Response to the reviews of TC-2016-97 "Assessment of Arctic and Antarctic sea ice predictability in CMIP5 decadal hindcasts" by Chao-Yuan Yang, Jiping Liu, Yongyun Hu, Radley M. Horton, Liqi Chen, Xiao Cheng

Response to comments by Referee #2

We would like to thank the reviewer for the helpful comments on the paper.

This study analyzed decadal hindcasts/predictions of Arctic and Antarctic Sea Ice from 11 CMIP5 models. The manuscript suggests that the broader prediction skill for the Arctic sea ice at increasing time leads is mainly due to the predicted decline of Arctic sea ice induced by anthropogenic forcing. In contrast, the Antarctic sea ice decadal hindcasts do not show broad predictive skill at any time scales, and almost all models predict the decline in Antarctic sea ice, opposite to the observations. The subject of the manuscript is suitable for The Cryosphere, and the results are interesting and contribute to the understanding of decadal prediction of Arctic and Antarctic sea ice. Some clarifications/diagnoses as suggested below would be helpful to strengthen the manuscript. I recommend the paper to be accepted for publications in The Cryosphere with minor revisions outlined below.

1. Page 6, Lines 126-128, as mentioned here, models tend to drift away quickly from the initialized states. Will the prediction results shown in this study change if the systematic model drift is removed (i.e. drift correction) before performing the analyses?

Thanks for the reviewer's comment. Here we used the bias-correction method mentioned in Ham et al. (2014) to remove the model drift (see Figure R1 and R2). This method removes the lead-time dependent mean bias based on the observation. The bias-corrected decadal hindcast is calculated as:

$$\widehat{Y_{jt}} = Y_{jt} - \sum_{k=1}^{N} (Y_{kt} - O_{kt})/N$$

where Y_{jt} and $\widehat{Y_{jt}}$ are the raw and bias-corrected predicted sea ice state, at the initialized year j and lead year t. O_{jt} is the observed sea ice state. We also applied this method to re-calculate the anomaly correlation coefficient between the observed and bias-corrected simulated regional sea ice indices for the Arctic and Antarctic (Figure R3 and R4). The results for the bias-corrected decadal hindcasts are similar to those having systematic model drift (Figure R3(R4) vs. Figure 6(11)). This is because the bias correction only minimally influences the variability of the time-series as reflected by the anomaly correlation coefficient.

Ham, Y.-G., Rienecker, M. M., Suarez, M. J., Vikhliaev, Y., Zhao, B., Marshak, J., Vernieres, G., and Schubert, S. D., Decadal prediction skill in the GEOS-5 forecast system. Clim. Dyn., 42, 1-20, 2014.

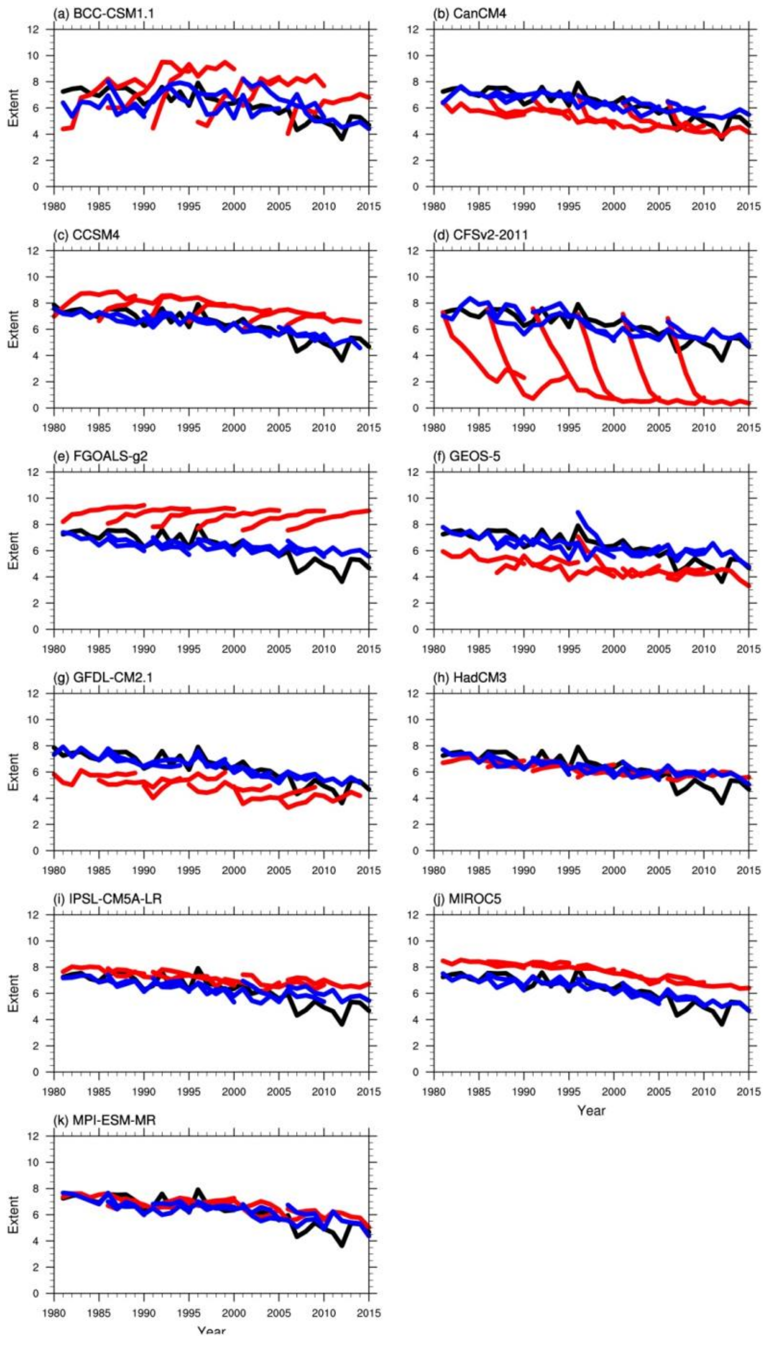

Figure R1 Time series of September Arctic sea ice extent (seasonal minimum) from the simulations of the 10-year hindcast for the ensemble mean of each individual model (thick red line), the bias-corrected ensemble mean of each individual model (thick blue line) and satellite observation (black line) from 1981 to 2015.

