest warming by the end of the 21st century (Collins et al., 2013)~~(Flato et al., 2013; IPCC, 2013)~~. Thus, the Barents Sea is one key region on which we focus in our analyses.

The Central Arctic is another region chosen for analysis. Until recent decades, and in preindustrial control integrations with climate models, this region has been covered by thick multi-year sea ice nearly all year round. Thus, in contrast to the Barents Sea, SIA variations there have been small and past SIA evolution in this region may be well suited not only to assess the models' ~~ability ~~performance but also get insights to the ongoing processes since ~~to realistically simulate sea ice variability and change~~this is the region with the large gap of satellite observations around the North Pole.

~~The~~ CMIP models differ considerably not only in simulated sea ice changes, but also in their representation of the temperature response to ~~identical~~ external forcing. Whether the differences in the simulated sea ice changes are related to the different warming pace or whether they represent regional and sea ice model-related uncertainties remains an open question. Therefore, we assess the sensitivity of sea ice changes in the Arctic region to Northern Hemisphere warming in both CMIP model ensembles. We also study the amplitude of the SIA seasonal cycle. It characterizes the sharpness of the seasonal contrasts and is an important parameter influencing various climate impacts~~, be they physical, chemical, biological or economical~~. For example, a shortened sea ice season may lead to considerable advantages for marine transportation using Northern Sea Route and North-West Passage (Khon et al., 2010). Furthermore, changes in sea ice area and thickness in the Arctic basin are accompanied by changes in variability (Holland et al., 2008). It still remains unclear how the interannual sea ice variability may change in a warmer climate. Therefore the interannual variability in ~~the~~ CMIP3 and CMIP5 models is analysed as well.

~~As was outlined above, internal climate variability modes including NAO and AMO were found (basing on empirical data analysis and some model simulations) to affect Arctic sea ice variations~~Analysis if empirical data and model results (Dickson et al. 2000, Bengtsson et al. 2004, Semenov, 2008, Day et al., 2012, Smedsrud et al., 2013, Miles et al., 2014) suggested a possible link between atmospheric variability and SIA in the Barents Sea. Simulating such links is a challenge for climate models as it requires the simulation of dynamical processes in the atmosphere and ocean, as well as their interaction with sea ice dynamics. Here, we assess CMIP models' ability to reproduce these links (in terms of linear relations) and estimate how these links may change in a warmer climate.

The paper is organized as follows. In the next section, we provide a description of the data sets and methodology used in this study. In section three, the results are presented. They include changes in spatial sea ice concentration (SIC) variability, analysis of September and March SIA for the Entire Arctic, Barents Sea and Central Arctic regions, sensitivity of SIA changes to Northern Hemispheric warming, changes in SIA variability~~, SIA~~ and seasonal cycle~~ amplitude evolution~~, Barents Sea SIA links to NAO~~,~~ ~~AMO~~ and ~~BSI~~ atmospheric pressure gradient across the eastern opening ~~indices~~of the Barents Sea. The ~~main~~ conclusions and ~~a~~ discussion of the results can be found in section four.

2 Data and methods

The analysis is based on the World Climate Research Programme's (WCRP's) Coupled Model Intercomparison Projects phase 3 (CMIP3) and phase 5 (CMIP5) multi-model dataset covering the period 1900 – 2100 (see Tables 1 and 2). ~~Observations~~ Model data are compared with ~~are presented from~~ the gridded HadISST1 dataset (Rayner et al., 2003) that provides~~ing~~ sea surface temperature (SST) and sea ice concentration (SIC) since 1870. ~~The observational data prior to 1953 are sparse and highly inhomogeneous (Walsh and Chapman, 2001). The recent study by Semenov and Latif (2012) suggested that there must have been a strong negative sea ice extent anomaly (comparable to the current decrease) in winter during the ETCW that is not present in the HadISST1 dataset. Therefore, we analyzed HadISST1 data only starting from 1950.~~

HadISST1 analysis employs NASA Team retrieval algorithms (Cavalieri et al., 1999) and it has been widely used for Arctic climate change studies. HadISST1 is also used in IPCC AR5 for representing historical sea ice changes in the Arctic and shown to agree well (in terms of SIE) with different satellite retrieval algorithms (Vaughan et al., 2013). The gap around the North Pole is filled by interpolated data assuming 100% SIC at the Pole (Rayner et al., 2003). The empirical estimates of SIC prior to 1953 are sparse and highly inhomogeneous (Walsh and Chapman, 2001). Furthermore, the recent study by Semenov and Latif (2012) based on comparison with temperature data suggested that there must have been a strong negative SIA anomaly (comparable to the current decrease) in winter during the ETCW that is not present in the HadISST1 dataset, and most reliable data start from 1960s. Therefore, we analyzed HadISST1 data only for 1960 to 2014 period.

When comparing the sea ice characteristics simulated by climate models against "reality", one has to keep in mind that the empirical data are also characterized by rather high uncertainties. Since the era of continuous satellite observations started in 1979, various algorithms have been developed to retrieve sea ice concentrations from passive microwave sensors' data (see Notz, 2014, Ivanova et al., 2014 for review). Results for all the algorithms have close agreement on the strength of the 1979-2012 trend in Arctic sea-ice area and extent, but are individually biased from the mean (Ivanova et al., 2014). The estimated spread among 11 algorithms amounts to about $1.0 \cdot 10^6$ km^2 for annual Arctic SIA and $0.5 \cdot 10^6$ km^2 for SIE. This uncertainty (about 10%) of the empirical estimates of the mean SIA has to be kept in mind when comparing model and observations-based results. Another inevitable problem with satellite-based observations is a data gap around the North Pole (about 600 km and 300 km for different sensors) due to the orbit inclination. This makes the empirical estimates for SIA in Central Arctic in summer, in presence of melting ice and ponds, even more uncertain.

From the CMIP database, 20C3M (CMIP3) and historical (CMIP5) runs for the 20th century incorporating observed climate forcings complemented by climate change simulations using A1B-scenario (CMIP3) and representative concentration pathway (RCP) future scenarios RCP 4.5 and RCP 8.5 (CMIP5) for the 21st century were analysed. Only one (the first) member of each climate model ensemble is used, since models have different numbers of ensemble simulations, some of them just one. ~~Observational and a~~All model data were interpolated onto a ~~2~~1° × ~~2~~1° grid (same resolution as HadISST1 dataset) for intercomparison using bi-linear interpolation method. This resolution is similar to oceanic grid resolution of the majority of CMIP5 models.

Sea ice area (SIA, area-integrated sea ice concentration) is analysed ~~here~~in this study. The results ~~may~~ thus ~~be~~ are quantitatively different to those studies using sea ice extent (~~SIC~~SIE) for analysis. When using ~~sea ice extent (~~SIE~~)~~, a grid cell area that is covered by more than 15% ice is fully integrated to the total value, whereas SIA accounts only for the cell fraction covered by sea ice. This leads to larger SIE values compared to analyses based on SIA and may even result in qualitative differences in climatic trends (Cavalieri and Parkinson, 2012). ~~Sea ice area is calculated as integrated sea ice concentration multiplied by grid box area. In the following, we present results for the Entire Arctic, Central Arctic and Barents Sea.~~ One should keep in mind that model differences ~~solely~~ can also result from different horizontal resolutions and land-sea masks. For example, smaller islands like Svalbard are not resolved in some models. Models with a coarse coastline resolution are marked with an asterisk in Table 1. The Central Arctic is defined as the basin north of 80°N. The Barents Sea is defined as the area between 70°N and 80°N and 20°E (Svalbard) and 62°E (Novaya Zemlya) (see Gloersen et al., 1992).

The analyses mostly use September and March values, corresponding on average to the minimum and maximum of the annual sea ice extent evolution, respectively. Seasonal averages are used in sensitivity analyses. The amplitude and phase of the seasonal cycle are calculated based on monthly values with the Fourier approach of Granger and Hatanaka (1964). The time series have been detrended by subtracting fourth order polynomial trends prior to the calculation of the annual harmonic of the monthly mean sea ice data.

3 Results

3.1 Spatial SIC variability

3.1.1 Spatial structure of interannual SIC variability in ~~1950~~1970-2000

~~The interannual variability of the Arctic sea ice concentration (SIC) is characterized by a distinct spatial structure.~~ Fig. 1 shows the observed (HadISST1) and multi-model mean interannual variability of SIC in March and September during the second half of the 20th century, represented by standard deviations calculated from the monthly ~~(detrended)~~ data (after subtracting long-term climatic trend). The ~~observations~~ empirical data (Fig. 1a, b) show that the regions with high interannual variability ~~basically~~ are ~~follow~~ encompassed by ~~the~~ average sea ice margins (depicted as 15% SIC contour). Highest variability regions in winter (March) are located in the Atlantic sector in the Barents, Greenland and Labrador Seas, regions characterized by strong wintertime atmospheric and oceanic variability, and in the Pacific sector in the Bering Sea and Sea of Okhotsk, another region ~~of~~ with strong atmospheric variability. In summer (September), the areas of high interannual variability are more symmetrically distributed, encompassing internal Arctic Seas and centred on the thickest sea ice region close to Canadian Archipelago.

The model SIC data are presented as multi-models means, i. a. by averaging the interannual variability over all ensemble members (models included here are according to Tables 1 and 2). Both ensembles qualitatively capture the main features of the observed variability structure. The models on average distinctly underestimate (by about 50% in the regions of highest observed variability) the variability both in March and September. The simulated variability in March is also marked by an obvious westward shift of the highest variability area in the Barents Sea, indicating an overestimation of sea ice area in the Barents Sea by a large number of models (Fig. 1c). Extensive sea ice coverage is also reflected in September by a southward extension of the variability area (Fig. 1d). ~~The major difference between CMIP5 and CMIP3 is related to an apparent improvement in the simulated variability.~~ In March, the simulated variability by CMIP5 models (Fig. ~~–~~1e) agrees much better with ~~observations~~ HadISST1 data compared to ~~former~~ CMIP3 results. In particular, the region of strong variability in the Barents Sea is much better ~~simulated than in CMIP3.~~ reproduced. However, the spatial spread of the sea ice edge is still too large in all regions.

In ~~summer (~~September~~)~~, the variability in CMIP5 models is strongly enhanced~~-~~ in the ~~internal~~ Arctic Seas (Fig. 1f) in comparison to CMIP3 ensemble and thus better fits to the observations. ~~The model spread is also reduced in comparison to CMIP3 (not shown).~~ Much better simulation of the interannual variability along the ~~Arctic shelf region~~ice margins by CMIP5 models, however, is accompanied by ~~overestimated variability~~a stronger positive bias relative to HadISST1 in large parts of the central Arctic region, suggesting an overall increase of summer SIC sensitivity to heat balance variations at the atmosphere-ocean interface due to in general thinner ice. ~~The interannual variability east of Greenland still shows an ice edge position too far away from the coast. In both Seas, the model spread becomes larger in the CMIP5 ensemble relative to CMIP3 ensemble (not shown).~~ We note that, as described in section 2, HadISST1 data may underestimate SIC variability around the Pole due to interpolation applied to fill the missing satellite observations. To sum up this part, ~~the~~ CMIP5 ensemble on average simulates higher interannual variability than CMIP3 models that is in most regions in a better agreement with the ~~observations~~empirical analysis, ~~especially~~ particularly in the Atlantic sector. A clear improvement in reproducing September SIC interannual variability in CMIP5 can be reported.

We note that presentation of ensemble variability by averaging variability patterns of individual models makes the multi-model mean result dependent on the position of the ice edge in individual models. To illustrate this, sea ice margins for two models from each ensemble that belong to low and high tails of the intra-ensemble distribution of present day SIA in the Entire Arctic are also shown in Fig. 1. This gives one a guess how strong a sea ice edge may differ within the ensembles. As can be seen, in winter, the large spread is likely to be observed in Labrador Sea and Sea of Okhotsk. In summer, there are models that simulate present day sea ice edge close to the North Pole. Thus, the overestimated ice variations in the Central Arctic and underestimations along the observed ice edges in the Atlantic sector in CMIP models may be partly due to this spread.

3.1.2 Simulated interannual SIC variability in ~~2050~~2070-2100

~~The~~ CMIP models, when forced by scenarios of future anthropogenic forcing, ~~simulate~~ show a ~~strong~~ considerable change in the interannual SIC variability pattern ~~in~~ to the ~~second~~

~~half~~end of the 21^{st} century (2070-2100) in comparison to ~~1950~~1970 – ~~-~~2000 (Fig. 1c-f). Figures 2 and 3 show changes in SIC variability for the ~~2050~~ 2070 – 2100 period simulated by ~~the~~ CMIP3 models under scenario SRES A1B and CMIP5 models using the RCP 4.5 and RCP 8.5 scenarios for March and September respectively. It should be noted that RCP 8.5 ~~reveals~~ corresponds to the strongest radiative forcing, whereas RCP 4.5 is weaker than the forcing of SRES A1B used in CMIP3. The latter~~ is~~, in terms of the CO_2 concentrations at the end of the 21^{st} century, is between the two RCPs (e.g., Meinshausen et al., 2011). A direct comparison of the results from the two CMIP ensembles is therefore not possible. Further, since sea ice dynamics is highly nonlinear, a simple linear interpolation may lead to erroneous interpretations.

