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Arctic sea ice in CMIP5 climate model projections and their seasonal variability

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Abstract

This paper is focused on the seasonality change of Arctic sea ice extent (SIE) from 1979 to 2100 using newly available simulations from the Coupled Model Intercomparison Project Phase 5 (CMIP5). A new approach to compare the simulation metric of Arctic SIE between observation and 31 CMIP5 models was established. The approach is based on four factors including the climatological average, linear trend of SIE, span of melting season and annual range of SIE. It is more objective and can be popularized to other comparison of models. Six good models (GFDL-CM3, CESM1-BGC, MPI-ESM-LR, ACCESS-1.0, HadGEM2-CC, and HadGEM2-AO in turn) are found which meet the criterion closely based on above approach. Based on ensemble mean of the six models, we found that the Arctic sea ice will continue declining in each season and firstly drop below 1 million km^2 (defined as the ice-free state) in September 2065 under RCP4.5 scenario and in September 2053 under RCP8.5 scenario. We also study the seasonal cycle of the Arctic SIE and find out the duration of Arctic summer (melting season) will increase by about 100 days under RCP4.5 scenario and about 200 days under RCP8.5 scenario relative to current circumstance by the end of the 21st century. Asymmetry of the Arctic SIE seasonal cycle with later freezing in fall and early melting in spring, would be more apparent in the future when the Arctic climate approaches to “tipping point”, or when the ice-free Arctic Ocean appears. Annual range of SIE (seasonal melting ice extent) will increase almost linearly in the near future 30–40 years before the Arctic appears ice-free ocean, indicating the more ice melting in summer, the more ice freezing in winter, which may cause more extreme weather events in both winter and summer in the future years.

Key words: Arctic sea ice, CMIP5, seasonal cycle, melting season, annual range

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1 Introduction

Arctic sea ice has been declining in recent years (Cavalieri et al., 1997, 1999; Parkinson et al., 1999; Stroeve et al., 2007; Serreze et al., 2007; Comiso et al., 2008). The sea ice extent (SIE) of Arctic reached the lowest point on September 16, 2012 in the history (3.41 million km^2) (NSIDC 2012) which was about 48.5% below the long-term mean (1979–2000). The melting process of Arctic sea ice accelerated which would have seriously influence on Arctic maritime activities and ecosystems, biogeochemical feedbacks, and extreme weather and climate in mid and high latitudes (e.g., Masson-Delmotte et al., 2006; Polyakov et al., 2002; Liu et al., 2012; Francis and Vavrus, 2012, 2015; Zhu et al., 2014; Wang et al., 2015).

Most of these studies focus on the change of Arctic sea ice on September and concentrate their attention on the total amount or trend of sea ice (Liu et al., 2013). Under the global warm, Arctic SIE is decreasing dramatically. While in the past decade, global warming seems in hiatus (Easterling and Wehner, 2009; Kosaka and Xie, 2013), as well as the Arctic sea ice after 2007, with fast declining trend instead of enhancing seasonal oscillation (Huang et al., 2014; Wang et al., 2015). Here arise our questions: will the Arctic SIE trend or oscillation maintain in the future? How about the SIE variation in different seasons? Since seasonal variability of sea ice, the onset time of melting and freezing seasons, are important to climate change responses, we argue that the Arctic SIE change in other seasons except for September is also important and its variability of seasonal cycle will dramatically influence on weather and climate.

2 Data and methods

This paper focuses on the sea ice concentration (SIC) and calculate the SIE which are determined by the 15% concentration threshold. The present analysis uses monthly mean SIC data from NSIDC (National Snow and Ice Data Center) and the future analysis is based on the projection simulations of monthly mean data from 1979 to 2100 of the Coupled Model Intercomparison Project Phase 5 (CMIP5) under the RCP4.5 and RCP8.5 scenarios. The RCP4.5 is a medium-mitigation emission scenario that stabilizes direct radiative forcing at 4.5 W/m^2 (~650 ppm CO$_2$ equivalent) at the end of the 21st century. The RCP8.5, in contrast, is a

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*Corresponding author, E-mail: huangf@ouc.edu.cn high-emission scenario with direct radiative forcing reaching 8.5 W/m^2 (~1 370 ppm CO_2 equivalent in 2100). We choose 31 CMIP5 models which include sea ice component in this paper and select the best of them to analyze the variability in the future.

3 Comparisons of sea ice simulation among models

Since the simulation of sea ice from CMIP5 models showed dispersive results (Liu et al., 2013), in order to simulate the future condition of Arctic sea ice exactly, we have to select some “good” models based on the models’ ability to reproduce the observed sea ice climatology and variability. The SIC data from NSIDC is considered as a standard observational value and each model will be compared to it.

Two factors, the Arctic SIE climatological average and trend were chosen to evaluate each model’s simulation and only the variability of September was focused on while other months are ignored (Liu et al., 2013). Another criteria for models with the simulated September SIE falling within 20% of the observations was also used. However, only two factors of average and trend may not completely reflect the ability of each model’s reproducing the present. Besides this, the threshold of 20% is not enough objective. So we bring into two other factors and establish a new method to evaluate each model comprehensively.