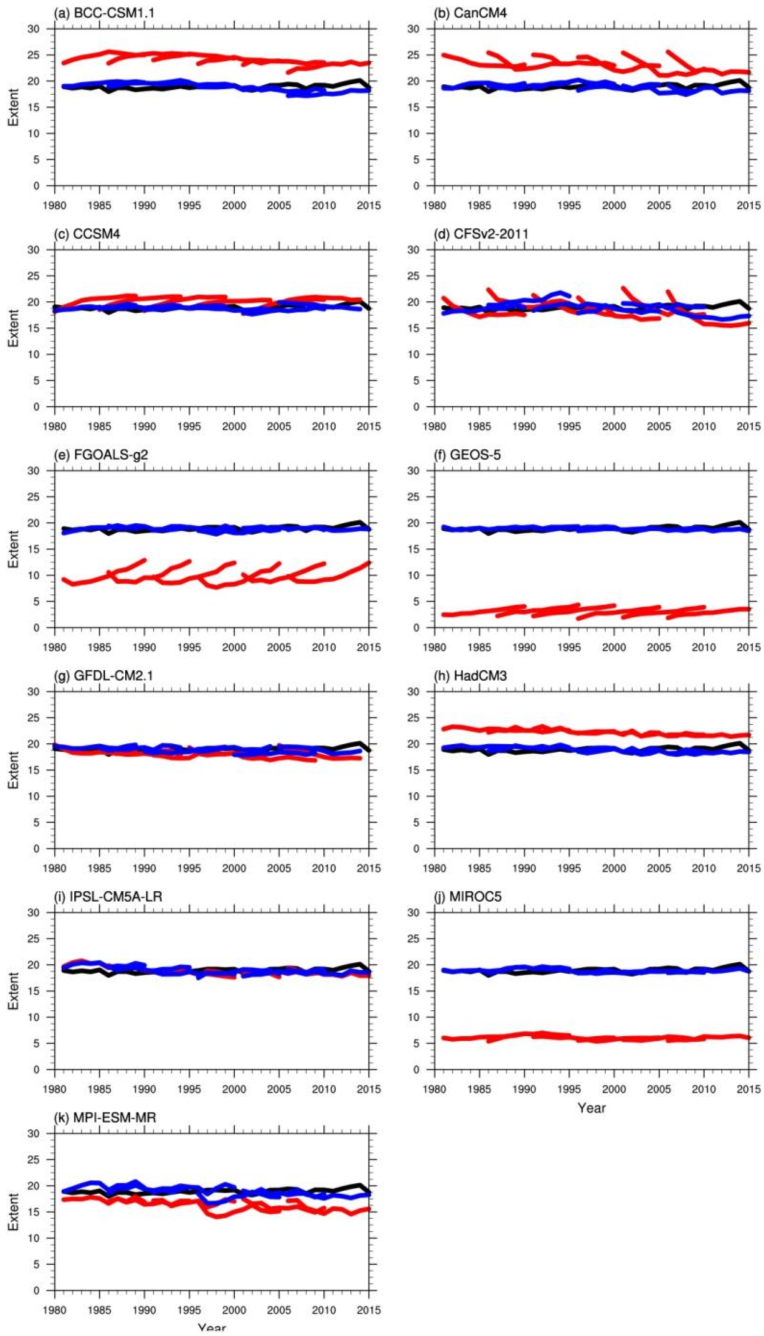

Figure R2 Time series of September Antarctic sea ice extent (seasonal maximum) from the simulations of the 10-year hindcast for the ensemble mean of each individual model (thick red line), the bias-corrected ensemble mean of each individual model (thick blue line) and satellite observation (black line) from 1981 to 2015.

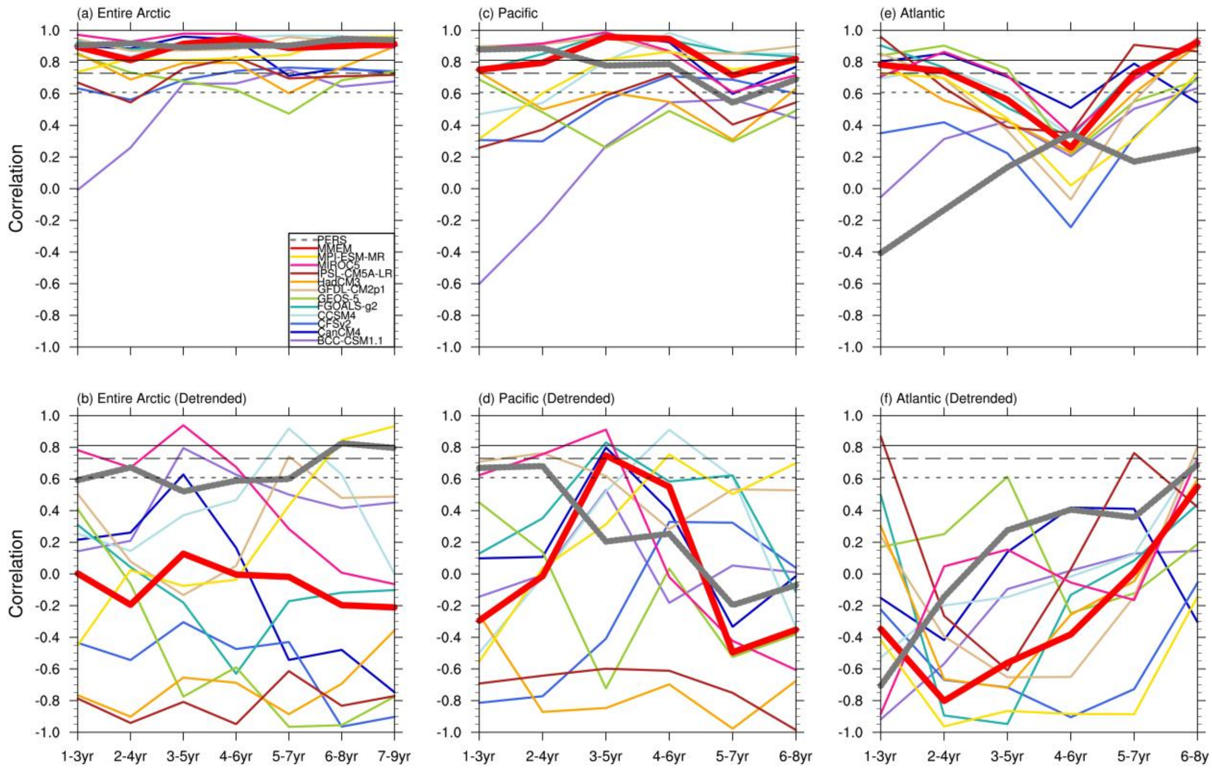

Figure R3 Anomaly correlation coefficients between the bias-corrected simulated and observed Arctic September sea ice extent anomalies for the three regional indices (the entire Arctic, Pacific and Atlantic) as a function of the lead-time. The top and bottom panels are the original and detrended time series, respectively. The horizontal dotted, dashed and solid lines represent 90%, 95% and 99% confidence levels, respectively. The thick gray line is the persistence prediction.