~~The~~ CMIP models project ~~for the 21^{st} century~~ marked changes in the interannual variability ~~during winter (~~in March~~)~~ ~~in response to anthropogenic forcing~~ (Fig. 2) to the end of the 21^{st} century. The left panels of Fig. 2 depict the patterns of interannual SIC variability during ~~2050~~2070-2100 in ~~three~~ CMIP ensembles, the right panels the changes relative to ~~1950~~1970-2000. In March, the SIC variability is strongly increased~~s~~ close to ice margins and towards the inner Arctic (Fig. 2). This is consistent with higher sensitivity of thinner ice to variations of atmospheric and oceanic heat fluxes. The strongest increase in the SIC variability during March is projected in the RCP 8.5 scenario exhibiting the largest radiative forcing, with a noticeable increase even in the C~~c~~entral Arctic, indicating much less compact sea ice in winter in this region (Fig. 2f). Interestingly, ~~the~~ CMIP5 models under the RCP 4.5 scenario, which is weaker than SRES A1B, show a stronger variability increase in ~~many~~ some regions in comparison to ~~the~~ CMIP3 models. This again suggests a higher sensitivity of SIC in ~~the~~ CMIP5 ensemble relative to CMIP3 possibly due to thicker ice in historical CMIP3 simulations. Reduced variability outside the sea ice margin reflects the complete removal of sea ice in those areas in the projected future. The same reasoning explains September SIC variability changes (Fig. 3). Complete disappearance of the sea ice cover in the marginal Arctic Seas leads to zero variability and results in a decrease in comparison to 197~~5~~0-2000; multi-year sea ice in the Central Arctic becomes thinner and more variable. ~~The smaller area of increased SIC variability in the Central Arctic in CMIP5 RCP 8.5 results from the stronger sea ice retreat in response to the stronger forcing. Again, higher interannual variability in RCP 4.5 relative SRES A1B suggests a higher sensitivity of SIC to external forcing in the CMIP5 models.~~

3.2 Changes in Arctic sea ice area

Changes in ~~sea ice area (~~SIA~~)~~ for the Entire Arctic, Central Arctic and Barents Sea as simulated ~~and projected~~ by ~~the~~ CMIP3 and CMIP5 models and ~~as observed~~from HadISST1 dataset ~~in March and September~~ are depicted in Figures 4 and 5 for March and September, respectively. We show only the RCP 8.5 scenario from CMIP5 to illustrate the consequences of the aggressive “business as usual” anthropogenic forcing.

3.2.1 Entire Arctic

In March (Fig. 4a, b), ~~the~~ CMIP5 ensemble-mean bias for SIA during the observation period becomes larger than in CMIP3, reaching almost $2.0\cdot10^6$ km² as compared to $1.5\cdot10^6$ km² in CMIP3. The ensemble-mean SIA decrease by the end of the 21st century amounts to 3.~~0~~5$\cdot10^6$ km² in CMIP3 (SRES A1B) and ~~5~~6.~~5~~0$\cdot10^6$ km² in CMIP5 (RCP 8.5). The CMIP5 ensemble-mean SIA ~~of~~ is about $10\cdot10^6$ km² by the end of the 21st century, which is still comparable to the observed present day conditions of about $13\cdot10^6$ km². ~~Two~~ Three models (~~NCAR-CCSM3.0 and GISS-MODEL-E-R~~GFDL-CM3, MIROC-ESM and MIROC-ESM-CHEM) show a very sharp decrease to less than 4.0$\cdot10^6$ km², while three others (~~MPI-ECHAM5, INM-CM3, and UKMO-HadGEM1)~~GFDL-ESM2G, BCC-CSM1.1 and BCC-CSM1.1m simulate excessive SIA exceeding $20\cdot10^6$ km² during the 20th century (Fig. 4b). Due to such “outliers”, the overall model spread becomes larger in CMIP5 compared to CMIP3.

In contrast to our findings for the SIA in March, a clear improvement of September SIA simulation is seen in ~~the~~ CMIP5 models ~~during 1950-2100~~for the period of observations (Fig 5a). When considering the Entire Arctic, the multi-model mean September SIA by the end of 21st century decreases by ~~4~~3.6$\cdot10^6$ km² ~~by the end of 21st century~~ in CMIP3 (Fig. 5a) and by ~~5~~6.0$\cdot10^6$ km² in CMIP5 (Fig. 5b) relative to the end of the 20th century. Practically all CMIP5 models (except for ~~GFDL-CM2.0~~CSIRO Mk3.6.0) simulate an ice-free Arctic by the end of the 21st century under the very strong RCP 8.5 scenario. Sea ice extent projections from ~~the~~ CMIP5 RCP 4.5 ensemble has been analysed by Stroeve et al. (2012) and these featured a decrease that, despite the weaker forcing, was comparable to that calculated from ~~the~~ CMIP3 SRES A1B ensemble. Several CMIP5 models (Fig 5b) project a strongly accelerating decrease of SIA around the 2030s, indicating a potential instability or “tipping point” (Lenton et al., 2008). The ~~very recent observed~~ accelerated Arctic sea ice loss in the last decade is, however, still not fully captured in the multi-model mean, which may suggest a significant contribution from internal variability (Day et al., 2012) or that the models are too conservative. The latter could imply that Arctic sea ice will continue retreating at the accelerated rate observed during the early 21st century and an ice-free Arctic by 2020 (Alekseev et al., 2009; Wang and Overland, 2009). The former is suggested by the strong decadal variability simulated in a number of climate models (Semenov and Latif, 2012) with amplitude large enough to explain the recent accelerated sea ice retreat. To sum up this part, ~~the~~ CMIP5 models better reproduce (when compared to HadISST1 data) the long-term trend of the Entire Arctic SIA in September for the observational period ~~(~~when predominantly historical radiative forcing was applied~~)~~.

We note that our results for the Entire Arctic during the period of observations differ ~~somewhat~~ from those reported by Stroeve et al. (2007; 2012). The reason is related to using different sea ice cover variables and differences in methodology. Stroeve et al. (2007; 2012) use sea ice extent that sums up grid cells with more than 15% area covered by sea ice. ~~This makes the total results dependent on grid cell area and the contribution of grid cells with low sea ice concentration.~~ Further, Stroeve et al. (2012) restrict the analysis to a subset of models excluding "outliers", while we consider the whole ensembles.

3.2.2 Central Arctic

In winter, the Central Arctic is totally covered by sea ice in all models (Figs. 4c, d) until around the 2050s, when SIA begins to shrink. The ensemble-mean decrease from the end of the 20th to~~by~~ the end of the 21st century is rather modest, amounting to $0.15{\cdot}10^6$ km² and 0.~~45~~50$\cdot 10^6$ km² in CMIP3 and CMIP5, respectively. Again, the ~~same~~ CMIP5 ~~-~~low "outliers" (as for the Entire Arctic) exhibit an outstanding drop down to $0.50{\cdot}10^6$ km². In September, ~~T~~the CMIP3 and CMIP5 ensemble mean SIA ~~-~~ is smaller than that in ~~e observed~~ HadISST1 ~~SIA~~(Fig 5c, d) with CMIP5 having stronger disagreement. ~~in September.~~ This indicates that the majority of models may underestimate the September SIA in the Central Arctic during the observation period~~ in both CMIP3 and CMIP5 (Fig 5c, d), with CMIP5 being slightly worse~~. Here, we note that due to the absence of satellite data around the Pole and problems with distinguishing melt ponds in summer, the empirical SIA estimates in the Central Arctic are characterized by a higher uncertainty an the obtained results may as well indicate that HadISST1 data overestimate SIA around the North Pole due to the outlined above problems. When forced by the RCP 8.5 scenario, a ~~majority~~ part of ~~the~~ CMIP5 models show very steep SIA reduction within 2-3 decades, from the present day level to complete sea ice removal.

The large inter-model spread in the two ensembles results from different timing of fast SIA decline, with ~~a~~ two distinct groups of CMIP5 models clustering around 2030 and 2050 (Fig. 5d).

3.2.3 Barents Sea

~~As is already outlined in the Introduction, the Barents Sea region may play a key role for large-scale atmospheric variability, atmosphere-ocean feedbacks and even multi-decadal climate variations in the Arctic and Northern Hemisphere (Semenov and Bengtsson, 2003; Bengtsson et al., 2004; Semenov et al., 2009; Semenov et al., 2010; Smedsrud et al., 2013).~~ With SIA on average constituting only about 5% of the total Arctic SIA, the Barents Sea makes a minor contribution when considering the total Arctic SIA mean, trends and overall variability. Uncertainties in simulations of the sea ice cover in the Barents Sea thus contribute a minor part to the total sea ice bias, but may lead to a ~~significant~~ principal difference in simulating the extra-tropical atmospheric circulation in winter (e.g., Petoukhov and Semenov, 2010; Semenov and Latif, 2015~~; Yang and Christinsen, 2012; Inoue et al., 2012~~), as well as in the atmosphere-ocean feedbacks which are important for decadal to multi-decadal variability in the Arctic sector (Mysak and Venegas, 1998; Bengtsson et al., 2004; Goosse and Holland, 2005).

In March, the mean SIA for the observation period is fairly similar in both model data sets ($1.1 \cdot 10^6$ km²~~???? And ????~~), strongly overestimating the ~~observed value~~empirical estimate (deline from 0.810^6 km² to less than 0.610^6 km²~~????~~).~~,~~ ~~whereas~~ CMIP5 models on average simulate a stronger SIA reduction, thus better fitting observations (Fig.4e, f). It is worth mentioning that mean model bias is stronger than the observed trend during 196~~5~~0-2010. Both in September and March, the simulated SIA in individual runs exhibits strong decadal variability that may in part explain the observed decadal variations, in particular the observed sharp SIA decrease in March in the beginning of the 21st century~~2005~~ (Fig.4f). The models (both CMIP3 and CMIP5) on average also strongly overestimate SIA in the Barents Sea in September (by a factor of 3 to 4) and exhibit a very large spread from a nearly ice free Barents Sea in the 20th century to almost fully ice covered conditions (Fig. 5e, f). The Barents Sea is currently almost ice free in summer, while the models on average simulate such conditions by the end of the 21st century or around 2050 in ~~the~~ CMIP3 and CMIP5 ensembles, respectively.

CMIP5 models reproduce September SIA noticeably better.

3.3 Sensitivity of sea ice area to surface air temperature changes

The large SIA spread in the model results is related to various reasons. Highly intense atmospheric variability in high latitudes, complicated ocean dynamics, model uncertainties related to ice albedo parameter choice and simulation of Arctic cloud cover are among the factors leading to divergent estimates (Eisenman et al., 2007; Karlsson and Svensson, 2013; Koenigk et al., 2014). One of the most important questions in this respect is how future SIA change is related to global warming rate. This issue was addressed in several studies for total summer Arctic sea ice in ~~the~~ CMIP3 models, ~~with the aim o~~aiming to~~f~~ reduce~~ing~~ uncertainty in model projections with respect to reaching ice free Arctic conditions (Zhang, 2010; Winton, 2011; Mahlstein and Knutti, 2011; Massonnet et al., 2012).

~~We calculated from the CMIP models the sea ice area~~SIA sensitivity to changes in Northern Hemisphere (NH) surface air temperature (SAT) is estimated as the ratio between seasonal SIA and SAT changes averaged over the periods 1970 – 2000 and 2070 – 2100 based on CMIP models' data. The scatter diagrams in Figure 6 (winter – January, February, March) and Figure 7 (summer – July, August, September) show the sensitivities obtained from CMIP3 (SRES A1B scenario) and CMIP5 (RCP 8.5) for the Entire Arctic, Central Arctic and Barents Sea. The intra-ensemble regressions and correlations are summarized in Table 3 (which also includes results from CMIP5-RCP 4.5). For the Entire Arctic SIA, a robust linear dependence of winter ~~sea ice area~~SIA on the NH SAT change can be seen (see Fig. 6a, b) among CMIP3 and CMIP5 models with a correlation coefficient close to -0.8 in both ensembles. The slope of the regression line in CMIP3-A1B is -1.9~~2~~$\cdot 10^{6}$ km² $°C^{-1}$, -~~1.58~~1.9$\cdot 10^{6}$ km² $°C^{-1}$ in CMIP5-RCP8.5 and -~~1.31~~1.4$\cdot 10^{6}$ km² $°C^{-1}$ in CMIP5-RCP4.5. Thus, winter SIA in ~~the~~ CMIP5 models is less sensitive to NH SAT increase in comparison to ~~the~~ CMIP3 models. Further, the different sensitivities in CMIP5-RCP 4.5 and CMIP5-RCP8.5 suggest that a ~~higher warming~~stronger forcing ~~rate~~ leads to accelerated summer SIA decrease (Fig. 7a, b). These differences are, however, within the model uncertainty range (Table 3). We note that the models depicting very strong NH warming by the end of the 21st century (about 6 °C and ~~even~~ more) exhibit SIA sensitivities which strongly depart from the regression line, suggesting non-linear effects.

Central Arctic SIA does not exhibit a robust relationship to NH SAT in winter in ~~the~~ CMIP models (Fig. 6c, d, Table 3). This is due to the ~~only~~ modest SIA changes in many models, even by the end of the 21^{st} century. The stronger regression slope in ~~the~~ CMIP5 models is related to the aforementioned outliers, whereas the majority of models do not show significant changes even under RCP 8.5 scenario. Barents Sea winter SIA ~~change as a function of NH SAT~~sensitivities (Fig 6e, f) ~~is~~ are characterized by a large intra-~~model~~ ensemble spread which is particularly strong for ~~the~~ CMIP5 ensemble. We note, however, that there is a noticeably larger portion of CMIP5 models that simulate historical Barents Sea SIA reasonably well both in March and September, whereas the majority of CMIP3 models distinctly overestimate SIA. This can be related to a larger total number of models in CMIP5 ensemble with a mixture of more sophisticated and basic sea ice models. ~~This implies higher uncertainty in the future projections, which is important in the context of the strong and non-linear impact of Barents SIA on the atmospheric circulation over the northern continents (Petoukhov and Semenov, 2010; Yang and Christensen, 2012).~~

Summer sensitivities (Fig. 7) exhibit noticeable differences in comparison to those obtained for winter. Whereas ~~the~~ CMIP3 ensemble depicts a rather close link between NH SAT and SIA~~C~~ changes (Fig. 7a), CMIP5 models show a weaker dependence on surface air temperature changes (Fig. 7b). This is partly related to the stronger radiative forcing which drives ice free conditions by the end of the 21^{st} century in the majority of the models. Thus, the presented sensitivities largely depend on the SIA values during 1970-2000 that are almost randomly distributed. Therefore, the intermediate forcing scenario RCP 4.5 leads to a stronger sensitivity (Table 3). This is also valid for the Central Arctic SIA (Fig.7c, d). However, for the Barents Sea (Fig. 7e, f), neither of ~~the~~ CMIP ensembles shows a statistically significant correlation of intra-model SIA differences and NH SAT changes. This, as well, may be explained by the disappearance of sea ice already by the middle of the 21^{st} century, making SIA sensitivity strongly dependent on the present-day state.