We use four independent factors to evaluate each model based on all data from January 1979 to December 2005 (observational data of NSIDC began in 1979 and model data of historical

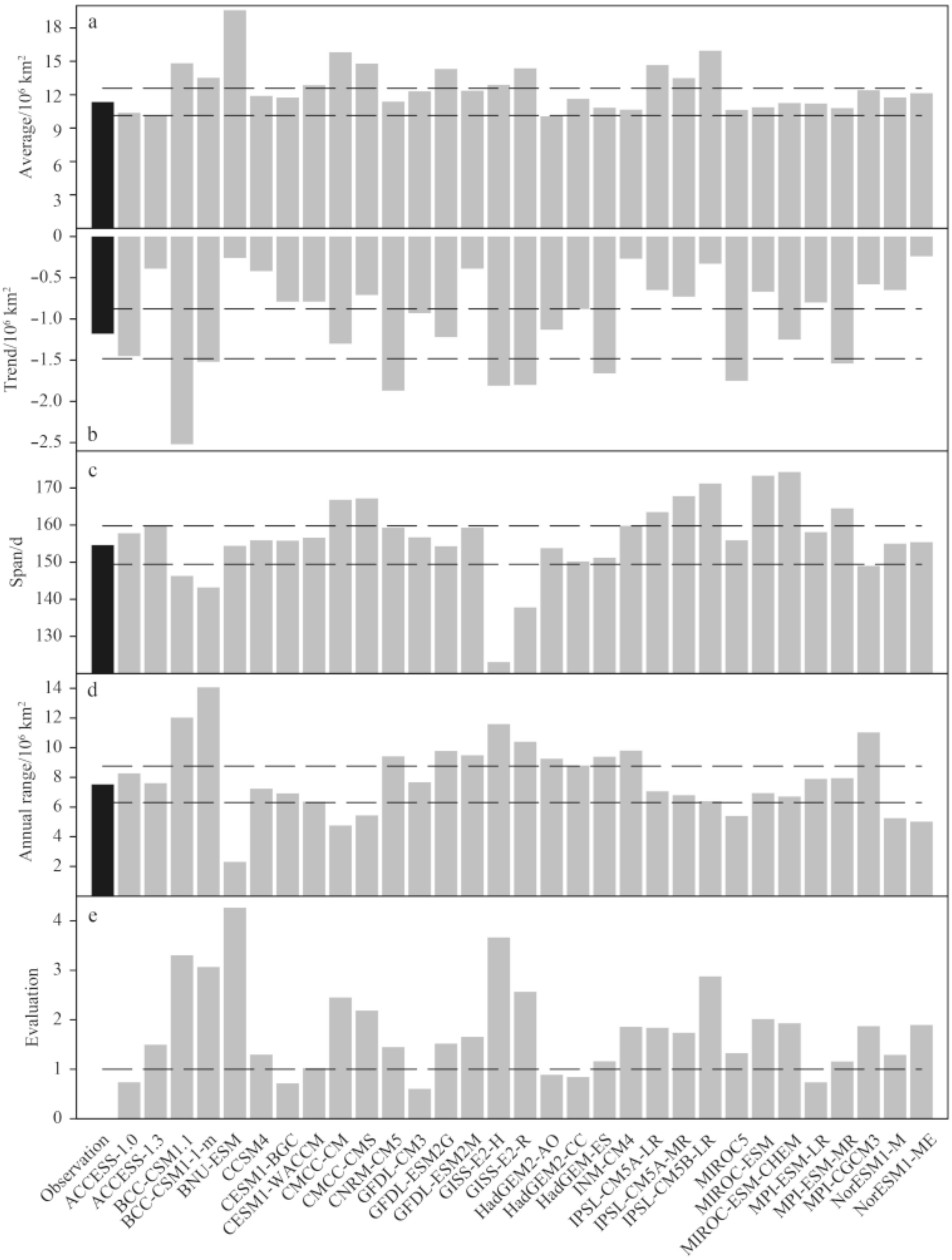

Fig. 1. Comparison of climatology (average) (a), linear trend of monthly mean sea ice extent (b), span of melting season (in days) (c), annual range of SIE seasonal cycle (d) and evaluation (e) for the observation (first black bar) and each CMIP5 model (gray bars) from 1979 to 2005. The black dashed lines in Figs 1a–d are the values in which means a standard deviation and that in Fig. 1e is the threshold of selected models criteria.