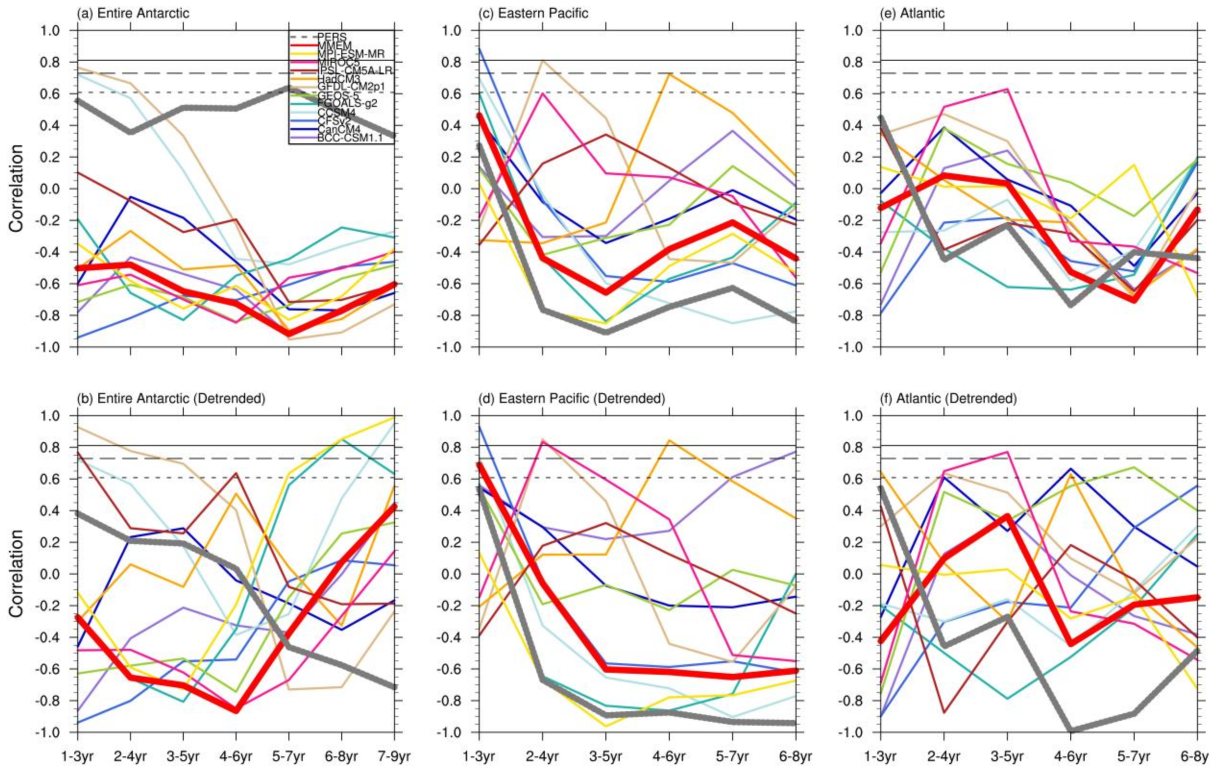

Figure R4 Anomaly correlation coefficients between the bias-corrected simulated and observed Antarctic September sea ice extent anomalies for the three regional indices (the entire Antarctic, eastern Pacific and Atlantic) as a function of the lead-time. The top and bottom panels are the original and detrended time series, respectively. The horizontal dotted, dashed and solid lines represent 90%, 95% and 99% confidence levels, respectively. The thick gray line is the persistence prediction.

2. The manuscript shows that the CMIP5 decadal prediction of sea ice extent is strongly affected by anthropogenic external forcing (i.e. decline in both Arctic and Antarctica sea ice extent). How is the CMIP5 decadal prediction of Arctic and Antarctic sea ice extent compared to uninitialized CMIP5 historical+RCP4.5 simulations? Is the predictive skill enhanced with initialization compared to uninitialized hindcasts?

As suggested by the reviewer, we downloaded the historical and RCP4.5 simulations (hereafter referred to as uninitialized simulation) for all the models except CFSv2 and GEOS-5 (they did not provide historical and RCP4.5 simulations), and then repeated the analyses. Figures R5 to R12 show the results for the uninitialized simulation. For the Arctic, the predictive skill of sea ice cover is enhanced for the initialized hindcast compared to the uninitialized simulation for most models and MMEM. After the trend is removed (Figure R8), there is no obvious difference between the initialized hindcast and the uninitialized simulation. Note that Figure R6 and R8 do not include CFSv2 and GEOS-5, which have poor predictive skills in the initialized hindcast. It is possible that the predictive skill of MMEM for the uninitialized simulation would be worse when

CFSv2 and GEOS-5 were included. For the Antarctic, there is no significant difference between the initialized hindcast and the uninitialized simulation, largely due to that most models in the uninitialized simulation cannot capture the observed increasing Antarctic sea ice. However, after the linear trend is removed, the areas with significant predictive skill for the initialized hindcast become relatively larger relative to those of the uninitialized simulation (Figure R10 and R12).

Figures for the Arctic:

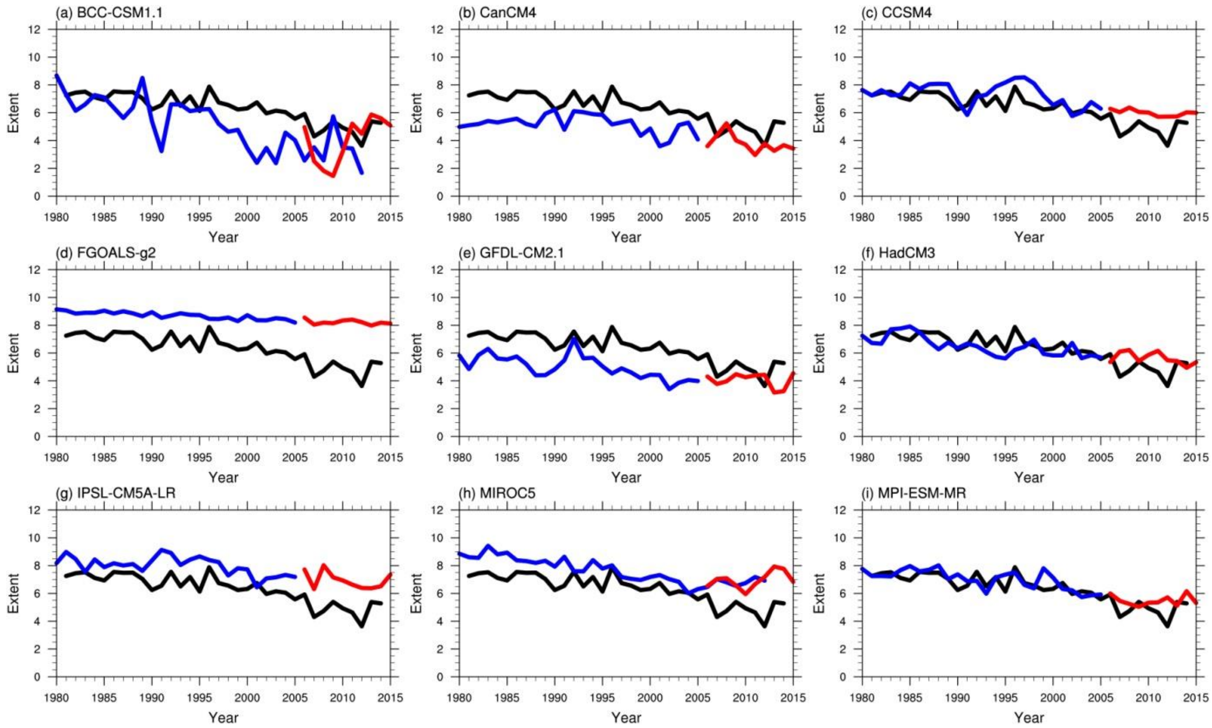

Figure R5 Time series of September Arctic sea ice extent (seasonal minimum) from the simulations of the historical scenario for each individual model (thick blue line), the simulations of the rcp45 scenario for each individual model (thick red line) and satellite observation (black line) from 1981 to 2015.

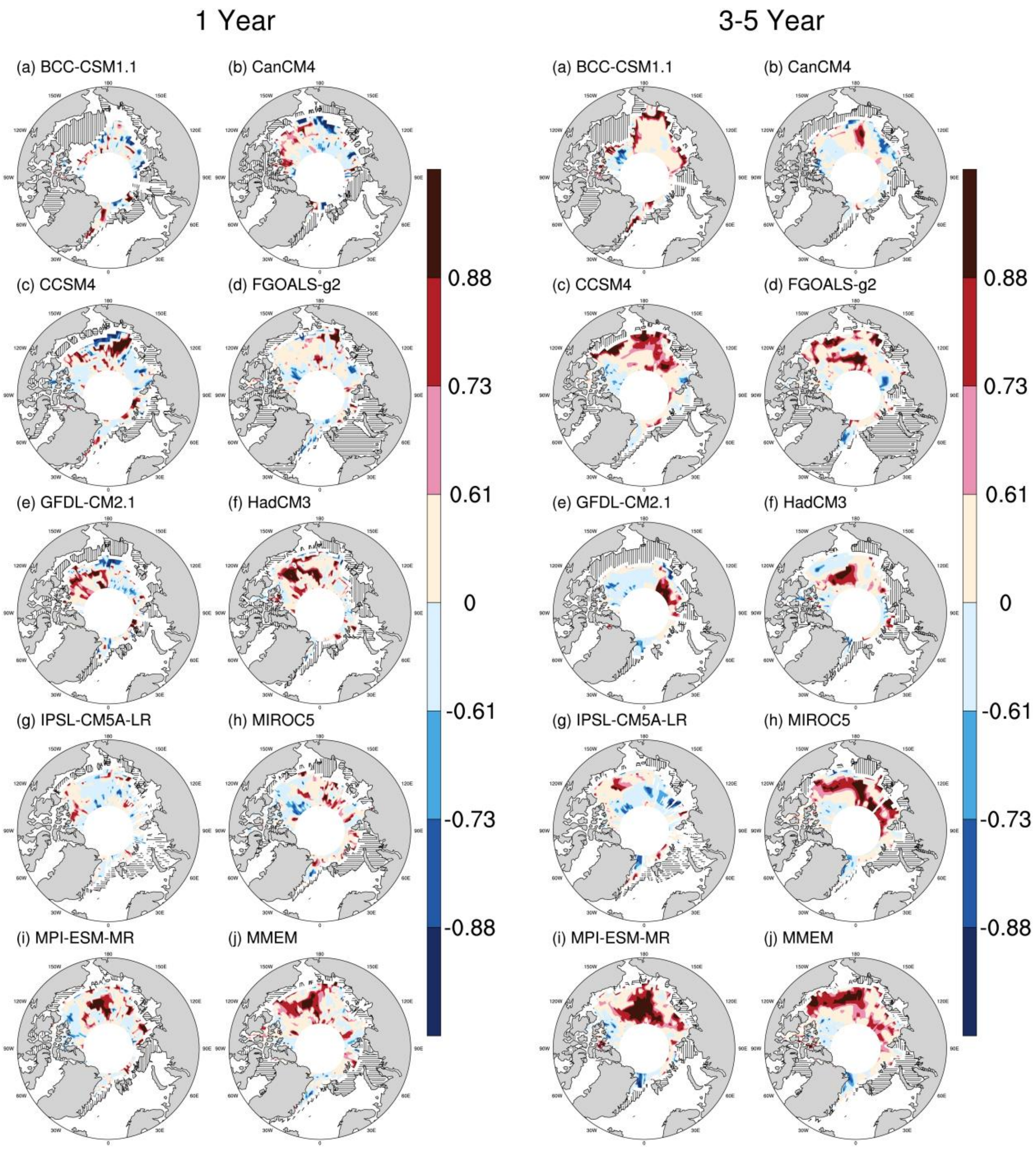

Figure R6 Anomaly correlation coefficients between the simulated and observed Arctic September sea ice concentration anomalies for the lead-time of 1-year (left panel) and 3-5 years (right panel). The correlation coefficient 0.61, 0.73 and 0.88 represents 90%, 95% and 99% confidence levels, respectively. Horizontal lines depict the areas where the model simulation has sea ice whereas the observation does not have sea ice. The opposite is the case for vertical lines.