3.4 Changes in SIA seasonal cycle amplitude

The stronger decrease of the ~~sea ice area (~~SIA~~)~~ during September in comparison with March, as observed and simulated by ~~the~~ CMIP models (Figs. 4, 5), implies an increase in the seasonal cycle amplitude (Fig. 8). This can be clearly seen in the ~~observations~~ HadISST1 data for the Entire Arctic and Central Arctic (Fig. 8a-d). ~~The~~ CMIP models tend to underestimate the observed trend. At the end of the 20^{th} century, the amplitude of the SIA seasonal cycle for the Entire Arctic is about 5~~6~~.9~~0~~·10^6 km^2 in CMIP5-RCP 8.5 (5.~~0~~3·10^6 km^2 in CMIP3-A1B~~), which amounts to about 40% (35%) of the maximum winter sea ice area~~). We note that the presented amplitude is a half of peak to peak amplitude estimated by harmonic analysis and thus is not equal to a half of September to March SIA difference. ~~By the end of~~The amplitude increases during the 21st century. In ~~the, the amplitude in~~ CMIP5-RCP 8.5 ensemble, the amplitude reaches maximum values of 6.8~~6~~·10^6 km^2 ~~(55% of the March sea ice area)~~ around 2060 and then decreases to present day values. This behaviour is related to the fact that many models become seasonally ice free after 2050 and seasonal cycle amplitude change due to slower winter sea ice decrease. Amplitude increase in CMIP3-A1B models proceeds monotonically ~~increases to values of~~reaching about~~ about~~ ~~6·10^6 km^2 (5~~6.2~~5~~·10^6 km^2 ~~in CMIP3-A1B) in the ensemble mean, which amounts to 60% (45%) of the maximum sea ice area~~to the end of the 21st century. ~~These values are about 35% at the end of the 20th century for both CMIP5-RCP 8.5 and CMIP3-A1B. A decrease in the seasonal cycle amplitude is seen in CMIP5-RCP 8.5 after reaching a maximum around 2060 (Fig. 8b). This behaviour is related to the fact that many models become seasonally ice free after 2050 and seasonal cycle amplitude change due to slower winter sea ice decrease.~~

During the overlapping period, the observations show a much (at least three times) stronger trend in the seasonal cycle amplitude of the Entire Arctic SIA than both the CMIP3-A1B and CMIP5-RCP 8.5 ensemble means (Fig. 8a, b). Further, the models noticeably overestimate the ~~observed~~ HadISST1 amplitude during 196~~5~~0-2010. In this respect, ~~the~~ CMIP5 models even exhibit a ~~much~~ twice larger bias (about 1.0·10^6 km^2) than those from CMIP3.

The major portion of the simulated increase of the SIA seasonal cycle amplitude for the Entire Arctic ~~may be~~is caused by changes in the Central Arctic (Fig. 8c, d). In this region, both model ensembles ~~reasonably well~~better reproduce the observed trend in the recent two decades, but still show a ~~strong~~ positive bias, which is particularly visible in CMIP5-RCP 8.5 (about 0.2·10^6 km^2). This difference, as already noted above, can also be related to underestimated SIA changes in HadISST1 dataset in this region.

In the Barents Sea region, the observations indicate a small reduction in the SIA seasonal cycle amplitude, with strong decadal variability superimposed (Fig 8e, f). Here (as well as for the Central Arctic), both ensembles are characterized by very large spread. The ensemble-mean trends seemingly do not correspond to the ~~most probable trends~~mode of the trend distribution, with a majority of models falling into the tails of the distribution~~s~~. The ensemble-mean SIA seasonal cycle amplitude decrease after 2000 in CMIP5-RCP 8.5 results from the majority of the models predicting an ice free Barents Sea in summer, with 5 very strong outliers that simulate excessive ice cover after 2050 (Fig. 8f). In CMIP3-A1B, the ensemble mean does not exhibit ~~much~~ strong changes during the 21st century. ~~Strong decadal to inter-decadal variability of the sea ice cover in the Barents Sea is simulated by the majority of the models, be they from CMIP3-A1B or CMIP5-RCP 8.5, consistent with the notion that the Barents Sea is a region that is strongly affected by natural variations of the oceanic inflow and atmospheric circulation. The marginal Arctic Shelf Seas, which are important regions for natural resources exploration, fishery and marine transportation (Khon et al., 2010), are characterized by the largest biases and projection uncertainties.~~

The evolution of the seasonal cycle phase during the 20th and 21st century is characterized by very large uncertainties (not shown). When considering the Entire Arctic, ensemble-mean phase changes from both CMIP3-A1B and CMIP5-RCP 8.5 amount to only about 5 days during the whole 21st century. The observations do not indicate a long-term trend, but strong decadal variability in all regions (not shown).

3.5 Changes in interannual variability

Climate change not only affects the annual-mean and seasonal cycle of Arctic sea ice, but also its interannual variability. Changes in interannual variability are ~~of large societal relevance, as they may are~~ important for sea ice prediction and the frequency of occurrence of extreme SIA anomalies. We analyze the standard deviation~~s~~ of interannual SIA variability during the ~~following three time periods: preindustrial (using the results of the preindustrial control integrations),~~ 19~~5~~70 – 2000 (in historical CMIP simulations) and ~~2050~~ 2070 – 2100 (in CMIP3 SRES A1B, and CMIP5 RCP4.5 and RCP8.5 runs). The long-term trend has been subtracted as a fourth order polynomial fit before computing standard deviations. ~~Calculations for the preindustrial period and 1950 – 2000 are very similar. Therefore, we present only results for the latter period.~~ Figure 9 shows the standard deviation (STD) of the SIA for the Entire Arctic in the individual CMIP3 and CMIP5 models as well as averaged STD in each ensemble for March ~~and ratio between STD in~~versus September ~~and March (R_{SM}) for both CMIP ensembles~~. Also shown are corresponding values for HadISST1 dataset for 1970-2000 period.

During the 1970-2000 ~~20th century~~ period ~~(1950-2000)~~, both ensembles on average ~~the~~ exhibit stronger variability of a similar magnitude in March ($3.2\cdot10^5$ km^2 and $3.0\cdot10^5$ km^2 for CMIP3 and CMIP5 respectively) in comparison to HadISST1 data ($2.5\cdot10^5$ km^2). This overestimation is, in part, related to the overestimated mean SIA (Fig. 4a,b). In September, CMIP3 ensemble average STD almost exactly fits HadISST1 estimate ($3.5\cdot10^5$ km^2), whereas CMIP5 ensemble mean STD is noticeably higher ($4.3\cdot10^5$ km^2) (Fig. 9a)~~interannual variability in March is considerably weaker in CMIP3 than in CMIP5 (Fig 9a) and fits better to observations~~. This is despite smaller SIA in CMIP5 models that better fits to HadISST1 SIA in September (Fig. 5a,b). ~~-~~The majority of CMIP5 and CMIP3 models are located above the diagonal dotted line indicating that September variability is higher than that in March. On average, this ratio is 1.6 for CMIP5 models, 1.4 for HadISST1 and 1.3 for CMIP3. ~~The results shown in Figure 9 indicate that the ratio R_{SM} is strongly linked to the strength of the interannual variability in March. Models that exhibit higher variability in March, exceeding about $3\cdot10^5$ km^2 (R_{SM} >1), tend to have enhanced variability in September with a stronger enhancement to that in March. Models with variability in March that is below the threshold have reduced variability in September with an opposite dependence. In the observations, interannual variability in September is almost 2.5 times stronger than in March (Fig. 9a). During 1950-2000, the CMIP3 models on average reproduce the observed variability in March, but strongly underestimate it in September. The CMIP5 models simulate a much higher variability in March, which is almost twice as strong as that observed, but a realistic variability in September.~~

During the 2070-2100 period, CMIP3 ensemble average STD virtually does not change keeping on average the same September to March variability ratio close to one. For CMIP5, average STD does not change in RCP4.5 scenario and increases to $3.5\cdot10^5$ km^2 under RCP8.5 scenario. STD changes in September are considerably stronger with reduction from $4.3\cdot10^5$ km^2 to $3.5\cdot10^5$ km^2 and $2.0\cdot10^5$ km^2 in RCP4.5 and RCP8.5 scenarios respectively. September STD decreases in CMIP5 is related to a large number of models becoming ice free in September under aggressive RCP8.5 scenario. As was stated above, March STD noticeably increases in CMIP5 RCP8.5 (presumably due to thinner ice) thus resulting in the average September to March variability ratio 0.6. Observations for the last decades suggest an increase of interannual sea ice extent variability (Holland et al., 2008). Decrease of September STD to the end of 21st century in CMIP5 models does not contradict to empirical findings and can be explained by nonlinear dependence of the variability on the mean SIA (Goosse et al., 2009).

~~Changes in interannual variability simulated during the second half of the 21st century are principally different in CMIP3 and CMIP5. In CMIP3, the number of models with R_{SM}>1 markedly increases and variability in March is slightly enhanced (Fig 9b). In contrast, the majority of the CMIP5 models project a strong reduction of interannual SIA variability in both March and September. Variability is more strongly reduced in RCP 4.5 than in RCP 8.5, rendering RCP 4.5 being very close to CMIP3 during 1950-2000 in terms of the ensemble means. The projected future increase of SIA interannual variability in September in CMIP3 is consistent with what may be expected from observational data analysis by Holland et al. (2008), Holland and Stroeve (2011) and Goosse et al. (2009). Holland et al. (2008) argued that thinner September sea ice melts faster, but can also faster converge and form big areas. Goosse et al. (2009) also argued that the increasing interannual SIA variability in September is related to thinner sea ice. Holland and Stroeve (2011) propose less impact of the atmospheric circulation on the September sea ice variability because of a shift in the surface pressure (SLP) anomalies in the Eastern Arctic.~~

~~3.6 Sea ice variability and AMOC~~

~~The North Atlantic (NA) Ocean transports heat poleward, reducing imbalance of radiative fluxes between low and high latitudes (e.g.; Trenberth and Caron, 2001). The Atlantic Meridional Overturning circulation (AMOC) makes the major contribution to the oceanic heat transport in the NA with about 1 PW of heat at about 30°N (where in general the maximal heat transport is observed) (e.g.; Delworth and Mann, 2000 and references therein). Observations of various sources and model simulations suggest a strong multi-decadal variability of the AMOC that impacts poleward heat transport, NA surface temperatures and turbulent heat fluxes and Arctic sea ice (Koltermann et al., 1999; Latif et al., 2004; Semenov, 2008; Polyakov et al., 2010; Day et al., 2012; Gulev et al., 2013). Multi-decadal variability in the North Atlantic may noticeably contribute to globally averaged SAT variability (e.g.; Semenov et al., 2009) and is a major source of uncertainty in SAT projections for the 21st century (e.g.; Kravtsov and Spannagle, 2008).~~

~~*SIA change and AMOC*~~

~~The AMOC is projected to slow with global warming due to stronger warming and enhanced fresh water input in high latitudes (e.g.; Schneider et al., 2007). This implies less heat~~

~~transported to the Arctic that may mitigate sea ice loss, constituting a dynamical negative feedback. Thus the relationship of the Arctic SIA to the mean AMOC may indicate which factor (AMOC slowing or temperature increase) dominates SIA change. We present here an overview of SIA sensitivity in CMIP models to changes in mean AMOC. Figure 10 shows changes of March and September SIA from 1970-2000 to 2070-2100 as a function of an AMOC index (defined as the maximum of the overturning streamfunction at 30°N) in CMIP3-A1B and CMIP5-RCP 8.5. We note that AMOC data are not available from all CMIP models. Both CMIP ensembles generally depict a negative correlation between March SIA and AMOC changes (Fig. 10a, c). In both ensembles, models with stronger SIA reduction depict less AMOC weakening, again with a closer link for the CMIP5-RCP 8.5 ensemble. This suggests that in winter, AMOC slowing and the associated reduction in oceanic poleward heat transport plays a more important role for SIA than in summer, with a reduced AMOC strength overriding the local effects of radiative forcing.~~

~~The relationship between the AMOC strength and September SIA change is opposite to that in March (Fig. 10b, d). In CMIP5-RCP 8.5, this relation is much (about 5 times) stronger and the model spread smaller (correlation 0.68) than in CMIP3 (correlation 0.20), which may partly be explained by the stronger forcing. Thus, models with a stronger Arctic SIA loss also simulate a stronger weakening of the AMOC, indicating that AMOC weakening does not determine the SIA response in the Entire Arctic. One may expect that both the AMOC and SIA changes within the model ensembles are negatively correlated with hemispheric SAT. This, however, is not the case. Both the CMIP3 and CMIP5 models do not show any significant link between NH SAT and AMOC strength changes (not shown).~~

~~*SIA and multidecadal AMOC variability*~~

~~In climate models, decadal to multidecadal AMOC variability strongly impacts Arctic sea ice, even determining Arctic surface climate variability on these time scales. Further, deep ocean convection sites are affected and oceanic transports through the Fram Strait and Barents Sea Opening modulated (Jungclaus et al., 2005; Goosse and Holland, 2005; Semenov, 2008; Mahajan et al., 2012). We analyse the linear relationships between multidecadal AMOC and SIA variability during 1900-1970 and 2030-2100. Again, long-term trends represented by a fitted fourth order polynomial have been removed and correlations computed for 9-year~~

~~running means. The strength of correlations during 1900-1970 and 2070-2100 are depicted on the x- and y-axis, respectively. Such a presentation helps to demonstrate how the correlation may change in the future. If the correlation-pair of a particular model is located in the bottom-left or upper-right quadrant means that the link between the multidecadal variability in the AMOC and SIA is (qualitatively) the same in the 20^{th} and 21^{st} centuries. Location in the two other quadrants indicates a change of the sign in the relation. Since oceanic heat transport variability associated with the AMOC is strongest during winter, we analyse only March SIA.~~

~~During 1900-1970, the majority of the CMIP3 models simulate a negative correlation between AMOC and SIA variations in the Entire Arctic and Barents Sea (Fig. 11 a, c). This is consistent with previous modelling studies and the physical notion of decreased SIA associated with enhanced poleward heat transport. However, some models depict a positive correlation in the 20^{th} or 21^{st} centuries, or in both. The majority of the CMIP5 models also show a negative correlation between multidecadal AMOC and SIA variations in the Entire Arctic (Fig. 11b) and Barents Sea (Fig 11d), with roughly half of models showing a change in the sign of the relationship during the 21^{st} century. It should be noted in this context that variations in oceanic and atmospheric heat transport may be in anti-phase (referred to as "Bjerknes compensation"). This relation may also vary with time, as shown in climate model simulations (Jungclaus and Koenigk, 2010).~~

3.~~7~~ 6 SIA and large scale atmospheric variability

~~Arctic SIA variations are also linked to large-scale atmospheric circulation changes.~~ The major mode of atmospheric winter time variability in the Extratropics is the North Atlantic Oscillation (NAO) (van Loon and Rogers, 1978; Hurrel, 1995). Although hypotheses have been put forward that the NAO is impacted by the ongoing global warming (e.g., Kuzmina et al., 2005) and low-frequency oceanic variability such as that linked to the AMOC (Peings and Magnusdottir, 2014), the recorder NAO ~~spectrum may~~variability over the last 150 years may not be distinguishable from white noise with statistical confidence (Wunsch, 1999; Semenov et al., 2008). The NAO has a strong impact on SIA in the Barents Sea~~, a region with strongest interannual and decadal SIA variability in winter~~ (Dickson et al., 2000). Barents Sea SIA is to a large extent directly affected by the atmospheric circulation and oceanic inflow. The latter ~~that itself~~ is also modulated by atmospheric variability (Smedsrud et al., 2013). Therefore, the Barents Sea represents a ~~good~~ key region to assess the models' performance with respect to the simulation of important physical links.