scenario end in 2005). We calculate the average and linear trend of the Arctic SIE of each model from January 1979 to December 2005 as the first and second factors (Figs 1a and b). In order to depict the seasonal variability of SIE in each model, we use the span of melting season (shortly as span hereafter) as the third factor, defined as the duration of SIE below average value (Fig. 1c). We use climatological SIE annual range (AR, the SIE difference between March and September) defined by Huang et al. (2011) of each model as the fourth factor (Fig. 1d). The four factors are independent and depict each model from different ways and they can express four kinds of information and jointly evaluate the ability of each model reproducing the present objectively. RMS (Root Mean Square) is also used to reflect the mean spread between observation and each model in each factor. The RMS is defined as

$$s_k = \sqrt{\frac{\sum\limits_{i=1}^{31} (x_{i,\,k} - B_k)^2}{31}} \qquad k = 1, 2, 3, 4,$$

where k and i represent the factor and model, s_k is the RMS, $x_{i,\,k}$ means the value of each model, B_k represents observation value of each factor. To evaluate each model using these four factors, we standardize each value and calculate the "distance" of each model from the observation which is defined as the final evaluation of each model:

$$e_i = \sqrt{\sum_{k=1}^{4} \left(\frac{x_{i,k} - B_k}{s_k}\right)^2} \qquad i = 1, 2, \cdots, 31,$$

where e_i is the final evaluation of each model (Fig. 1e). The parameter e_i is no less than zero and presents the extent how the model simulation approximating to the observations. The smaller the value of a given model, the better the model reproduces the observation. So the value of the observation is zero. The scores of all 31 CMIP5 models simulating the Arctic SIE compared to observations are listed in Table 1. We have selected six "good" models with the value of e_i less than 1, which meet the criterion based on above approach. They are GFDL-CM3, CESM1-BGC, MPI-ESM-LR, ACCESS-1.0, HadGEM2-CC and HadGEM2-AO in turn.

It is noticeable that the last rank model BNU-ESM is not good for simulation of the Arctic sea ice seasonal cycle since it showed quite well behavior on the simulation of the SIE average and trend in September (Liu et al., 2013). This result suggests that

Table 1. Score of the 31 CMIP5 models for Arctic SIE simulation

No.	Model	Score	Affiliation
1	GFDL-CM3	0.605	NOAA Geophysical Fluid Dynamics Laboratory
2	CESM1-BGC	0.715	Community Earth System Model Contributors
3	MPI-ESM-LR	0.737	Max Planck Institute for Meteorology
4	ACCESS-1.0	0.738	Commonwealth Scientific and Industrial Research Organization (CSIRO) and Bureau of Meteorology (BOM), Australia
5	HadGEM2-CC	0.842	Met Office Hadley Centre
6	HadGEM2-AO	0.889	Met Office Hadley Centre
7	CESM1-WACCM	1.025	Community Earth System Model Contributors
8	MPI-ESM-MR	1.158	Max Planck Institute for Meteorology
9	HadGEM-ES	1.161	Met Office Hadley Centre
10	NorESM1-M	1.291	Norwegian Climate Centre
11	CCSM4	1.296	Community Earth System Model Contributors
12	MIROC5	1.325	Atmosphere and Ocean Research Institute (The University of Tokyo), National Institute for Environmental Studies, and Japan Agency for Marine-Earth Science and Technology
13	CNRM-CM5	1.449	Centre National de Recherches Meteorologiques/Centre European de Recherche et Formation Avance en Calcul Scientifigue
14	ACCESS-1.3	1.496	Organization (CSIRO) and Bureau of Meteorology (BOM), Australia
15	GFDL-ESM2G	1.519	NOAA Geophysical Fluid Dynamics Laboratory
16	GFDL-ESM2M	1.654	NOAA Geophysical Fluid Dynamics Laboratory
17	IPSL-CM5A-MR	1.737	Institut Pierre-Simon Laplace
18	IPSL-CM5A-LR	1.837	Institut Pierre-Simon Laplace
19	INM-CM4	1.858	Institute for Numerical Mathematics
20	MRI-CGCM3	1.871	Meteorological Research Institute
21	NorESM1-ME	1.895	Norwegian Climate Centre
22	MIROC-ESM-CHEM	1.930	Japan Agency for Marine-Earth Science and Technology, Atmosphere and Ocean Research Institute (The University of Tokyo), and National Institute for Environmental Studies
23	MIROC-ESM	2.014	Japan Agency for Marine-Earth Science and Technology, Atmosphere and Ocean Research Institute (The University of Tokyo), and National Institute for Environmental Studies
24	CMCC-CMS	2.186	Centro Euro-Mediterraneo per I Cambiamenti Climatici
25	CMCC-CM	2.451	Centro Euro-Mediterraneo per I Cambiamenti Climatici
26	GISS-E2-R	2.566	NASA Goddard Institute for Space Studies
27	IPSL-CM5B-LR	2.877	Institute Pierre-Simon Laplace
28	BCC-CSM1-1-m	3.068	Beijing Climate Center, China Meteorological Administration
29	BCC-CSM1.1	3.305	Beijing Climate Center, China Meteorological Administration
30	GISS-E2-H	3.664	NASA Goddard Institute for Space Studies
31	BNU-ESM	4.266	College of Global Change and Earth System Science, Beijing Normal University

only good simulation of SIE in September is not enough. Seasonal variability of the Arctic sea ice also plays an important role in polar climate change. Therefore, simulation of SIE seasonal cycle in earth system models may be more important in future climate projections.