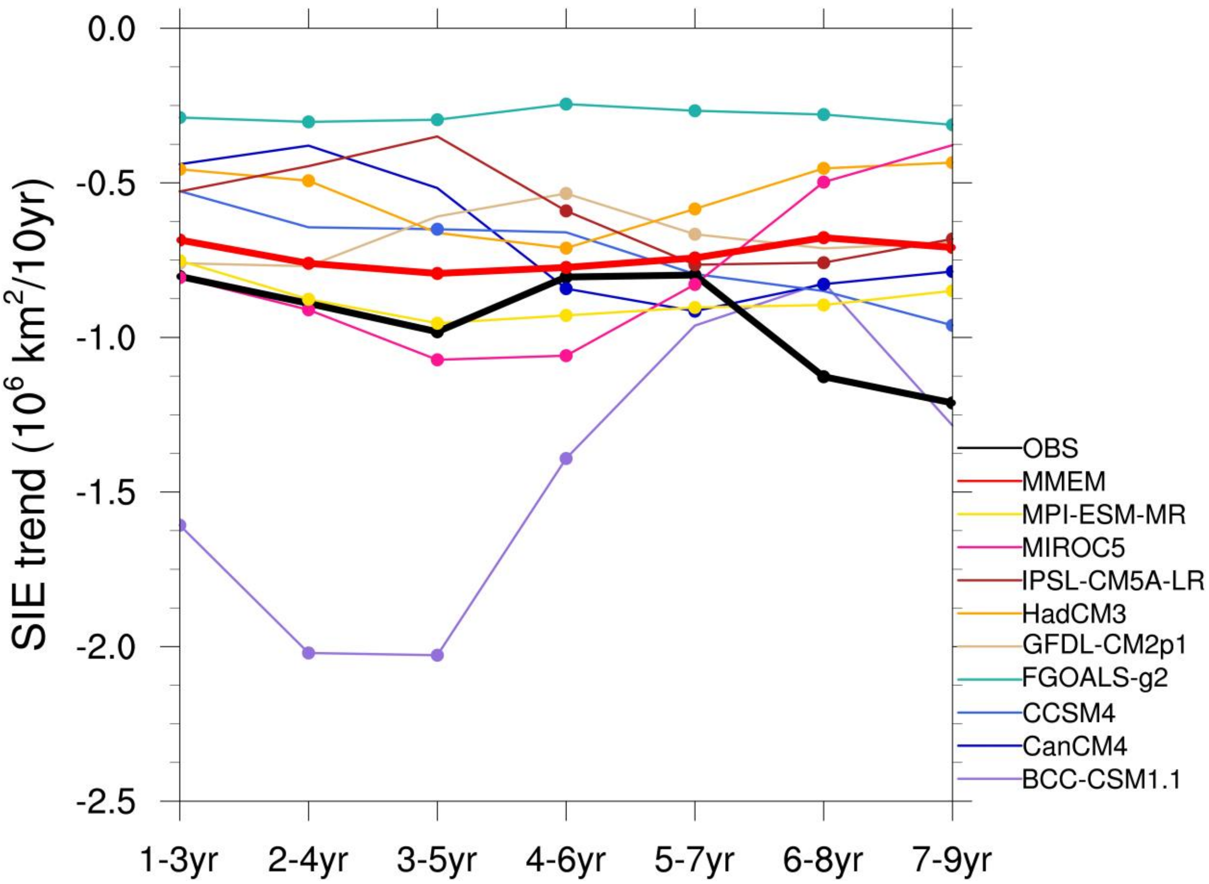

Figure R7 The predicted trend (slope of a linear regression) of September Arctic sea ice extent anomalies as a function of lead times after applying a 3-year average to filter out high frequency variability. The dots represent the trend exceeding 95% confidence level.

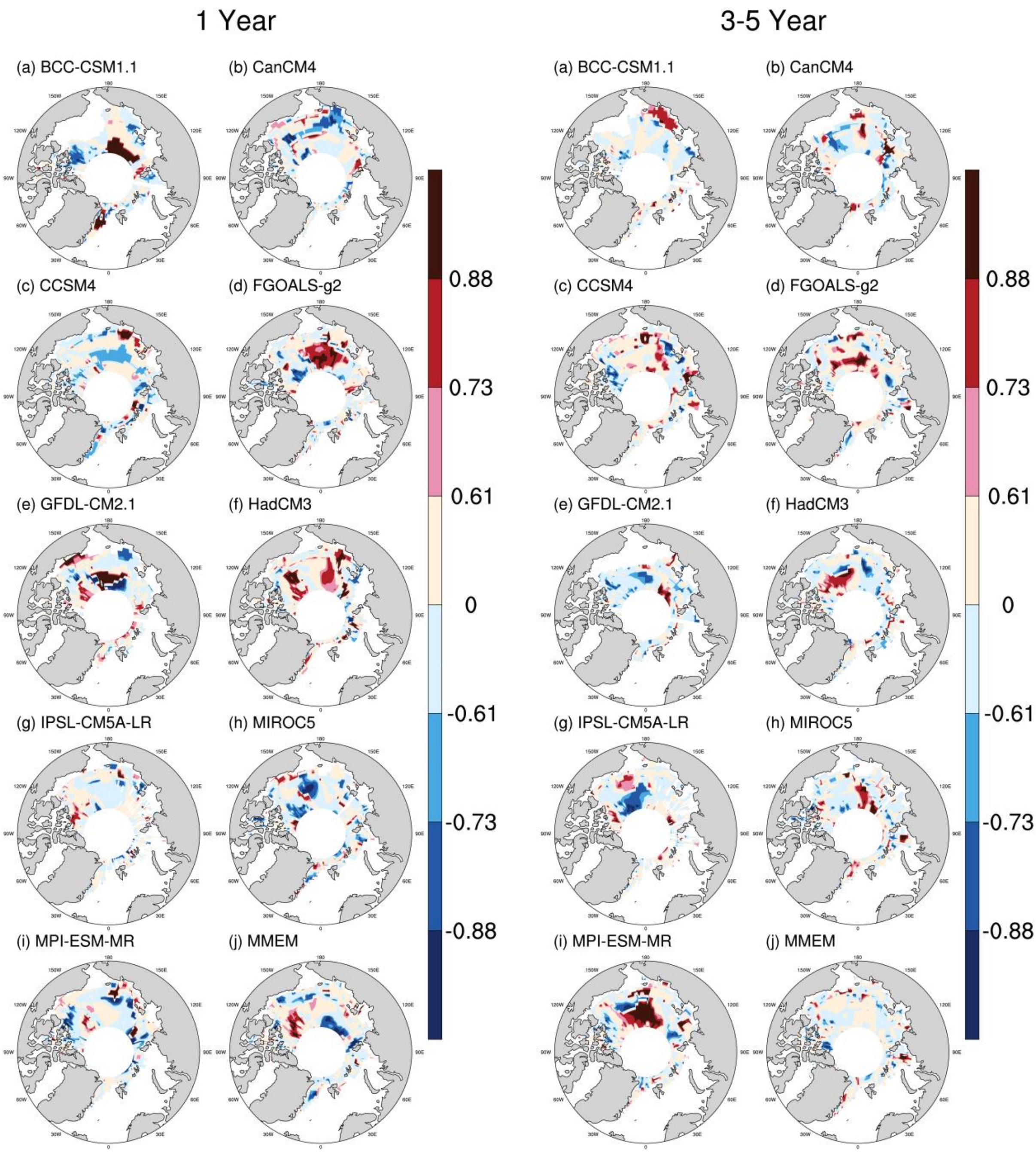

Figure R8 Same as Figure R6, but for detrended September sea ice concentration anomalies.