The oceanic inflow to the Barents Sea is impacted by the NAO, although this link is essentially non-stationary (Dickson et al., 2000; Bengtsson et al., 2004; Semenov, 2008; Smedsrud et al., 2013). The inflow is primarily wind-driven and thus depends on the strength of the south-westerly winds over the Barents Sea opening. This strength is related to the sea level pressure (SLP) gradient between the northern tip of Norway and Spitzbergen (Bengtsson et al., 2004). We therefore analyse the link between this SLP difference for JFM (that serves as an index of the winter oceanic inflow), the NAO and March SIA in the Barents Sea. ~~As for the link between SIA and AMOC, c~~Correlations are computed for detrended (using forth-order polynomial trend) time series for 1900-1970 and 2030-2100. The results are presented for interannual and decadal (5-year running means) variations.

3.6.1 Barents Sea SIA and NAO

~~Correlation between March SIA in the Barents Sea and the NAO index in CMIP3 and CMIP5-RCP 8.5 are shown in Figure 12. The same type of presentation is used as for the correlations with the AMOC (Fig. 11).~~ The strength of correlations during 1900-1970 and 2030-2100 are depicted on the x- and y-axis, respectively. Such a presentation helps to demonstrate how the correlation may change in the future. If the correlation-pair of a particular model is located in the bottom-left or upper-right quadrant means that the link between the atmospheric index variability and SIA is (qualitatively) the same in the 20th and 21st centuries. Location in the two other quadrants indicates a change of the sign in the relation. Since atmospheric circulation variability is strongest during winter, we analyse only March SIA.

Correlation between March SIA in the Barents Sea and the NAO index in CMIP3 and CMIP5-RCP 8.5 are shown in Figure 10. During the 20th century, ~~basically~~ almost all analysed models feature a negative correlation of the interannual SIA variability with the NAO index (Fig. 10~~2~~a, b), with, 10 and 13 models from CMIP3 and CMIP5 ensembles respectively ~~many~~ exceeding the 10~~5~~% level of statistical significance (0.~~24~~22). This demonstrates that ~~most~~ about half of the models from each ensemble ~~models~~ are capable ~~of, at least qualitatively, capturing the important~~to simulate the dynamical link between the NAO and Barents Sea SIA. Strength of the relationship is rather small but the empirical estimates of the correlation between NAO and Arctic climate characteristics are of the same magnitude

(Goosse and Holland, 2005, Semenov, 2008). The negative ~~correlation~~ link is also present during the 21^{st} century although with reduced number (8 and 7 for CMIP3 and CMIP5) of models passing the significance test. On the decadal time scale, the relationship is in general stronger in ~~both~~ both ensembles, but the spread becomes larger and the number of~~several~~ models that exhibit~~ed~~ a significant correlation ~~to the NAO~~in both ~~during the~~ 20^{th} and 21^{st} centuries~~y~~ ~~show now much weaker or even positive correlations~~become very small (1 and 3) (Fig. 10~~2~~c, d). ~~This may in part be related to the fact that several models reach an ice free regime in the Barents Sea towards around 2050.~~

3.6.2 Barents Sea SIA and SLP difference Scandinavia-Spitzbergen

Figure 11 depicts ~~The~~ correlations of the March Barents Sea SIA with JFM SLP difference between Scandinavia and Spitsbergen~~, which serves here as an index of the oceanic inflow to the Barents Sea through its eastern opening, are presented in Figure 13~~. We note that this pressure index associated with the strength of south-westerlies not only drives the ocean currents but also affects SIA -directly dynamically and thermodynamically. On interannual timescales, ~~Both~~ the majority of models from both ensembles (except for 2 and 5 models in CMIP3 and CMIP5 respectively) ~~generally show~~exhibit significant negative correlations ~~on interannual timescales~~ (Fig. 11~~3~~a, b~~), which is expected as more warm Atlantic waters enter the inner Barents Sea thereby reducing sea ice extent~~). ~~There are no considerable differences between the~~This link remains robust also in the ~~20^{th} and~~ 21^{st} century, although noticeably more (11) CMIP5 models do not pass significance test ~~results~~. In general, those ~~M~~models that depict a stronger correlation in the 20^{th} century also tend to ~~also~~ have stronger correlation in the 21^{st} century. ~~The relation is somewhat weaker in the CMIP5 ensemble.~~ The results are qualitatively similar for decadal timescales (Fig. 11~~3~~c, d), ~~although~~ again with both ensembles exhibiting a larger correlation spread. ~~It should be kept in mind, however, that time series are rather short to study decadal variability in detail.~~ There is a noticeable decrease of the number of models showing significant negative correlation in the 21^{st} century as compare to the 20^{th} century, especially in CMIP5 ensemble~~The correlation changes its sign in a considerable portion of CMIP5 models when moving from the 20^{th} century to the 21^{st} century~~ (Fig. 11~~3~~d). This again may be related to the rather strong radiative forcing that causes a strong reduction of the sea ice ~~to completely disappear~~ in the Barents Sea already in the middle of the 21^{st} century (Fig. 4f). The analysis indicates that~~,~~ despite the strongly overestimated SIA in the Barents Sea~~,~~ many models simulate a significant impact of the oceanic inflow on SIA at interannual to decadal time scales.

4 Summary and conclusions

~~Arctic sea ice in models that participated in the Coupled Model Intercomparison Project Phase 3 and 5 (CMIP3 and CMIP5) has been analyzed. Sea ice concentration (SIC) patterns and their variability have been studied first. This was followed by the investigation of changes in sea ice area (SIA) in the Entire Arctic, Central Arctic and Barents Sea in March and September. Further, the SIA seasonal cycle amplitude, interannual variability and decadal variability have been investigated. We also investigated the sensitivity of SIA changes to Northern Hemisphere surface air temperature (SAT) and Atlantic Meridional Overturning Circulation (AMOC) and links between SIA variability and the AMOC, North Atlantic Oscillation (NAO) and sea level pressure (SLP) gradient between Scandinavia and Spitsbergen serving as an index of oceanic inflow to the Barents Sea. In the following, we provide an overview of major findings.~~

Our analyses for summer sea ice area ~~(~~SIA~~)~~ in the Entire Arctic are ~~consistent~~ in general with previous studies (Stroeve et al., 2007; Stoeve et al. 2012; Wang and Overland, 2009) which considered summer sea ice extent ~~(SIE)~~. Both model ensembles show a consistent SIA decline when forced by estimates of historical external forcing and future scenarios of anthropogenic greenhouse gases and aerosols. ~~The~~ CMIP5 models much better reproduce both the mean state and ~~observed~~ long-term trend of the Entire Arctic SIA in September as represented by HadISST1 dataset. In particular, ~~the~~ CMIP5 ensemble on average simulates a stronger decline which is more consistent with the observed SIA trend. The recent accelerated Arctic sea ice loss during the early the 21st century, however, is still not fully captured, which may suggest a contribution from internal variability, ~~an~~ or underestimated sensitivity to the applied forcing and/or incomplete forcing. Many CMIP5 models exhibit a step like SIA decrease in the first half of the 21st century~~,~~ resulting ~~resulting~~ in ~~from~~ a seasonally ice free Arctic around 2050 and ~~possibly~~ suggesting ~~the existence of~~ a "tipping point" in the Arctic climate system. A clear improvement in the simulation of September SIA in the Entire Arctic by ~~the~~ CMIP5 models during 196~~5~~0-2014~~0~~ is seen in comparison to CMIP3, ~~but at the same time~~though it ~~is~~ is accompanied by slightly larger biases for March SIA when compare to HadISST1 data. Simulated SIA in the Barents Sea is characterized by stronger relative bias and higher uncertainties of future projections in comparison to the Entire Arctic. ~~Regional SIA changes are characterized by much stronger uncertainties that changes in the Entire Arctic.~~ The models in both ensembles tend to strongly overestimate SIA in the Barents Sea in September (by a factor of 3 to 4) and exhibit a very large spread ~~concerning~~ of the mean state and trends. ~~Many~~ The majority of models depict large departures from the observations. We note that there is a larger number of models in CMIP5 that simulate Barents SIA reasonably well both in Mach and September. SIA in individual runs (in all analysed regions) exhibits strong decadal variability in both March and September, which is consistent with the observed decadal variations seen at a regional scale and may also explain the accelerated sea ice retreat during the early 21st century.

The pattern of SIC interannual variability in September is also improved in ~~the~~ CMIP5 models, with larger interannual variability ~~than the~~relative to CMIP3 models. However~~,~~, the variability is still weaker than ~~in~~ that~~e~~ ~~observ~~in HadISST1~~ations,~~ especially in the Atlantic sector. The model spread is also reduced in comparison to CMIP3. Much better simulation of the interannual variability along the Arctic sea ice margin is, however, accompanied by overestimated variability in large parts of the Central Arctic, suggesting an overall increase of sensitivity of summer SIC to heat balance variations at the atmosphere-ocean interface. This difference, however, may also be caused by overestimated variability in HadISST1 dataset caround the North Pole due to missing satellite observations. In winter, ~~the~~ CMIP5 models also demonstrate a better agreement with observations, although not as much improved as in summer. In future projections, ~~the~~ CMIP5 models under the RCP 4.5 scenario exhibit a stronger variability increase in many regions in comparison to ~~the~~ CMIP3 models under the weaker SRES A1B scenario. This also may suggest~~s~~ a higher sensitivity of SIC to greenhouse warming in ~~the~~ CMIP5 ensemble.

The ~~dependence~~ link between~~of~~ SIA and~~on~~ NH SAT, when considering the Entire Arctic, is most robust in winter and of rather similar strength in the two model ensembles. In summer, ~~the~~ CMIP5 models when forced by the RCP 8.5 scenario show a considerably weaker ~~link~~ relationship between~~of~~ SIA and~~to~~ SAT than ~~the~~ CMIP3 models (employing the SRES A1B scenario). This may be explained by the much stronger radiative forcing ~~creating~~resulting, for the majority of models, in the ~~an~~ ice free Arctic during summer around 2050. For RCP4.5 scenario, summer sensitivity is stronger and comparable to the winter values. The results for the Entire Arctic imply a strong dependence of SIA on the hemispheric-scale SAT response to anthropogenic forcing and thus transient climate sensitivity. For the Central Arctic, ~~the~~ CMIP5 (RCP 8.5) models also generally depict a weaker dependence of summer SIA on SAT than ~~the~~ CMIP3 models. For the Barents Sea, the dependence on SAT is the weakest, particularly in summer, indicating a large spread of the model results in this region. ~~Overall, the large model spread implies a strong dependence of SIA on the hemispheric-scale SAT response to anthropogenic forcing and thus transient climate sensitivity.~~

The amplitude of the SIA seasonal cycle increases in the observations, as implied by the stronger decrease of SIA during September than that in March. This tendency is reproduced by the models in the Entire Arctic and Central Arctic, with stronger trends simulated by CMIP5 models (forced by RCP 8.5 scenario). However, both model ensembles overestimate the amplitude in comparison to HadISST1 data~~observations~~, with ~~the~~ CMIP5 models having, on average, a noticeably stronger positive bias in both the Entire Arctic and Central Arctic. The enhanced amplitude of the seasonal cycle along with lower SIA in all seasons results in a substantially increased (by about 50%) seasonality of the Entire Arctic sea ice cover, especially in ~~the~~ CMIP5 models. The increase in the SIA seasonal cycle amplitude may also serve as a good indicator of the amount of newly formed ice during autumn and winter. Both model ensembles are characterized by very large uncertainties in the Barents Sea. Strong decadal to inter-decadal amplitude variability in the Barents Sea is simulated by the majority of models, consistent with observations and the notion that the Barents Sea is a region which is strongly affected by internal variability.