4 Variability of Arctic sea ice in the future

4.1 *Linear trend*

Even if six “good” models have been selected, unfortunately, there is still a little inter-model spread in the simulation of SIE during 1979 to 2005 under both RCP4.5 and RCP8.5 scenarios. Therefore, we use ensemble mean of the six models to eliminate the spread of each model. Four months (March, June, September and December) are selected to represent the winter, spring, summer and autumn of Arctic SIE because the Arctic SIE usually reaches its maximum and minimum in March and September, respectively. The ensemble mean of the six models shows that it can reproduce the observation well in different month from 1979 to 2005 under both RCP4.5 and RCP8.5 scenarios. So we can assume that the simulation of models is credible under future scenario.

It is shown that the observed SIE ($\times 10^6$ km^2) decreases in each month from 1979 to 2012 and the trend from January 1979 to December 2012 is about –0.51 per decade (Figs 2 and 3). The trend of March, June, September and December are –0.23, –0.40, –0.95 and –0.35 per decade respectively. More striking feature is that the trend in September is the greatest and about twice as much as that of annual mean. It means even if the Arctic sea ice is melting rapidly in each month, it will melt much faster in September (summer) and disappear by nearly one hundred thousand km^2 per decade.

4.2 *RCP4.5 scenario*

Under RCP4.5 scenario (Fig. 2), a medium-mitigation emission scenario, the Arctic SIE will continue decreasing in all seasons from 2013 to 2100, which is more likely similar to the observed SIE variation before 2007 (Fig. 2). The averaged trend from January 2013 to December 2100 is about –0.36 per decade, a little less than the observation from 1979 to 2005. The trends of March, June, September and December are –0.21, –0.28, –0.37 and –0.38 per decade under RCP4.5. If we focus on September, we can find out the ensemble mean of the SIE will firstly decrease to 1.5 million km^2 in 2054 (about half of the record lowest SIE in September 2012) and will firstly reach below one million km^2 in 2065. One million km^2 is less than 10% of maximum sea ice extent in the history and usually considered as a threshold that the Arctic Ocean is free of sea ice. In addition, the SIE of March, June and December will decrease to 12.08, 9.14 and 8.53 million km^2 that are equivalent to about 81.3% of 2012.