Figures for the Antarctic:

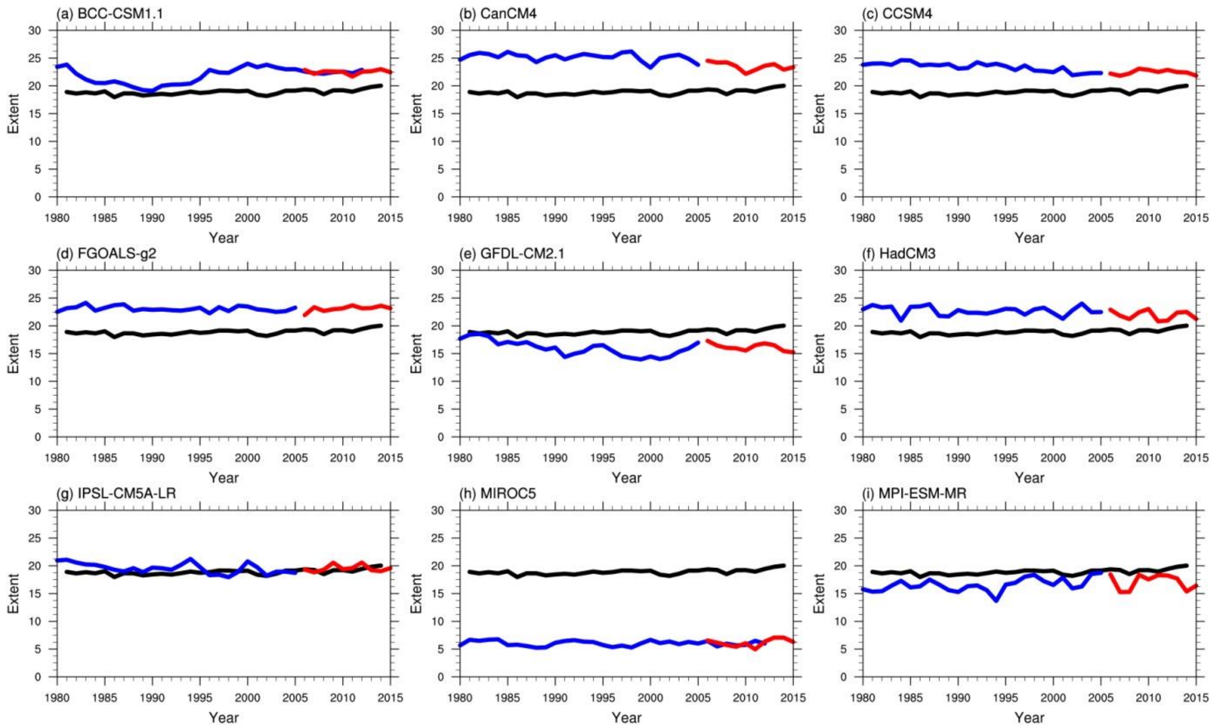

Figure R9 Time series of September Antarctic sea ice extent (seasonal maximum) from the simulations of the historical scenario for each individual model (thick blue line), the simulations of the rcp45 scenario for each individual model (thick red line) and satellite observation (black line) from 1981 to 2015.