SIA interannual variability changes in the Entire Arctic have been estimated by comparing SIA standard deviations simulated ~~during~~ in the end of the 20th and 21st centuries~~y with those during the 21st century~~. ~~The~~ CMIP3 models ~~generally~~ on average better reproduce the ~~observed~~ variability in HadISST1 in September that is overestimated in CMIP5 ensemble. In present days climate, both ensembles in general show higher variability in September that in March. To the end of the 21st century, STD decreases in CMIP5, most strongly under RCP8.5 scenario that is related to large number of models becoming ice free. STD changes in March are considerably smaller. Variability in CMIP3 ensemble of average remains unchanged. ~~March, but strongly underestimate it in September. The situation is the opposite in the CMIP5 models. Finally, in the second half of the 21st century, the number of CMIP3 models that simulate a stronger interannual variability in September relative to that in March considerably increases, whereas the majority of CMIP5 models predict a strong reduction of interannual SIA variability in both March and September.~~

~~The relation between SIA change and annual-mean AMOC change exhibits principally~~

~~different behavior in March and September in both model ensembles. The stronger decrease in SIA in September is associated with stronger AMOC slowing, whereas stronger SIA reduction in March is accompanied by weaker AMOC slowing. This suggests that the long-term AMOC slowdown under global warming and associated poleward oceanic heat transport reduction plays a more important role in SIA change during winter than in summer. The link between SIA and AMOC changes is much stronger in the CMIP5 models, implying more prominent role of dynamical processes.~~

~~During the 20^{th} century, most CMIP3 models simulate a negative correlation between AMOC and SIC variations in the Entire Artic, as well as for the Barents Sea. However, several models show a positive correlation during the 20^{th} or 21^{st} centuries, or both. The majority of CMIP5 models depict a negative correlation between AMOC and SIA variations in the Entire Arctic and Barents Sea, with roughly half of models changing the sign of the relationship. Thus, the models generally demonstrate a link between SIA and AMOC related oceanic heat transport changes.~~

The majority of models in both ensembles are capable of capturing the important dynamical link between the NAO and SIA in the Barents Sea, with roughly half of the both ensembles showing statistically significant link for interannual variability. The correlations are rather weak (usually not stronger than -0.5) indicating a relatively small portion of the explained variance. This relationship ~~is~~ remains generally unchanged in the 21^{st} century. Despite strongly overestimated SIA in the Barents Sea, ~~many~~ the majority of CMIP3 models and roughly a half of CMIP5 models are also capable of simulating a link between the SLP difference Scandinavia-Svalbard (an atmospheric index of oceanic inflow to the Barents Sea) and SIA variations on interannual ~~to decadal~~ timescale~~s~~. This indicates that dynamical processes related to natural oceanic and atmospheric variability ~~do~~ considarably contribute to variations in the sea ice cover in the models. This may explain stronger differences from observations on decadal timescales.

~~We conclude that the models forced by increasing greenhouse gas concentrations simulate not only a coherent decline of the Arctic mean sea ice area, but also exhibit consistent changes of the seasonal cycle characteristics and interannual variability. A clear improvement in simulating the SIA in summer by the CMIP5 ensemble in comparison to CMIP3 models is often accompanied by worse results for winter SIA characteristics, including changes of the mean, seasonal cycle and interannual variability. Regional changes are characterized by much~~

~~higher uncertainties than changes computed for the Entire Arctic. This is particularly the case for the Barents Sea ice which is strongly influenced by natural oceanic and atmospheric variability.~~ The high uncertainty and strong model biases for the Barents Sea are very important issues for the attribution of the recent climate and weather anomalies in the northern high latitudes to the Arctic sea ice changes (see Vihma 2014 for review). Given a strongly-nonlinear circulation response to Arctic SIC changes in the resent decades (Semenov and Latif, 2015) and strong dependence on the mean state (Petoukhov and Semenov, 2010), analysis of the future atmospheric circulation response based on CMIP models should be performed with caution.

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Table 1: CMIP3 models used for the analysis. Models marked with [*)] do not resolve smaller islands like Svalbard. Only models marked with [1)] have preindustrial control runs included.

Model		Resolution Atmosphere	Resolution Ice
BCCR-BCM2.0[1)]	Bjerknes Centre for Climate Research, Norway	T63 (~ 1.9° × 1.9°)	1° × 1°
CCCMA-CGCM3.1(T47)[1)]	Canadian Centre for Climate Modelling and Analysis, Canada	T47 (~ 2.8° × 2.8°)	~ 3.7° × 3.75°
CCCMA-CGCM3.1(T63)[1)]	Canadian Centre for Climate Modelling and Analysis, Canada	T63 (~ 1.9° × 1.9°)	~ 2.7° × 2.8125°
CNRM-CM3[1)]	Centre National de Recherches Meteorologiques, France	T63 (~ 1.9° × 1.9°)	1° × 2°
CSIRO-Mk3.0[1)]	Commonwealth Scientific and Industrial Research Organisation, Australia	T63 (~ 1.9° × 1.9°)	~ 1.8° × 1.875°
CSIRO-Mk3.5[1)]	Commonwealth Scientific and Industrial Research Organisation, Australia	T63 (~ 1.9° × 1.9°)	~ 1.8° × 1.875°
GFDL-CM2.0	Geophysical Fluid Dynamics Laboratory, USA	2.0° × 2.5°	0.3° − 1° × 1°
GFDL-CM2.1[1)]	Geophysical Fluid Dynamics Laboratory, USA	3° × 4°	0.3° − 1° × 1°
GISS-AOM[1)]	Goddard Institute for Space Studies, USA	4° × 5°	3° × 4°
GISS-MODEL-E-R[1)]	Goddard Institute for Space Studies, USA	4° × 5°	2° − 4° × 5°
INM-CM3.0[1)]	Institute for Numerical Mathematics, Russia	4° × 5°	2° × 2.5°
IPSL-CM4[1)]	Institut Pierre Simon Laplace, France	2.5° × 3.75°	2° × 1°
MIROC3.2(hires)[*) 1)]	Center for Climate System Research, Japan	T106 (~ 1.1° × 1.1°)	~ 0.5° × 1.125°
MIROC3.2(medres)[*) 1)]	Center for Climate System Research, Japan	T42 (~ 2.8° × 2.8°)	1° × 1°
MPI-ECHAM5	Max Planck Institut for Meteorology, Germany	T63 (~ 1.9° × 1.9°)	1° × 1°

MRI-CGCM2.3.2A[1)]	Meteorological Research Institute, Japan	T42 (~ 2.8° × 2.8°)	0.5° − 2° × 2.5°
NCAR-CCSM3.0[1)]	National Center for Atmospheric Research, USA	T85 (1.4° × 1.4°)	0.09° − 0.5° × 1.125°
UKMO-HadCM3[*)]	Hadley Centre for Climate Prediction and Research/Met Office, UK	2.5° × 3.75°	1.25° × 1.25°
UKMO-HadGEM1	Hadley Centre for Climate Prediction and Research/Met Office, UK	~ 1.3° × 1.9°	0.09° − 1° × 1°

Table 2: CMIP5 models used for the analysis.

Model		Resolution Atmosphere	Resolution Ice
ACCESS1-0	Commonwealth Scientific and Industrial Research Organisation and Bureau of Meteorology, Australia	1.875° x ~1.25	1° x 0.6°
ACCESS1-3	Commonwealth Scientific and Industrial Research Organisation and Bureau of Meteorology, Australia	1.875° x ~1.25	1° x 0.6°
BCC-CSM1-1-M	Beijing Climate Center, Meteorological Administration,China	1.125° x 1.125°	1° x ~0.8°
BCC-CSM1-1	Beijing Climate Center, Meteorological Administration,China	T42 (2.815° x 2.815°)	1° x ~0.8°
BNU-ESM	Beijing Normal University, China	T42 (2.8125° x 2.8125°)	1° x 0.9°
CCSM4	National Center for Atmospheric Research, USA	1.25° x ~0.9°	1.125° x ~0.5°
CESM1-BGC	National Center for Atmospheric Research, USA	1.25° x ~0.9°	1.125° x ~0.5°
CESM1-CAM5	National Center for Atmospheric Research, USA	1.25° x ~0.9°	1.125° x ~0.5°
CMCC-CMS	Centro Euro-Mediterraneo per i Cambiamenti Climatici, Italy	T63 (1.875° x 1.875°)	~1.98° x ~1.2°
CMCC-CM	Centro Euro-Mediterraneo per i Cambiamenti Climatici, Italy	T159 (0.75° x 0.75°)	~1.98° x ~1.2°
CNRM-CM5	Centre National de Recherches Meteorologiques, France	TL127 (1.4° x 1.4°)	~1° x 0.6°
CSIRO-Mk3-6-0	Centre National de Recherches Meteorologiques, France	T63 (1.9° x 1.9°)	1.9° x ~0.95°
CanESM2	Canadian Centre for Climate Modelling and Analysis, Canada	T63 (~ 2.8 x 2.8)	~1.4° x ~0.9
FGOALS-s2	Institute of Atmospheric Physics, Chinese Academy of Sciences, and Tsinghua University, China	2.8125° x 1.67°	1° x ~0.9°
GFDL-CM3	NOAA GFDL(201 Forrestal Rd, Princeton, NJ, 08540)	2.5° x 2°	1° x 0.9°
GFDL-ESM2G	NOAA GFDL(201 Forrestal Rd, Princeton, NJ, 08540)	2.5° x 2°	1° x ~0.86°

GFDL-ESM2M	NOAA GFDL(201 Forrestal Rd, Princeton, NJ, 08540)	2.5° x 2°	1° x 0.9°
GISS-E2-H-CC	Goddard Institute for Space Studies, USA	2.5° x 2°	2.5° x 2°
GISS-E2-H	Goddard Institute for Space Studies, USA	2.5° x 2°	2.5° x 2°
GISS-E2-R-CC	Goddard Institute for Space Studies, USA	2.5° x 2°	1.25° x 1°
GISS-E2-R	Goddard Institute for Space Studies, USA	2.5° x 2°	1.25° x 1°
HadGEM2-AO	National Institute of Meteorological Research, South Korea	1.875° x ~1.24°	1° x ~0.8°
HadGEM2-CC	Met Office Hadley Centre, UK	1.875° x ~1.24°	1° x ~0.8°
HadGEM2-ES	Met Office Hadley Centre, UK	1.875° x ~1.24°	1° x ~0.8°
INMCM4	Institute for Numerical Mathematics, Russia	2° x 1.5°	1° x 0.53°
IPSL-CM5A-LR	Institut Pierre Simon Laplace, Paris, France	3.75° x 1.875°	~1.98° x ~1.21°
IPSL-CM5B-LR	Institut Pierre Simon Laplace, Paris, France	3.75° x 1.875°	~1.98° x ~1.21°
MIROC-ESM-CHEM	Japan Agency for Marine-Earth Science and Technology, AORI (Atmosphere and Ocean Research Institute, The University of Tokyo and National Institute for Environmental Studies, Japan	T42 (2.8125° x 2.8125°)	~1.41° x ~0.94°
MIROC-ESM	Japan Agency for Marine-Earth Science and Technology, AORI (Atmosphere and Ocean Research Institute, The University of Tokyo and National Institute for Environmental Studies, Japan	T42 (2.8125° x 2.8125°)	~1.41° x ~0.94°
MIROC5	Atmosphere and Ocean Research Institute, The University of Tokyo, National Institute for Environmental Studies and Japan Agency for Marine-Earth Science and Technology, Japan	T85 (~1.4° x ~1.4°)	~1.41° x ~0.8°
MPI-ESM-LR	Max Planck Institute for Meteorology, Germany	T63 (1.875° x 1.875°)	~1.41° x 0.82°

MPI-ESM-MR	Max Planck Institute for Meteorology, Germany	T63 (1.875° x 1.875°)	~0.45° x ~0.45°
MRI-CGCM3	Meteorological Research Institute, Japan	TL159 (1.125° x 1.125°)	1° x ~0.49°
MRI-ESM1	Norwegian Climate Centre, Norway	TL159 (1.125° x 1.125°)	1° x ~0.5°
NorESM1-ME	Norwegian Climate Centre, Norway	2.5° x 1.875°	1.125° x ~0.47°
NorESM1-M	Norwegian Climate Centre, Norway	2.5° x 1.875°	1.125° x ~0.47°

Table 3: Sensitivity of the Entire Arctic sea ice area to Northern Hemisphere surface air temperature (SAT) in CMIP model ensembles as a ratio between SIA and SAT changes averaged over the periods 1970 – 2000 and 2070 – 2100. Presented are the slope of a linear regression in 10^6 km^2/°C and the correlation coefficient (in brackets) for corresponding model ensembles (see Fig.6 and 7).

	Winter			*Summer*		
	CMIP3 SRES A1B	CMIP5 RCP 4.5	CMIP5 RC P8.5	CMIP3 SRES A1B	CMIP5 RCP 4.5	CMIP5 RCP 8.5
	10^6 km^2 /°C					
Entire Arctic	-1.9 (-0.88)~~-1.9 (-0.85)~~	-1.4 (-0.81)~~-1.3 (-0.76)~~	-1.9 (-0.81)~~-1.6 (-0.75)~~	-1.0 (-0.49)~~-1.0 (-0.57)~~	-1.3 (-0.71)~~-1.3 (-0.73)~~	-0.5 (-0.38)~~-0.6 (-0.46)~~
Central Arctic	-0.3 (-0.63)~~-0.2 (-0.60)~~	-0.2 (-0.72)~~-0.1 (-0.64)~~	-0.6 (-0.73)~~-0.4 (-0.71)~~	-0.9 (-0.64)~~-0.7 (-0.66)~~	-0.7 (-0.56)~~-0.5 (-0.56)~~	-0.2 (-0.36)~~-0.2 (-0.35)~~
Barents Sea	-0.2 (-0.56)~~-0.2 (-0.64)~~	-0.3 (-0.63)~~-0.3 (-0.64)~~	-0.1 (-0.29)~~-0.1 (-0.38)~~	0.1 (0.28)~~0.6 (0.21)~~	0.02 (0.07)~~-0.01(-0.03)~~	0.04 (0.14)~~0.01 (0.04)~~

Figures

Figure 1: Standard deviation (STD) of interannual sea ice concentration (SIC) variability (in %) in March (left) and September (right) during 1970-2000 as estimated from historical observational data (HadISST1) (a, b), CMIP3 (ensemble average; c, d), and CMIP5 (ensemble average; e, f). The CMIP results are from historical simulations. The long-term trend was removed from all datasets before estimating the STDs. White contours indicate corresponding ensemble average 15% ice concentration position. Blue lines represent models with Arctic SIA close to high values of the corresponding intra-ensemble spread (GFDL-CM2.0 (c), CSIRO-MK3.0 (e), CMCC-CM (e, f), whereas the green lines represent models simulating low SIA (INM-CM 3.0 (c, d), GISS-E-2H (e, f).