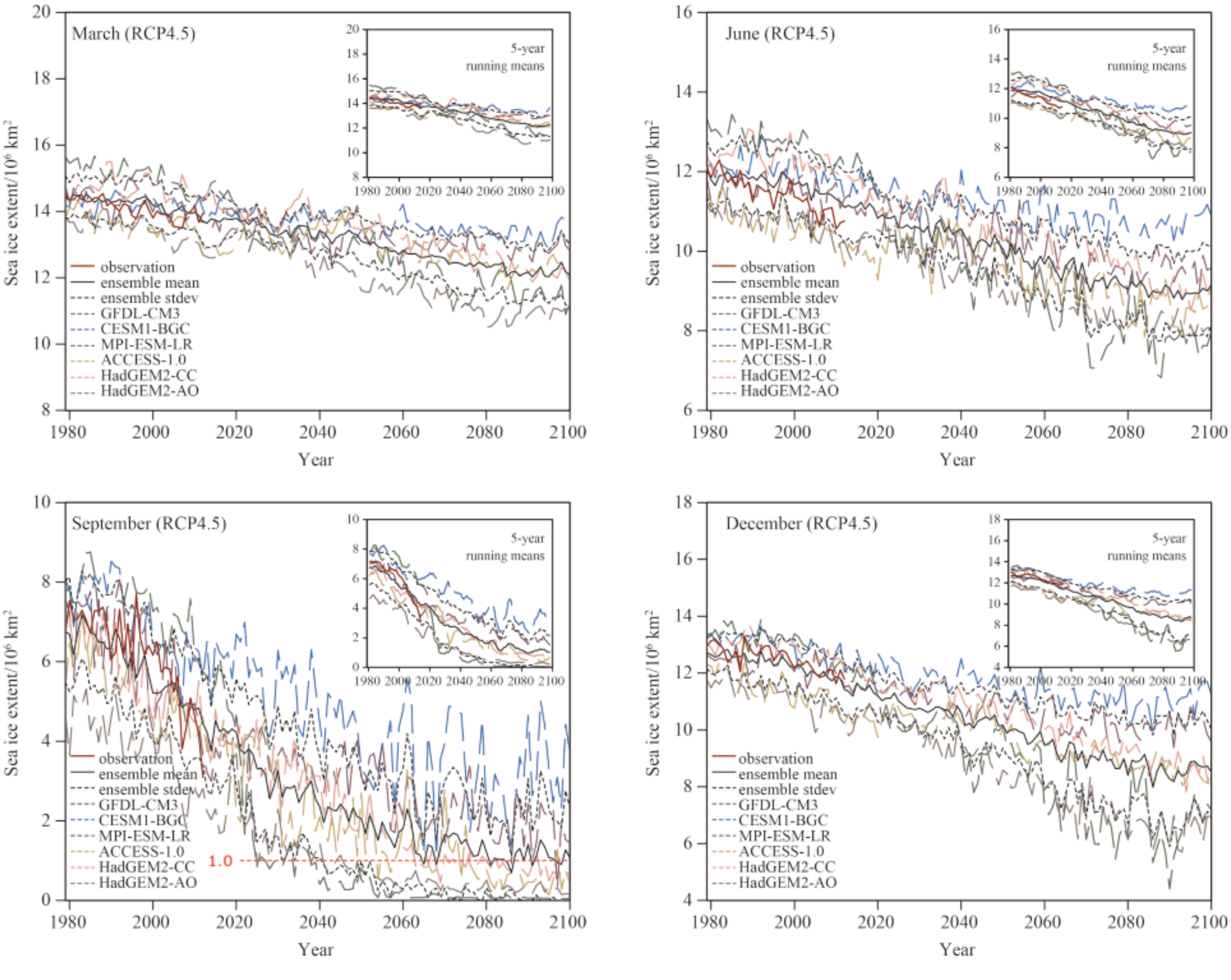

Fig. 2. Time-series of sea ice extent in different seasonal month-March (a), June (b), September (c) and December (d) from 1979 to 2100 averaged by the six selected models of CMIP5 under RCP4.5 scenario. The thick red line is the observation and the thick black line is the ensemble mean of the six models. The sub graph shows the five-year running mean.

