Reducing spread in climate model projections of a September ice-free Arctic

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This paper addresses the specter of a September ice-free Arctic in the 21st century using newly available simulations from the Coupled Model Intercomparison Project Phase 5 (CMIP5). We find that large spread in the projected timing of the September ice-free Arctic in 30 CMIP5 models is associated at least as much with different atmospheric model components as with initial conditions. Here we reduce the spread in the timing of an ice-free state using two different approaches for the 30 CMIP5 models: (*i*) model selection based on the ability to reproduce the observed sea ice climatology and variability since 1979 and (*ii*) constrained estimation based on the strong and persistent relationship between present and future sea ice conditions. Results from the two approaches show good agreement. Under a high-emission scenario both approaches project that September ice extent will drop to ∼1.7 million km^2 in the mid 2040s and reach the ice-free state (defined as 1 million km^2) in 2054–2058. Under a medium-mitigation scenario, both approaches project a decrease to ∼1.7 million km^2 in the early 2060s, followed by a leveling off in the ice extent.

Arctic sea ice has undergone dramatic decline in recent years (1). The minimum sea ice extent set on September 16, 2012 (3.41 million km^2, ref. 2) was 48.5% below the long-term mean (1979–2000) and broke the previous record minimum set on September 18, 2007. The last six years (2007–2012) have featured the lowest September ice extents during the satellite era. This decline raises the specter of a September ice-free Arctic in the coming decades, which would have significant impacts on Arctic maritime activities and ecosystems, biogeochemical feedbacks, and extreme weather and climate in mid and high latitudes (3, 4).

The Intergovernmental Panel on Climate Change Fourth Assessment Report (IPCC AR4) concluded that "Arctic sea ice responds sensitively to warming, . . . late-summer sea ice is projected to disappear almost completely towards the end of the 21st century under the A2 scenario in some models" (5). Subsequent research suggested the ice-free Arctic might occur from as early as the late 2030s to the end of the 21st century under the Special Report on Emissions Scenarios (SRES) A1B and A2 scenarios based on the IPCC AR4 model simulations (also referred to as the CMIP3). An abrupt reduction in sea ice cover (i.e., 2–6 million km^2 within a decade) during the 21st century seems to be a common feature in a number of climate projections by the IPCC AR4 models. This could result in ice-free September conditions (less than ∼1.5 million km^2) by 2040 according to one simulation from the Community Climate System Model (CCSM) (6). Using the observed September sea ice extent in 2007 as a starting point, together with the projections of a subset of the IPCC AR4 models that better reproduce the observed climatological September ice extent, one study suggested the Arctic could be ice-free in September (less than 1 million km^2) in the late 2030s (with a large uncertainty bound spanning the late 2010s to the mid 2070s, ref. 7). Based on the relationship between the simulated September sea ice cover during the 21st century and trends of sea ice cover for the past three decades from a subset of the IPCC AR4 models, another study projected September sea ice cover in the Arctic would vanish near the end of the 21st century (8).

Arctic sea ice is not only shrinking in extent but is also thinning dramatically (9, 10). The "best" estimate of sea ice volume (extent multiplied by thickness) from the recently updated Pan Arctic Ice Modeling and Assimilation System (11) shows that September sea ice volume has decreased ∼75% from 1979 to 2011, which is faster than the observed decrease of September sea ice extent over the same period (∼36%, ref. 12). As sea ice volume has declined dramatically, the *Arctic Marine Shipping Assessment 2009 Report* (13) and some scientists (14) have made predictions that the Arctic might be ice-free as early as 2015. Thus, there is large uncertainty in the projected timing of the ice-free Arctic in a warming environment.

The CMIP5 simulations have recently become available (15). Relative to the CMIP3, a more diverse set of model types is included in the CMIP5 (i.e., climate/Earth system models with more interactive components such as atmospheric chemistry, aerosols, dynamic vegetation, ice sheets, and carbon cycle). Further, a number of improvements in physics, numerical algorithms, and configurations are implemented in the CMIP5 models. For example, some CMIP5 models include more realistic sea ice thermodynamics and dynamics in sea ice components, displaced pole to eliminate the singularity in sea ice and ocean components, better treatments of subgrid parameterizations in all of the components, and higher resolution in all of the components. Finally, a new set of scenarios called representative concentration pathways (RCPs) are used in the CMIP5 simulations (16).

Methods and Results

Here we focus on the projection simulations 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 high-emission scenario with direct radiative forcing reaching 8.5 W/m^2 (∼1,370 ppm CO_2 equivalent) in 2100. The RCP4.5 is more conservative than the SRES A1B (end-of-century CO_2 of 720 ppm) scenario used in the CMIP3 simulations, whereas the RCP8.5 is more aggressive than both the SRES A1B and A2 (end-of-century CO_2 of 850 ppm) scenarios. We analyze 30 CMIP5 models on the Program for Climate Model Diagnosis and Intercomparison (PCMDI) data portal that provide both "all-forcings" historical simulations and projection simulations under the RCP4.5 and RCP8.5.