Figure 2: Standard deviation (STD) of interannual sea ice concentration (SIC) variability (in %) during 2070-2100 in March in CMIP3-A1B, a) and CMIP5 (RCP 4.5, c; and RCP 8.5, e). Difference between STD during 2070-2100 and 1970-2000 for CMIP3-A1B (b) and CMIP5 (RCP 4.5, d; and RCP 8.5, f) . The STDs have been computed for detrended data.

Figure 3: Same as in Fig. 2 but for September.

Figure 4: Time series of the sea ice area (SIA) for March (km^2) as observed (thick red) and simulated by CMIP3-A1B(left) and CMIP5-RCP 8.5 (right) models (thin colored) for the Entire Arctic (a, b), Central Arctic (c, d), and Barents Sea (e, f). Time series are smoothed with a five year running mean. The thick black lines represent the multi-model mean. Grey shading depicts the 90% confidence intervals estimated from the standard deviation of the intra-ensemble spread.

Figure 5: Same as in Fig. 4 but for September.

Figure 6: Changes of sea ice area in winter (January, February and March) between 1970 -

2000 and 2070 – 2100 periods as a function of corresponding changes of Northern Hemisphere surface air temperature for CMIP3 (20c3m/SRES A1B left) and CMIP5 (historical/RCP 8.5, right). Shown are results for the Entire Arctic (a, b), Central Arctic (c, d), and Barents Sea (e, f). Corresponding regression and correlation values are shown in Table 3.

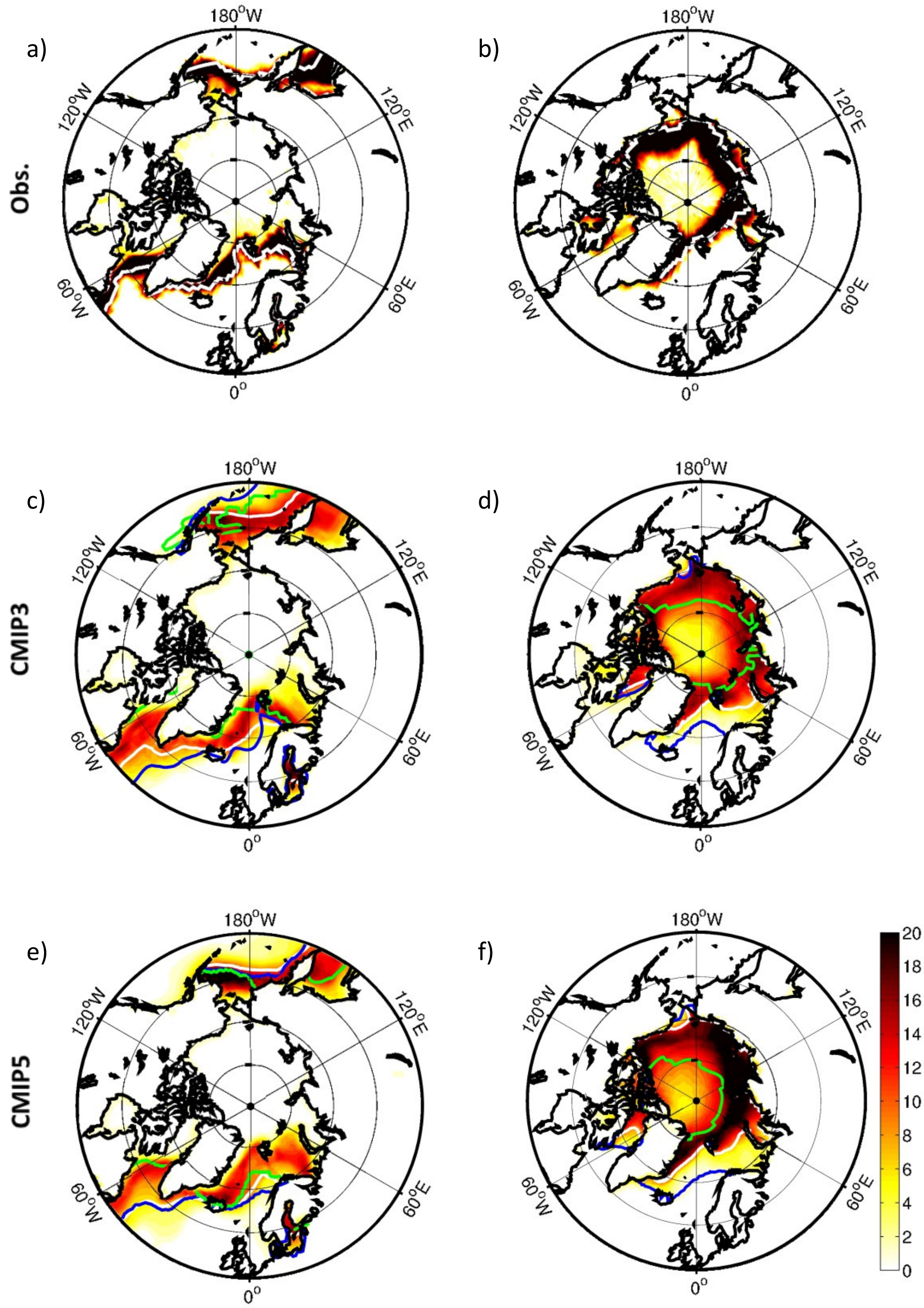
Figure 7: Same as in Fig. 6 but for summer (July, August and September).

Figure 8: The peak amplitude of the sea ice area (SIA) seasonal cycle as estimated from observations (HadISST1) (thick red) and the CMIP3 (20c3m/SRES A1B) (left) and CMIP5 (historical/RCP8.5) (right) ensembles (thin colored). Shown are the results for the Entire Arctic (a, b), Central Arctic (c, d), and Barents Sea (e, f). The individual models are presented by different colors. Time series have been smoothed with a five year running mean. The thick black lines represent~~s~~ the multi-model mean.

Figure 9: Standard deviation (STD) of September SIA variability in the Entire Arctic (in 10^5 km^2) as a function of March STD in (a) 1970-2000 and (b) 2070-2100. Small symbols depict results for individual models; large symbols are for the ensemble means. The bars indicate intra-ensemble standard deviation.

Figure 10: The correlations between the NAO index and March SIA in the Barents Sea as simulated by the CMIP3 (a, c) and CMIP5 (b, d) models during 1900-1970 and 2030-2100 periods. The correlation for 1900-1970 and 2030-2100 periods is shown on the x-axis and y-axis, respectively. Correlations have been computed using annual data (a, b) and after applying a 5-year running mean filter (c, d). Correlations significant at 90% confidence level are indicated by dotted lines.

Figure 11: Same as in Fig. 10 but for the correlation of with the sea level pressure difference Scandinavia-Svalbard.



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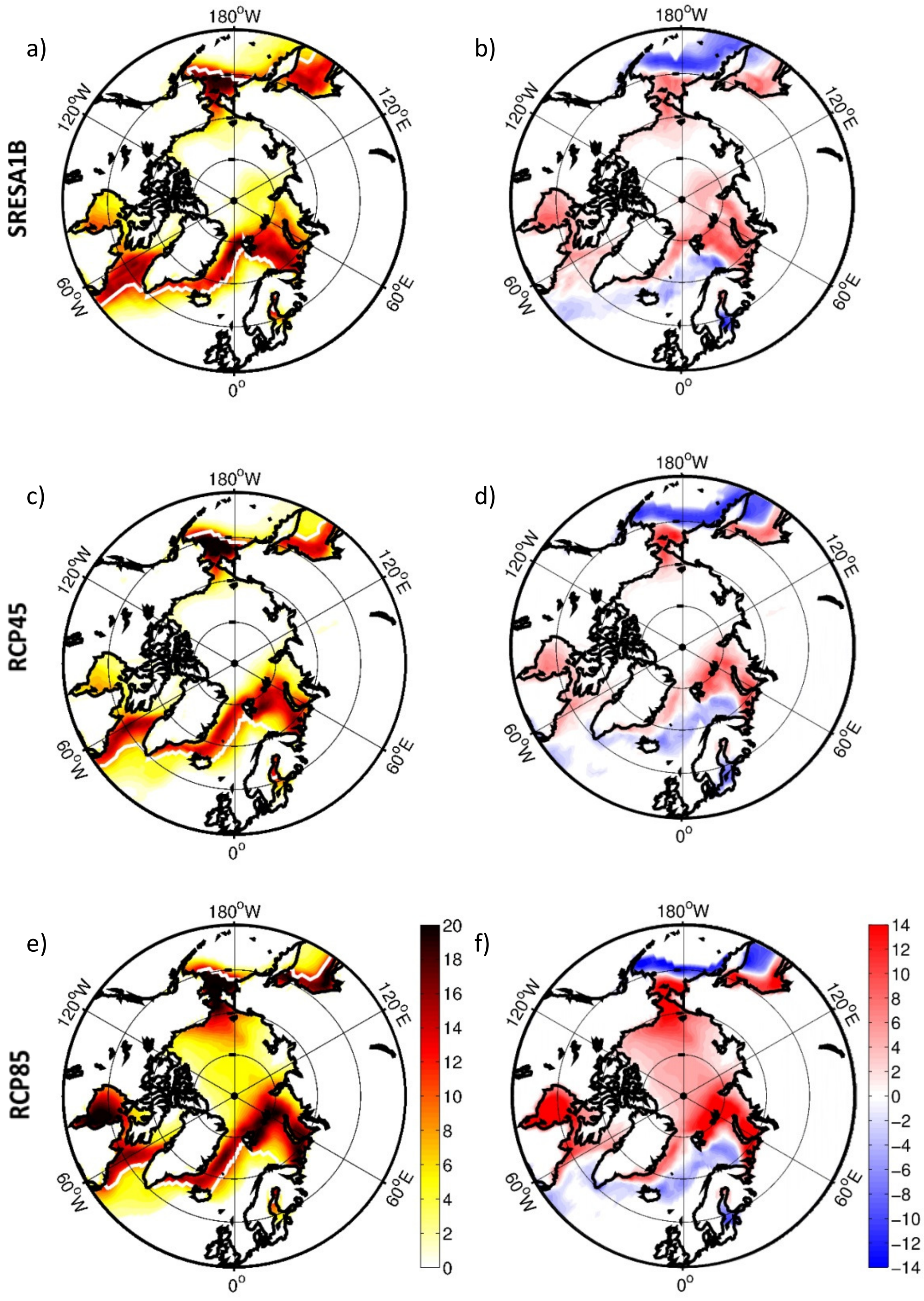

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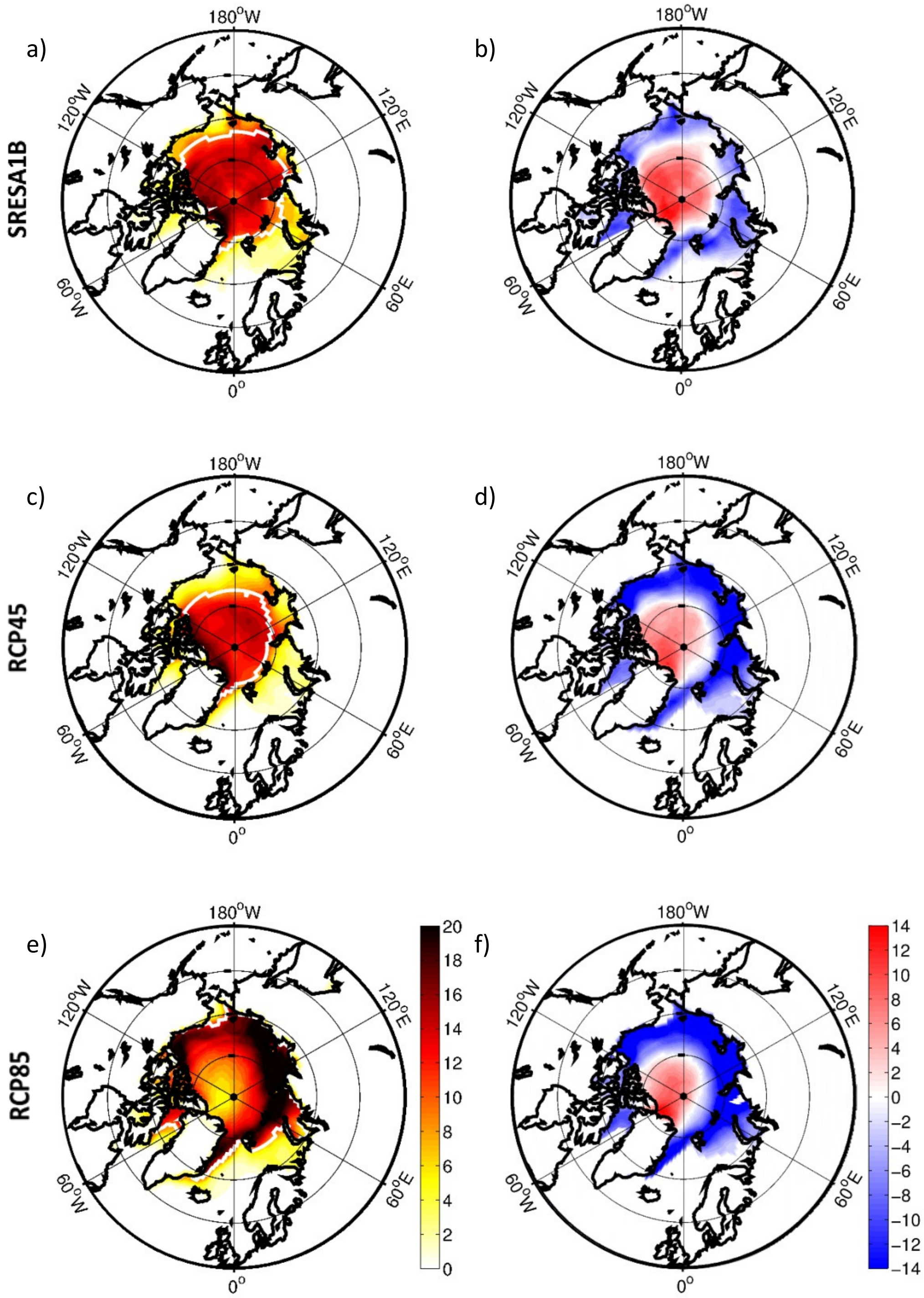