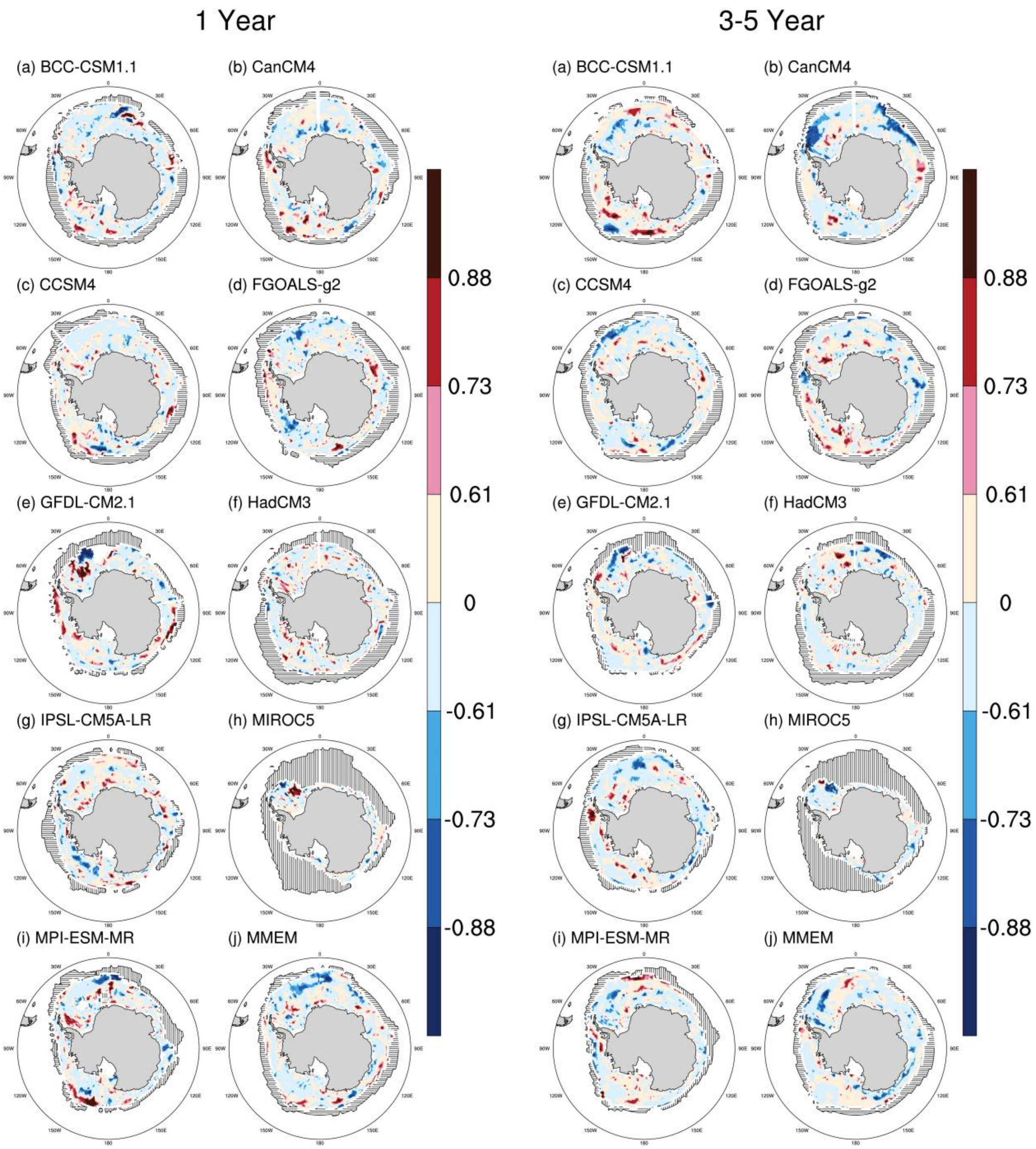

Figure R10 Anomaly correlation coefficients between the simulated and observed Antarctic September sea ice concentration anomalies for the lead-time of 1-year (left panel) and 3-5 years (right panel). The correlation coefficient 0.61, 0.73 and 0.88 represents 90%, 95% and 99% confidence levels, respectively. Horizontal lines depict the areas where the model simulation has sea ice whereas the observation does not have sea ice. The opposite is the case for vertical lines.

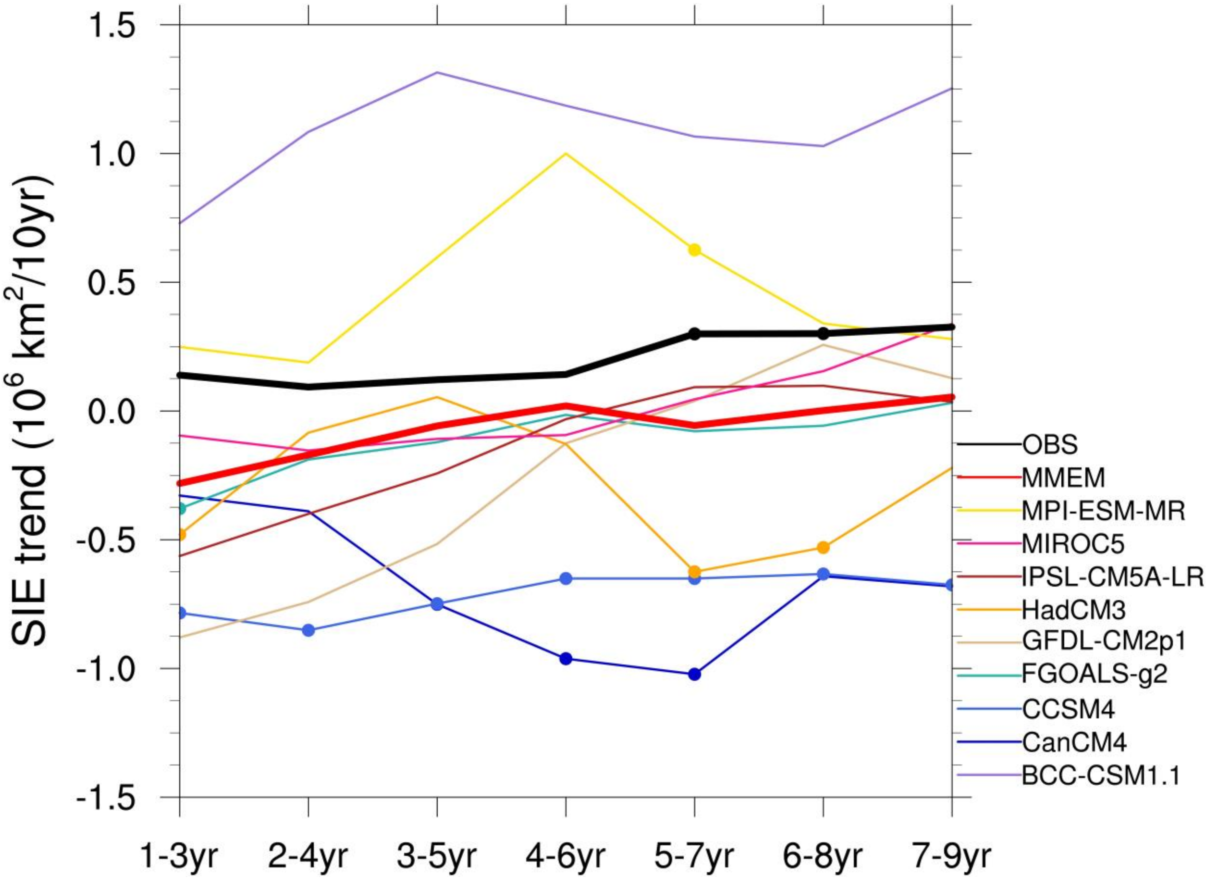

Figure R11 The predicted trend (slope of a linear regression) of September Antarctic sea ice extent anomalies as a function of lead times after applying a 3-year average to filter out high frequency variability. The dots represent the trend exceeding 95% confidence level.