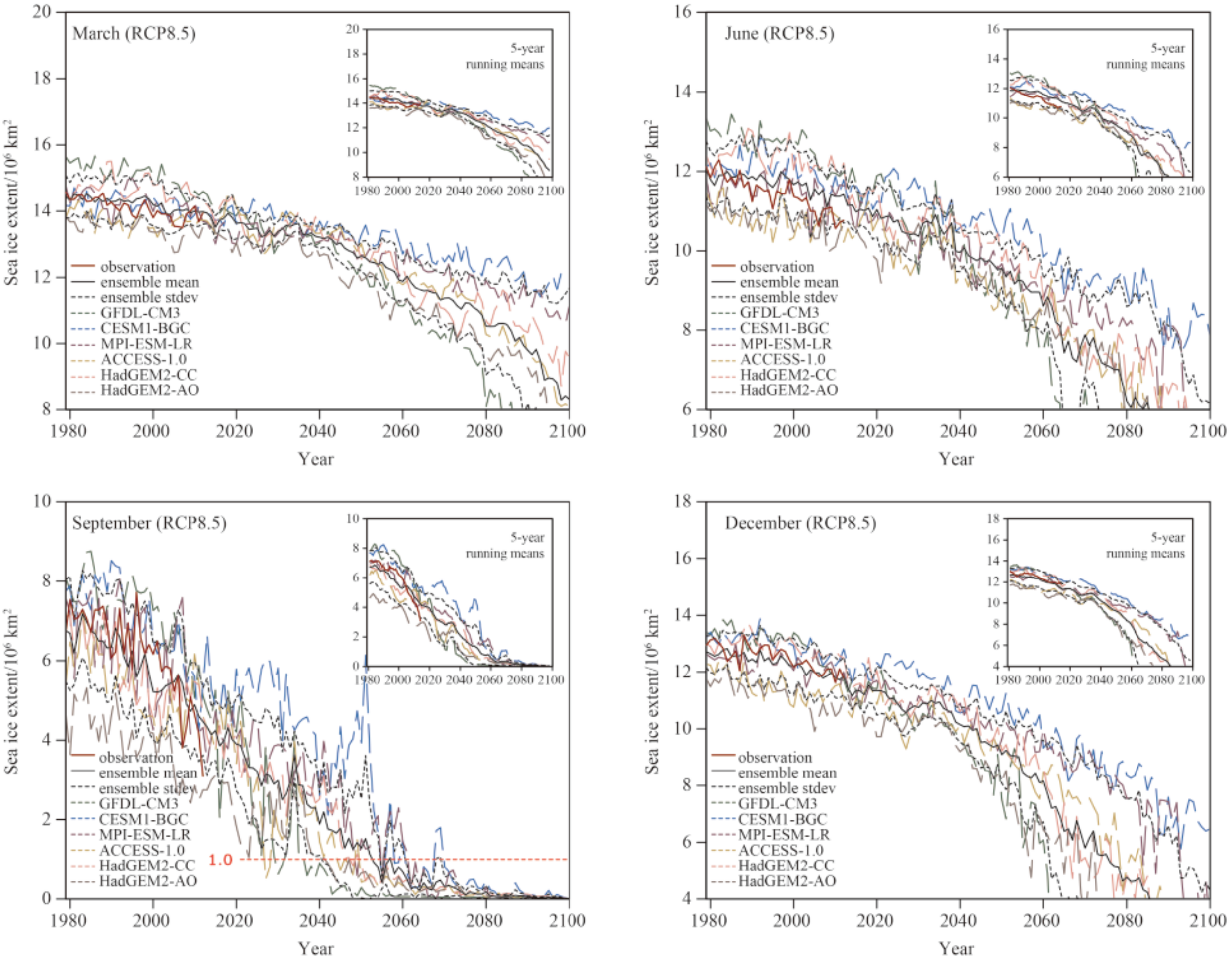

Fig. 3. Time-series of sea ice extent in different seasonal month-March (a), June (b), September (c) and December (d) from 1979 to 2100 averaged by the six selected models of CMIP5 under RCP8.5 scenario. The thick red line is the observation and the thick black line is the ensemble mean of the six models. The sub graph shows the five-year running mean.

4.3 *RCP8.5 scenario*

Under RCP8.5 scenario (Fig. 3), a high-emission scenario, the Arctic SIE will decrease more rapidly in each month from 2013 to 2100, especially in September and December. The averaged trend from January 2013 to December 2100 is up to –0.81 per decade, much greater than observation from 1979 to 2012 and RCP4.5 scenario from 2013 to 2100. The trend of March, June, September and December are –0.36, –0.49, –0.82 and –0.71 per decade under RCP8.5 from 2013 to 2060 (the Arctic will be almost free of ice in September after 2060). They are much greater than RCP4.5 scenario and the trend is more than twice greater than that in September and December. It shows that the ice-free Arctic, which the SIE decreases to less than one million km^2, will first appear before September 2053. Some models even display that it will appear before 2040. It means that the Arctic summer will be almost free of ice in less than 40 years, which is regarded as the "tipping point" of the Arctic climate (Lenton, 2012; Wadhams, 2012). The sea ice of other seasons will continue melting fast and the sea ice extent of March, June and December will probably decline to 8.2, 3.5, 2.0 million km^2 by 2100. They are only about 59.4%, 32.6% and 16.6% of the SIE in 2012, respectively. Different from RCP4.5 scenario, the ice will melt dramatically not only in summer but also in other seasons especially in winter. The total amount of sea ice will decrease seriously by the end of 21st century.

In short, the Arctic sea ice will melt dramatically in the future, especially in September and the ice-free summer will arrive in several decades. Each model under both RCP4.5 and RCP8.5 scenarios all display the reducing trend. The difference is that it is more serious under RCP8.5 scenario. Considered the speed of melting in summer is much faster than that in March especially under RCP8.5 scenario, it means the summer of Arctic will last longer and it will relative be shorter in winter. The extent of annual range will become greater than ever, namely, the amplitude of Arctic SIE will become larger.

5 Seasonal variability of the Arctic sea ice

5.1 *Climatological seasonal cycle of SIE*

Figure 4a shows the observed Arctic SIE annual cycle of climatological mean from 1979 to 2012 and models ensemble mean in different epochs and scenarios. As two factors of span and annual range are considered in the process of selecting models, the ensemble mean of selected models (blue line) can simulate the observation (red line) well. Therefore, the mean annual cycle of the selected models from 1979 to 2012 is chosen as a standard (Standard Annual Cycle or SAC for convenience). We consider the SAC represents the average situation of present annual cycle.

The climatological seasonal cycle of the Arctic SIE show a sine-like curve with maximum in March and minimum in