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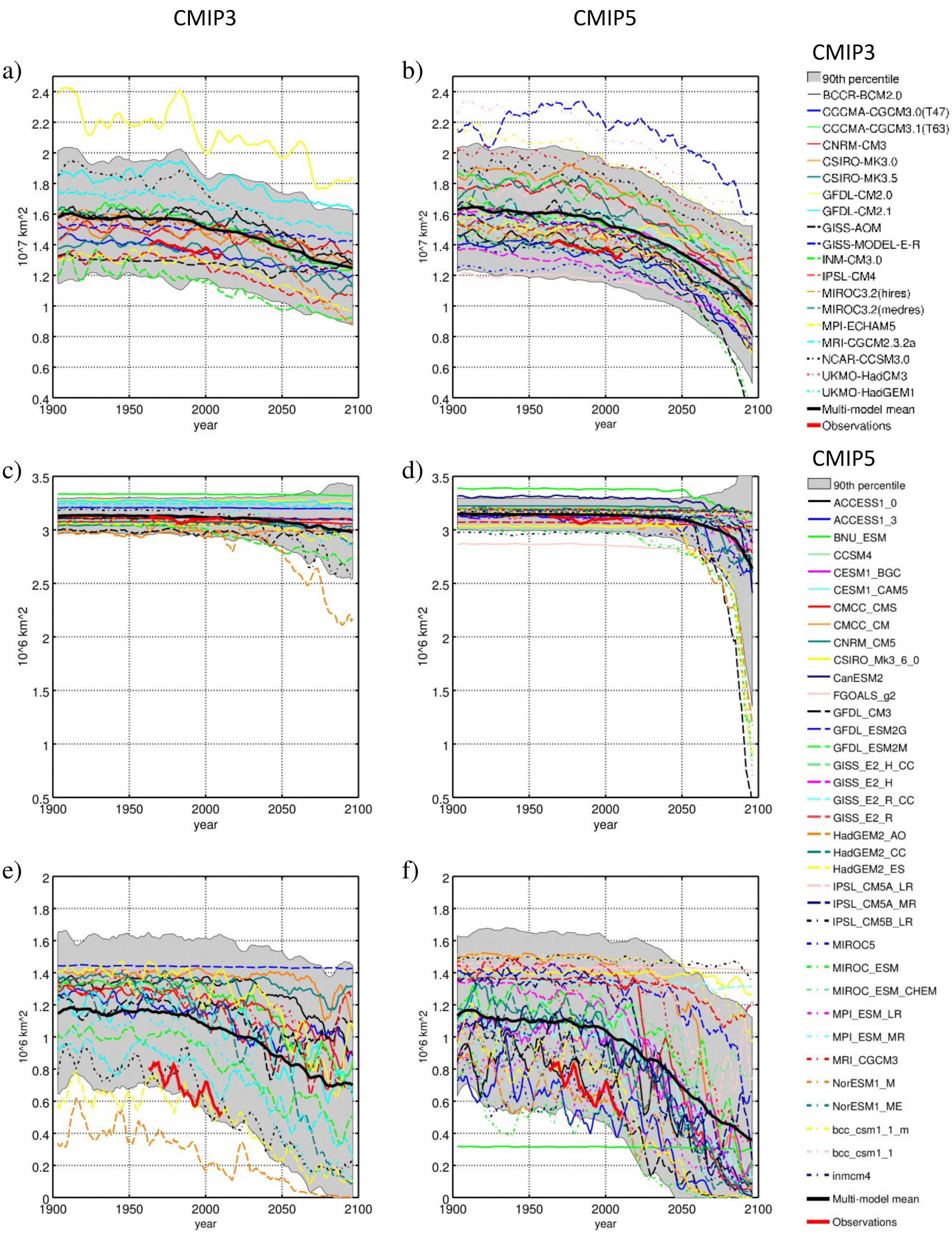

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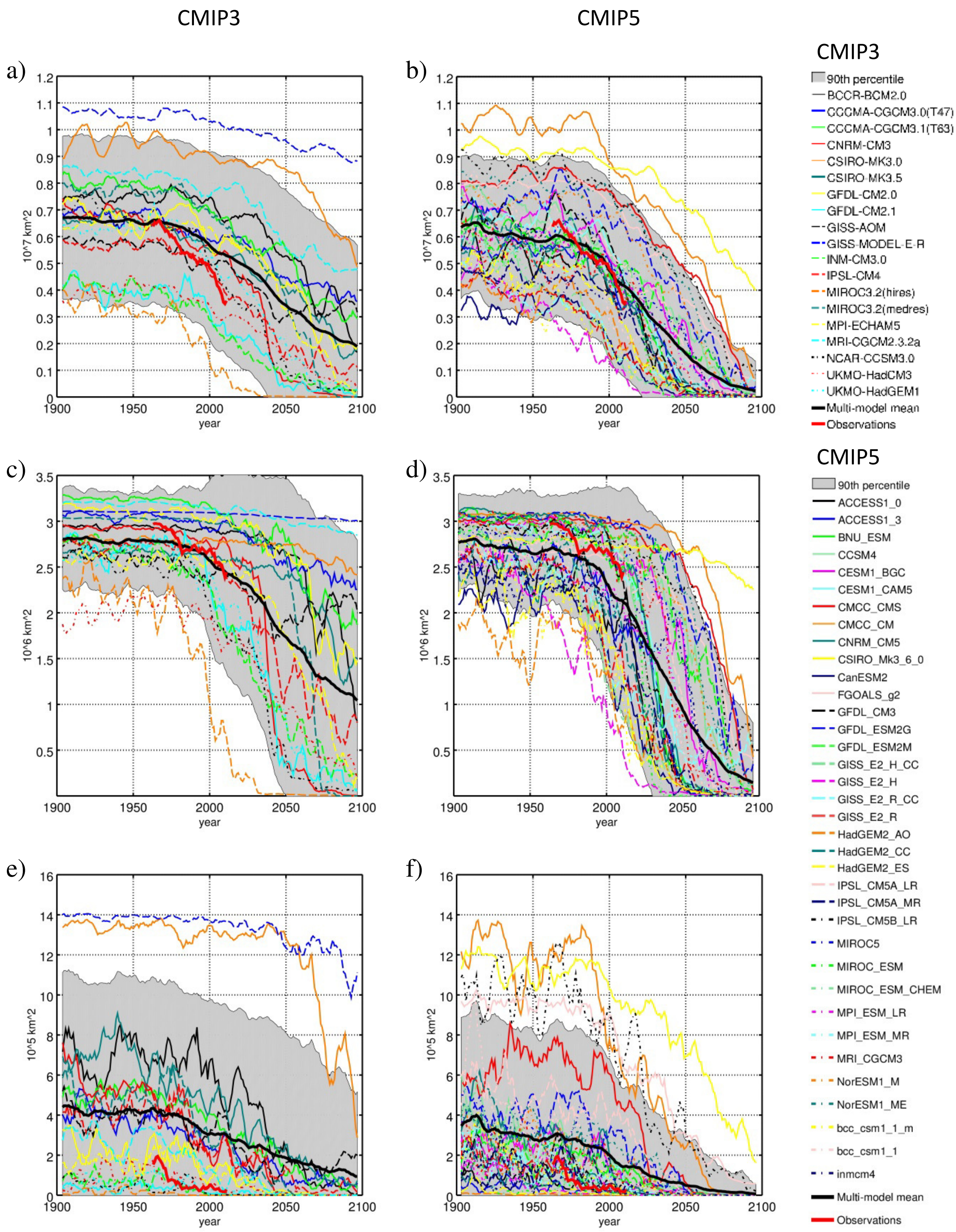

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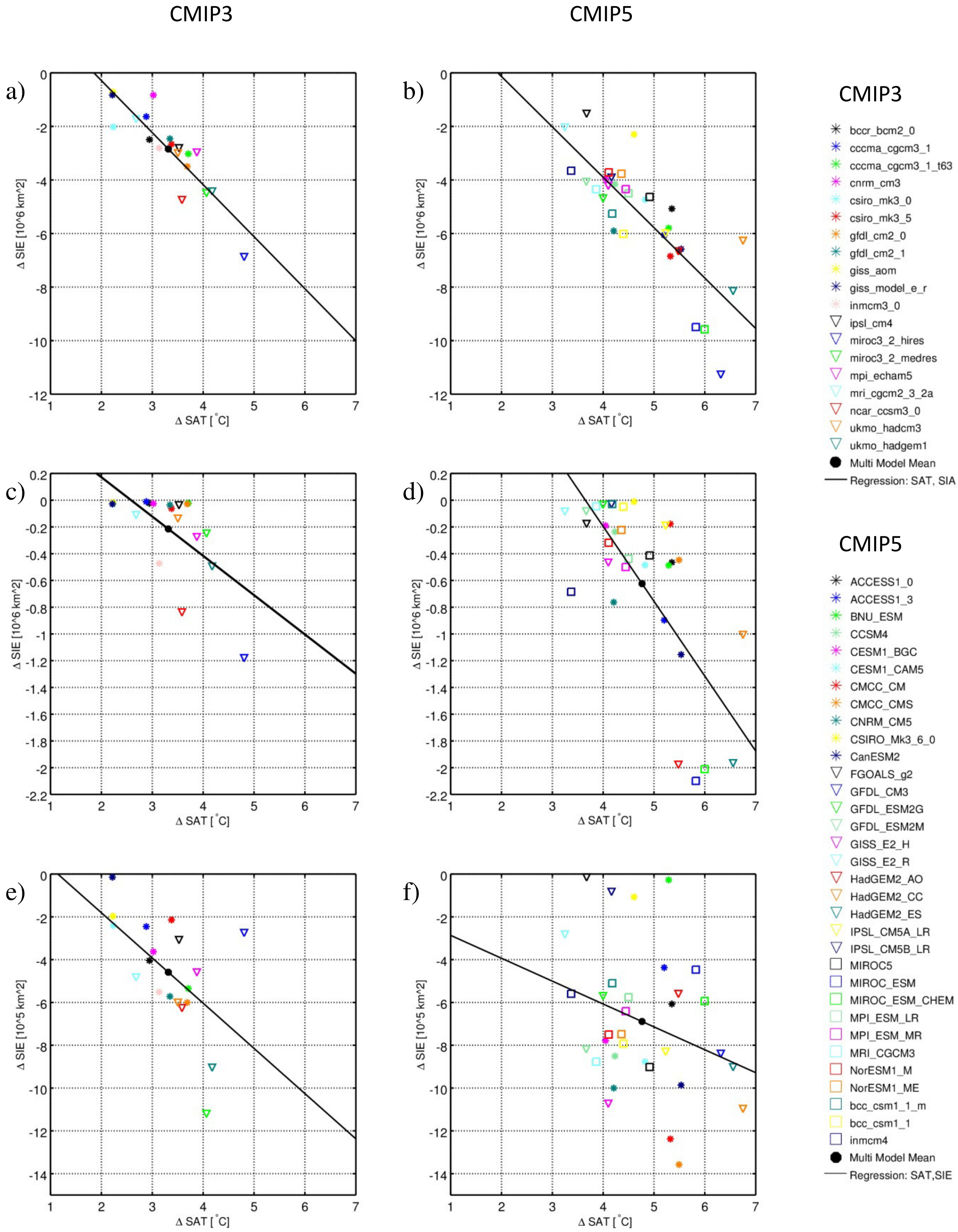

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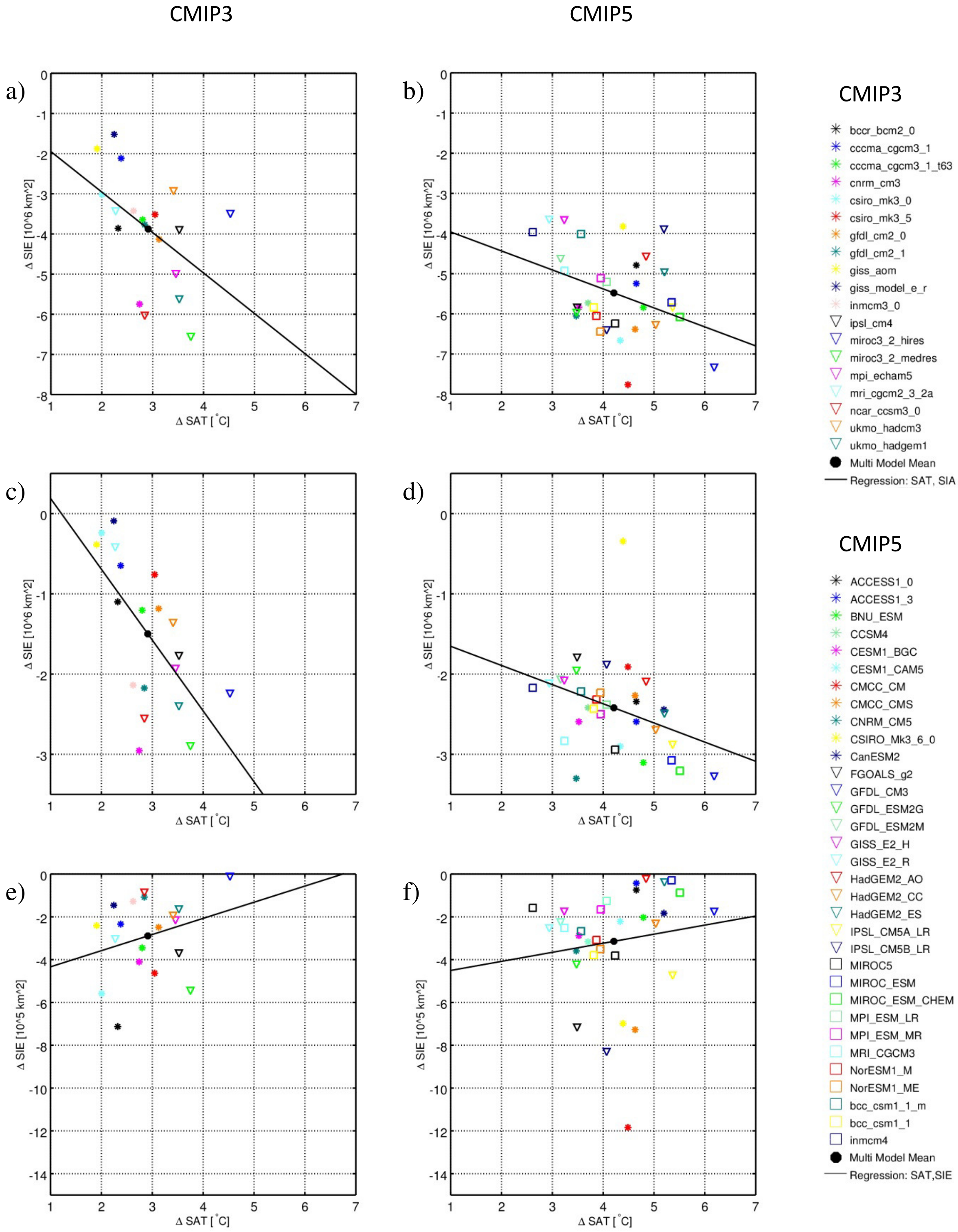