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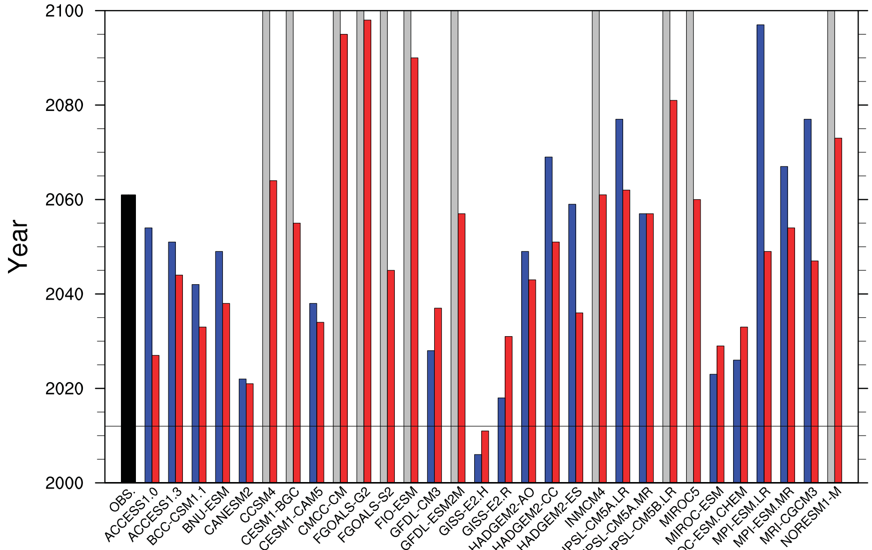

Fig. 1. Projected timing of September ice-free Arctic for 30 Coupled Model Intercomparison Project Phase 5 (CMIP5) models under the RCP4.5 (blue bars) and RCP8.5 (red bars), and the linear extrapolation of the observed trend (black bar).

As shown in Fig. S1, unfortunately the large intermodel spread in the simulated September sea ice extent during the 21st century that was a feature of the CMIP3 simulations (17) remains in the CMIP5 simulations under both the RCP4.5 and RCP8.5. This is consistent with recent studies (18, 19). It should be noted that all 30 models show a convergence of the simulated September sea ice extent (below 1 million km^2) near the end of the 21st century under the RCP8.5. A number of CMIP5 models show trends comparable to the observed trend, and five models even show a decline larger than that observed for 1979–2011 (Fig. S1). In contrast, none of the CMIP3 models have trends of September Arctic sea ice decline as large as that observed (17).

Fig. 1 shows the time interval when the projected September sea ice extent in the Arctic is less than 1 million km^2 (defined here as "ice-free") for each model. Under the RCP4.5, about one-third of the models do not reach the ice-free condition by the end of the 21st century (Fig. 1, gray bars). By contrast, under the RCP8.5, all 30 models reach the ice-free condition within the 21st century. A few models realize the ice-free state as early as from the mid 2000s to the 2020s. Comparison between the RCP4.5 and RCP8.5 suggests that the projected timing of the ice-free Arctic is sensitive to the prescribed greenhouse gas forcings, although a few models with the ice-free state before the late 2020s show that the timing for the RCP8.5 is delayed relative to those for the RCP4.5.

As indicated in figure 4 of Wang and Overland (20), different initial conditions have an effect on the projected timing of the ice-free Arctic, ranging from a few years to a decade. Here we find that the projected timing of the ice-free Arctic varies remarkably in the same family of models that differ only in the physics of the atmospheric model components (i.e., using the same initial conditions, sea ice and ocean model components, and resolution). Among the National Center for Atmospheric Research model family, Community Earth System Model (CESM)-CAM5 uses the Community Atmospheric Model version 5 (CAM5), whereas CCSM4 uses version 4 (CAM4). CAM5 has been modified substantially to include new and revised schemes of moist turbulence, shallow convection, three-mode modal aerosol, stratiform microphysical processes, and cloud macrophysics (21). Relative to CCSM4, the use of CAM5 advances the timing of the ice-free Arctic by more than six decades under the RCP4.5, and two decades under the RCP8.5. The Institut Pierre Simon Laplace (IPSL) family of models shows similar differences. Compared with IPSL-CM5A-LR, IPSL-CM5B-LR includes a new set of physical parameterizations in the atmospheric model (i.e., new parameterizations of