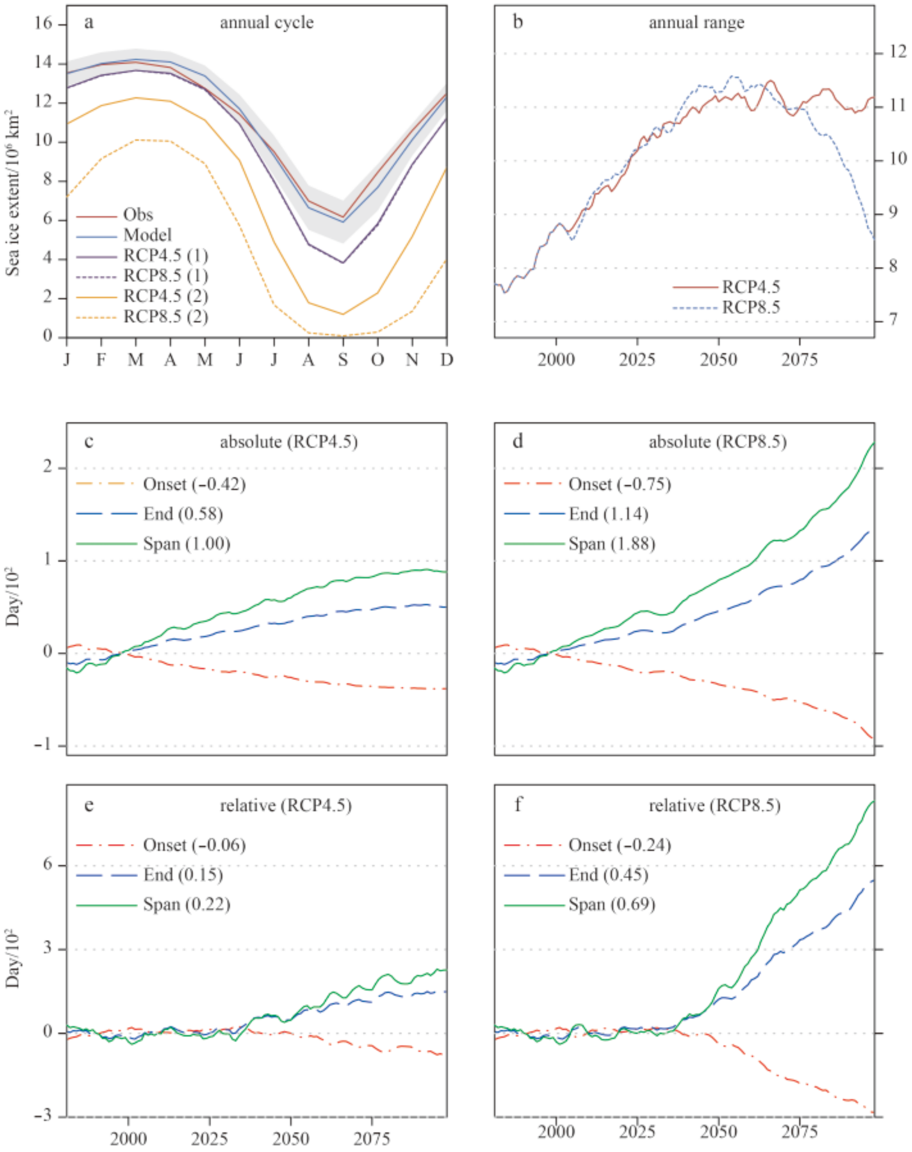

Fig. 4. Seasonal variability of the Arctic sea ice extent in observation and ensemble mean by six CMIP5 models from 1979 to 2010. a. Annual cycle of SIE from observation averaged by 1979–2005 (red line), CIMIP5 model historical simulation 1979–2005 (blue line), RCP4.5 scenario averaged by Epoch 1 (2021–2050) (purple solid line) and Epoch 2 (2071–2100) (orange solid line), RCP8.5 scenario averaged by Epoch 1 (purple dashed line) and Epoch 2 (orange dashed line). b. Annual range of SIE in RCP4.5 (red solid line) and RCP8.5 (blue dashed line) scenarios respectively. "Overall" (c, d) and "cycle" (e, f) changes of melting season for SIE in RCP4.5 (c, e) and RCP8.5 (d, f) scenarios respectively. The red dot-dashed line and blue long-dashed line denote the onset and end date anomaly of melting season, respectively, and the green solid line is the span anomaly of melting season. The number in brackets means the linear trend (day per year) from 1979 to 2100.

September. Because of global warming the SIE decreases in all seasons, thus seasonal cycle curves in Epoch 1 (2021–2050) and Epoch 2 (2071–2100) move down gradually under RCP4.5 and RCP8.5 scenarios. Continual decline of the total amount of sea ice leads to earlier melting/later freezing and prolonged melting season even if the shape of annual cycle line in the future is the same as the SAC. This change of the SIE melting season is mostly due to the overall decline of the sea ice in all seasons, so we call it "overall change". It is also shown from Fig. 4a that declines of SIE in different month and epochs under different scenarios are not uniform, that is, faster melting in summer and slow decline in winter. This will lead to asymmetry of SIE annual cycle. Even if the effects of the "overall change" mentioned above have been removed, the melting season will still become longer. It means the annual cycle line itself will vary in shape, so named as "cycle change". Both of the variations contribute to the change of the SIE seasonal cycle in the future.

5.2 *Amplitude variation of seasonal cycle of SIE*

Amplitude variation of the SIE seasonal cycle could be approximately regarded as its annual range (AR). The AR represents melting ice in each year, namely, seasonal melting ice or one-year ice, which could be a good indicator for Arctic sea ice variability (Huang et al., 2011). Observed Arctic SIE annual range in recent three decades appears increasing (black line in Fig. 4b) especially after 2007 (Niu et al., 2015), in which year the Arctic sea ice first declined to its recorded low. In the future scenarios (Fig. 4b), it is shown that either under RCP4.5 or RCP8.5 scenario, the SIE AR both increase almost linearly in the near future 30–40 years before the Arctic sea ice reaches "tipping point", indicating the more ice melting in summer, the more ice freezing in winter, which may cause more extreme weather events in both winter and summer in the future. When the Arctic Ocean approaches to be ice-free ocean during about 2050–2060, the AR seems hiatus with decadal oscillation instead of continuously increasing under RCP4.5 scenario and even decreases under RCP8.5 scenario.