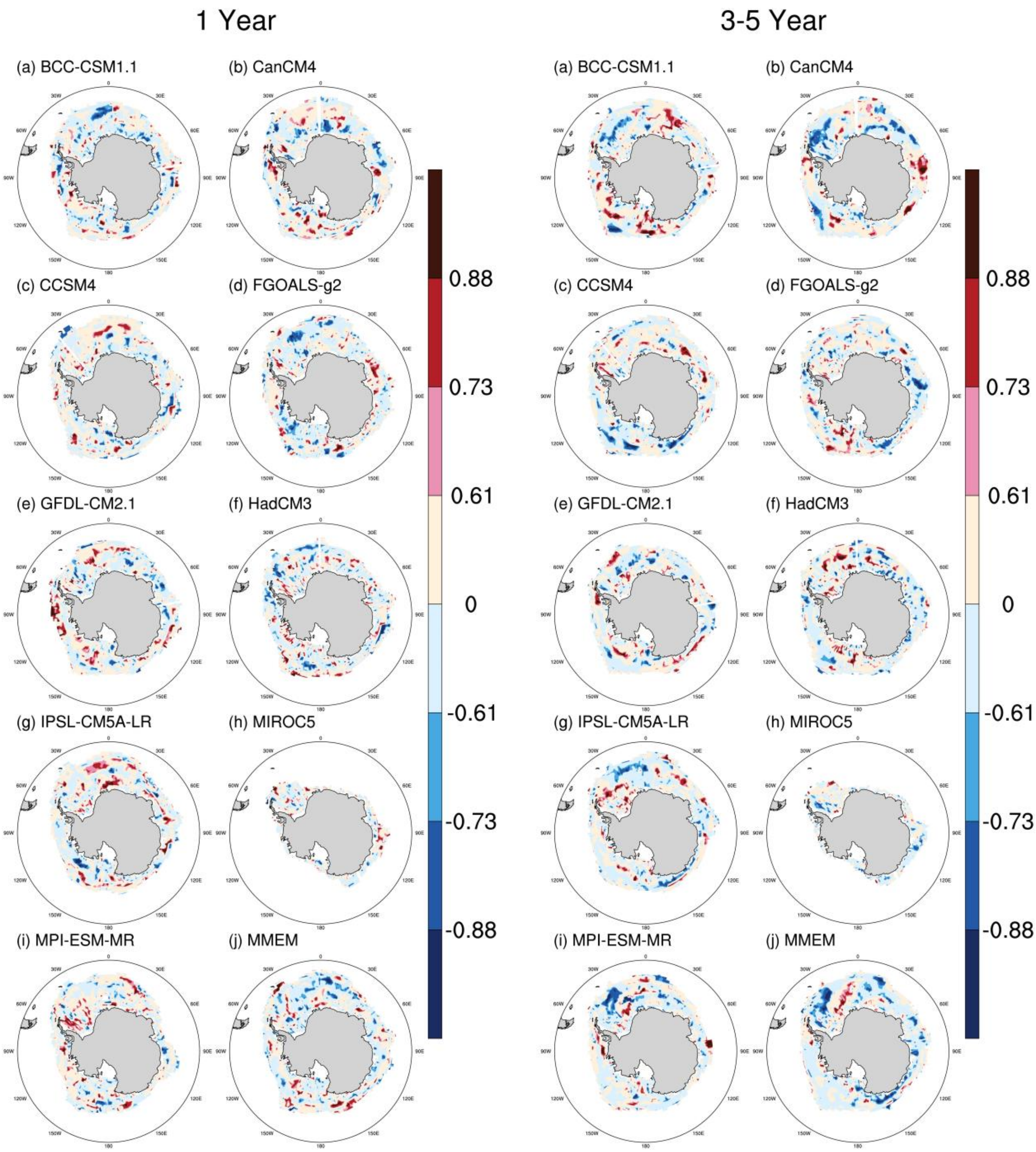

Figure R12 Same as Figure R10, but for detrended September sea ice concentration anomalies.

3. Page 18, Lines 380-387, a very recent study (Zhang, 2015) suggested that to predict September Arctic sea ice extent variations, it is important to monitor internal variability associated with the three key contributors (Atlantic/Pacific heat transport into the Arctic, and Arctic Dipole), in addition to the focus on anthropogenic changes. The study also pointed out that the Atlantic heat transport is the prime driver for low-frequency variability of winter Arctic sea ice extent, while all three contributors (Atlantic/Pacific heat transport and AD) are important for summer Arctic sea ice extent variability at low frequency. Please add discussions on these related results.

Reference: Zhang, 2015, Mechanisms for low-frequency variability of summer Arctic sea ice extent. PNAS, 112, DOI:10.1073/pnas.1422296112.

Thanks for the reviewer's suggestion. We added the following text in the discussion and conclusion: "Zhang (2015) suggested that it is important to monitor internal variability associated with the heat transport into the Arctic from the Atlantic and Pacific, and the Arctic Dipole for predicting September Arctic sea ice extent variations. This study also pointed out that all these processes are important for low-frequency variability of summer sea ice extent, while the Atlantic heat transport might be the prime driver for winter Arctic sea ice extent variability at low frequency"

4. Almost all models predict the decline in Antarctic sea ice, opposite to the observations. Please add more discussions on what caused such a discrepancy (internal variability, ozone depletion?).

Thanks for the reviewer's comment. We added the following text in the discussion and conclusion: "The reasons behind recent increase of Antarctic sea ice are complex, and several recent studies show that scientists are still trying to understand it. The possible mechanisms include variations in atmospheric circulation linked to the Antarctic Oscillation, Amundsen Sea low pressure system, stratospheric ozone depletion, and increased greenhouse gases, changes in zonal and meridional near surface winds, the increase in fresh water flux which stabilizes the upper ocean layer, and the influence of internal variability (e.g., Zhang, 2007; Turner et al., 2009; Sigmond and Fyfe, 2010; Liu and Curry 2010; Holland and Kwok, 2012; Zunz et al. 2013; Polvani and Smith, 2013). However, it is not clear which is the dominant process. Further investigating a range of other variables such as simulated sea ice thickness, sea ice velocity, near surface wind, and ocean stratification will help elucidate the reasons why the trends in these models are different from observations."

Holland, P. R., and Kwok, R., Wind-driven trends in Antarctic sea-ice drift, Nat. Geosci., 5, 872–875, 2012.
Liu, J., and Curry, J. A., Accelerated warming of the Southern Ocean and its impacts on the hydrological cycle and sea ice. Proc. Natl. Acad. Sci. USA, 107, 14 987–14 992, 2010.
Polvani, L. M., and Smith, K. L., Can natural variability explain observed Antarctic sea ice trends? New modeling evidence from CMIP5, Geophys. Res. Lett., 40, 3195–3199, doi:10.1002/grl.50578, 2013.
Sigmond, M., and Fyfe, J. C., Has the ozone hole contributed to increased Antarctic sea ice extent?, Geophys. Res. Lett., 37, L18502, doi:10.1029/2010GL044301, 2010

Turner, J., and Coauthors, Non-annular atmospheric circulation change induced by stratospheric ozone depletion and its role in the recent increase of Antarctic sea ice extent. Geophys. Res. Lett., 36, L08502, doi:10.1029/2009GL037524, 2009.
Zhang, J., Increasing Antarctic sea ice under warming atmospheric and oceanic conditions, J. Clim., 20, 2515–2529, 2007.
Zunz, V., H. Goosse, and Massonnet, F., How does internal variability influence the ability of CMIP5 models to reproduce the recent trend in Southern Ocean sea ice extent? Cryosphere, 7, 451–468, 2013.