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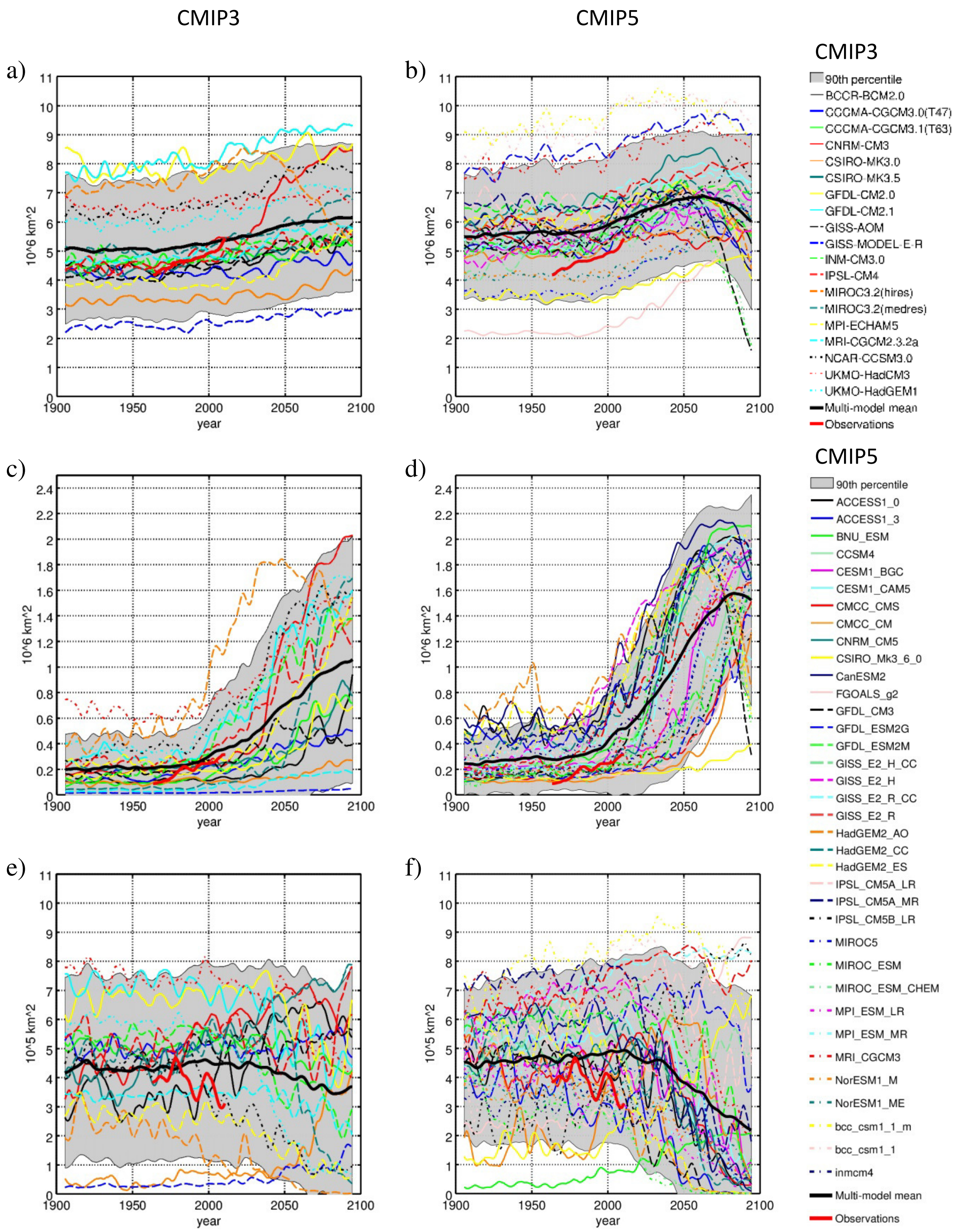

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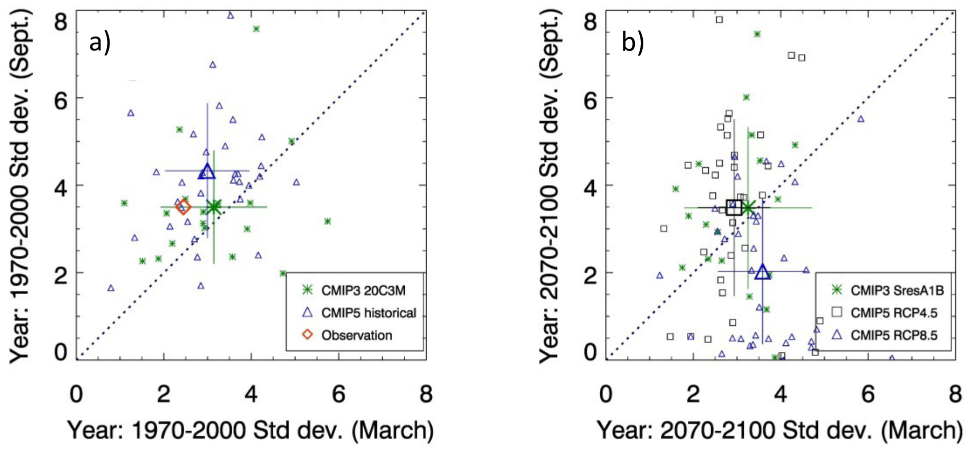

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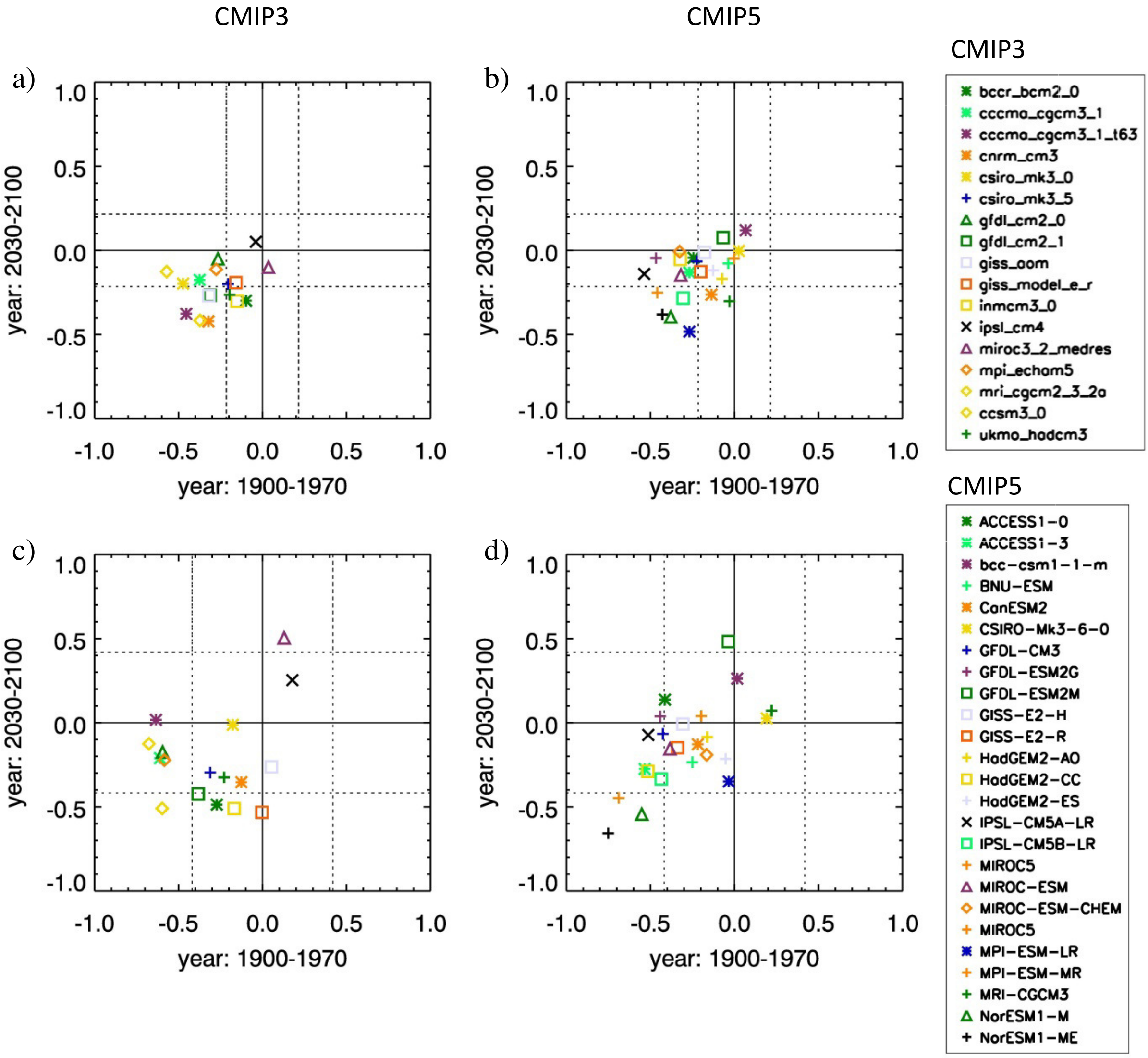

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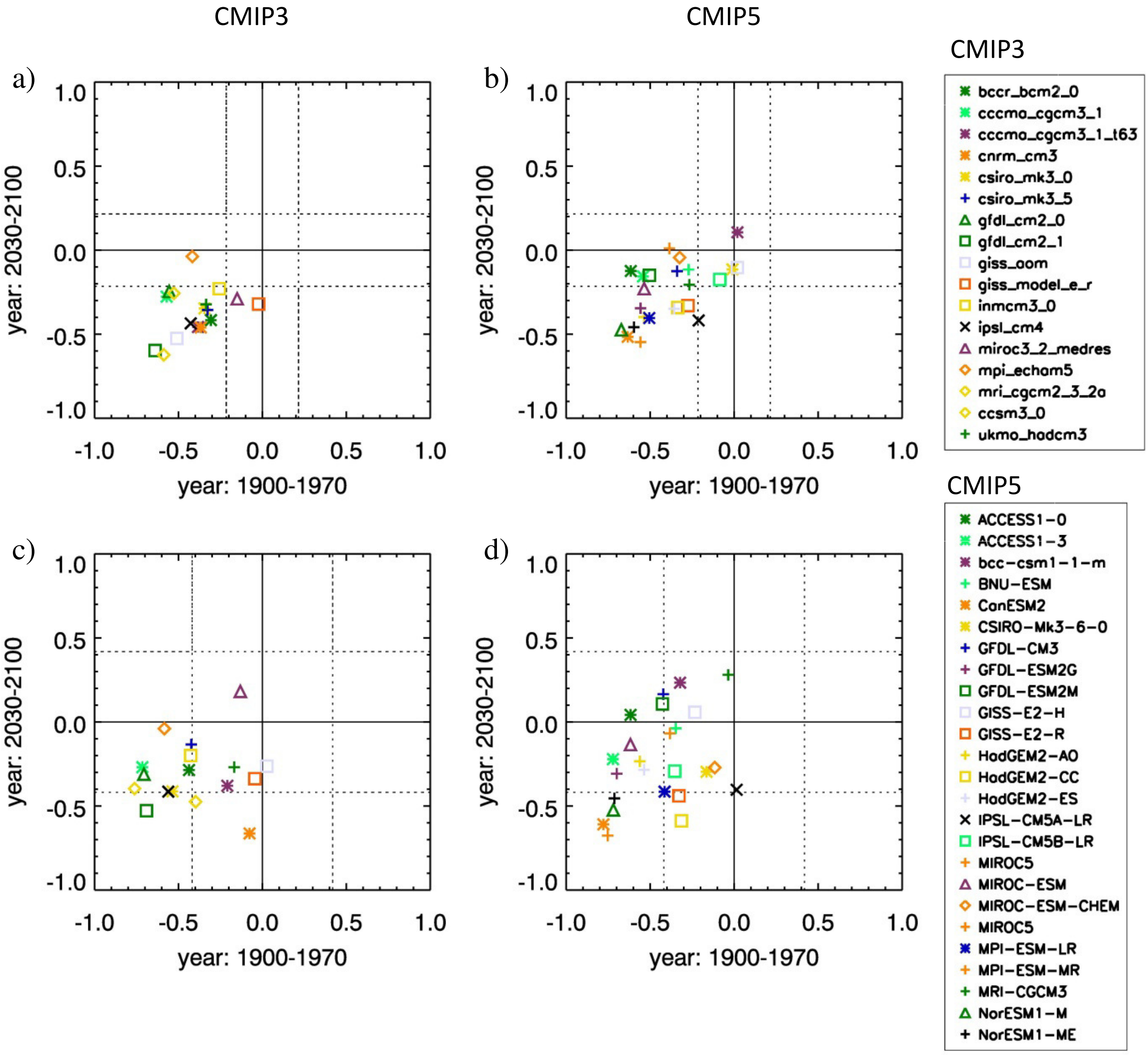

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