5.3 *Duration of melting season*

Here we consider the value reaching a quarter of SAC for SIE as a threshold and define the duration of SIE below this threshold as melting season. The first moment of the SIE below the threshold in each year is the "onset" of melting season and the first moment of that above the threshold in each year is the "end" of melting season. As for SAC, the start of the melting season is the 225th day of a year, the end is the 304th day and it lasts for 79 days (Table 2). The threshold is about 8.0 km^2.

We calculate the onset and end moment of the ensemble mean of each year based on the threshold of 8.0 km^2 and compare it to the moment of SAC (Figs 4c and d). It shows the change of melting season relative to present, namely the "overall change". We can find out the onset of melting season will begin earlier and the end will come later under each scenario in the future, so the span of melting season will last longer. The rate of increase will continue and the most striking thing is that the speed of increase will be more and more quickly under RCP8.5 scenario in the future (Table 2). The later end of melting season makes a greater contribution to the extension of the summer. The days of melting season will probably increase by about 100 days under RCP4.5 scenario (Fig. 4c) and more than 200 days under RCP8.5 scenario (Fig. 4d) by the end of 21st century (Table 2).

Table 2. Onset and end days of melting season and its duration (days) for the annual cycle of Arctic SIE climatological mean from 1979 to 2012 (standard) and anomaly days relative to standard time in different scenarios (negative value denotes days earlier onset than standard onset days, positive value means later than standard end days of melting season)

	Onset		End		Duration	
	RCP4.5	RCP8.5	RCP4.5	RCP8.5	RCP4.5	RCP8.5
Standard	225		304		79	
Overall change	–51	–90	70	136	120	226
Cycle change	–8	–28	18	45	26	83
Cycle change contribution/%	15.2	31.6	26.2	39.9	21.8	36.6

Now we remove the effect of the "overall change" and analyze the variability of the "cycle change" alone by calculating the melting season duration based on its own threshold of each year (Figs 4e and f). We can find that the melting season will still become longer even if the overall decrease of the sea ice is almost constant. The seasonal cycle change contributes about 21.8% and 36.6% (Table 2) to the extension of summer in average under RCP4.5 and RCP8.5 scenario respectively and it will explain the extension ratio of summer more and more after 2040, when the ice-free Arctic Ocean comes. It is worth to notice that the "cycle change" of the SIE plays a dominant role in the asymmetry variation of the SIE seasonal cycle in the future, namely as, the end time of melting season will be much more later than that early onset. This suggests that delayed freezing in fall may heat the atmosphere in the following winter, and then influence the early melting of sea ice in the next spring, which may lead to a positive feedback to accelerate the asymmetry variation of the SIE seasonal cycle. The positive feedback may be important to the Arctic amplification (Manabe and Wetherald, 1975; Barron, 1983; Chapman and Walsh, 1993; Holland and Bitz, 2003; Serreze and Francis, 2006; Lu and Cai, 2009; Bekryaev et al., 2010; Screen and Simmonds, 2010; Serreze and Barry, 2011) and extreme climate.

6 Conclusions and discussion

A new approach to compare the simulation metric of Arctic SIE between observation and 31 CMIP5 models was established. Six good selected models show little spread and they can successfully reproduce the observation. We argue that this kind of method can not only be used in the comparison of sea ice models but also be popularized to other models comparison. It is more objective and can select best models according to their average, trend, span and annual range.

The Arctic sea ice will continue melting in the future in each season especially in summer. The free-ice summer will arrive in several decades. The summer in the future will start earlier, end later and the melting season will become longer. Two factors of "overall change" and "cycle change" jointly contribute to this kind of change. Although the later contributes only one fifth to one third variation of SIE seasonal cycle, it may play dominant role in asymmetry variability of the seasonal cycle and the positive feedback of the Arctic amplification.

This kind of change will dramatically influence on the atmosphere, ocean, ecology or economy of Arctic area in the future. First, the quickly melting of Arctic sea ice will produce more underlying surface covered with seawater whose albedo is much lower than sea ice. The Arctic will absorb more shortwave radiation from the sun and become warmer and make the decrease of sea ice more seriously. At the same time, as the summer become longer, the annual range or amplitude will be greater than ever. In response to the change of Arctic sea ice, the atmospheric circulation will change in the future. It probably will bring more extreme weather and climate to mid-high latitude area, such as flood, drought, extremely high or low temperature, etc. The variability of Arctic sea ice will influence the ocean and atmosphere in most parts of the globe.

In addition, the variability of sea ice will have a serious influence on the ecosystem. Sea ice loss emerges as an important driver of marine and terrestrial ecological dynamics, influencing productivity, species interactions, population mixing, gene flow, and pathogen and disease transmission. The extension of summer will also change the habits of plants and animals. In addition, the Arctic waterway has become possible as the decline of the sea ice and the extension of summer. The shipping time and shipping area will be expanded. It will be more convenient and economical shipping from eastern Asia to Europe or North America through the Arctic than any other route.

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