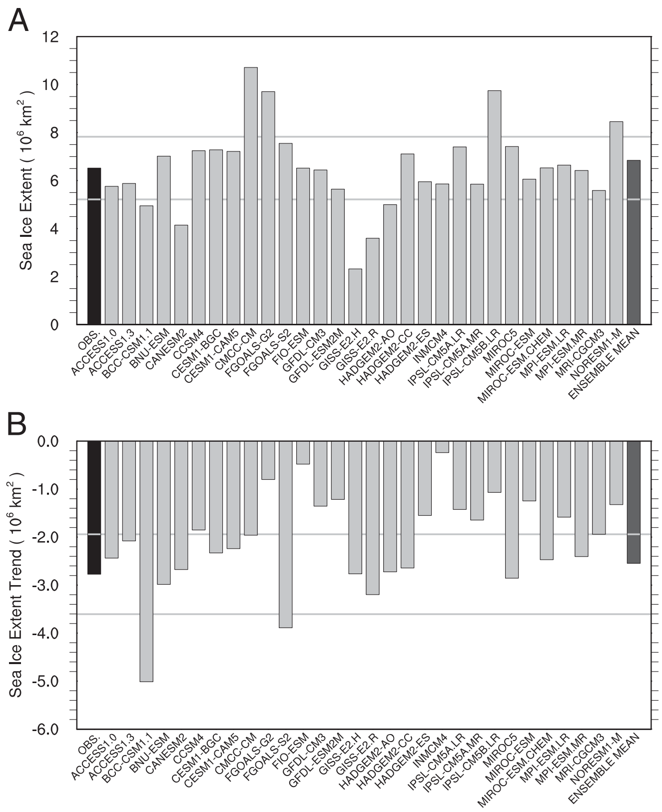

Fig. 2. (*A*) Climatology (average) and (*B*) linear trend of September sea ice extent for the observations (black bar, *Left*) and each CMIP5 model (gray bars) during 1979–2011. The dark gray bar (*Right*) is the ensemble mean for the nine selected models.

boundary layer, deep convection, and clouds processes). This results in about three and two decades difference in the projected timing of the ice-free Arctic under the RCP4.5 and RCP8.5, respectively.

In the same family of models that hold everything else unchanged (e.g., physics and initial conditions) except resolution, the projected timing of the ice-free Arctic is strongly influenced by the model resolution. The Max Planck Institute (MPI) models have different resolution for the sea ice and ocean model components, and the IPSL-CM5A models differ in the resolution of their atmospheric model component. The MPI low resolution (~1.4° × 0.8°) delays the timing by three decades relative to the MPI medium resolution (~0.4°, Fig. S2). Also, the IPSL-CM5A low resolution (3.75° × 1.875°) delays the timing by two decades compared with the IPSL-CM5A medium resolution (2.5° × 1.25°, Fig. S2). Kirtman et al. (22) showed that the Arctic warming is associated with significant losses of sea ice in the simulation with high resolution of sea ice and ocean model components using CCSM3.5 (the forerunner to CCSM4). DeWeaver and Bitz (23) suggested the simulation of Arctic sea ice and surface winds changes significantly when the resolution of the atmospheric model component is increased. A scatter plot of the resolution versus the timing of the ice-free Arctic for the 30 CMIP5 models under the RCP4.5 and RCP8.5 scenarios is provided in Fig. S2. No obvious linear relationship is discernible between the resolution and the timing of the ice-free Arctic across the full suite of the models. This is primarily because the influence of the resolution is lost in the complexity of the 30 CMIP5 models with different physics and numerical methods. More coordinated experiments are needed to confirm the resolution effect.

One approach for reducing the large spread in the projected timing of the September ice-free Arctic is through model selection based on the models' ability to reproduce the observed sea ice climatology and variability (19, 20). Here we first evaluate which CMIP5 models have a reasonable climatological September ice extent for 1979–2011, a good constraint to eliminate outlier models that have large systematic biases in sea ice characteristics. We retain the models with the simulated September sea ice extent falling within 20% of the observations (20% is also used in other recent studies, ref. 20). Encouragingly, 20 of the 30 CMIP5 models satisfy that requirement (Fig. 2*A*).

We further evaluate which CMIP5 models successfully simulate the rate of Arctic sea ice decline for 1979–2011 as a good constraint to eliminate outlier models with erroneous sensitivity to natural variability and external forcings. We retain those models with simulated September sea ice extent trend falling within 30% of the observations, on the assumption that no more than 30% of the observed trend is natural. This assumption is generally consistent with recent analyses of sources of multidecadal Arctic sea ice variability based on model simulations. Day et al. (24) indicated that ~5–30% of multidecadal variability in Arctic sea ice can be attributed to climate mode variability. Stroeve et al. (18) suggested that 33–48% of the observed decline

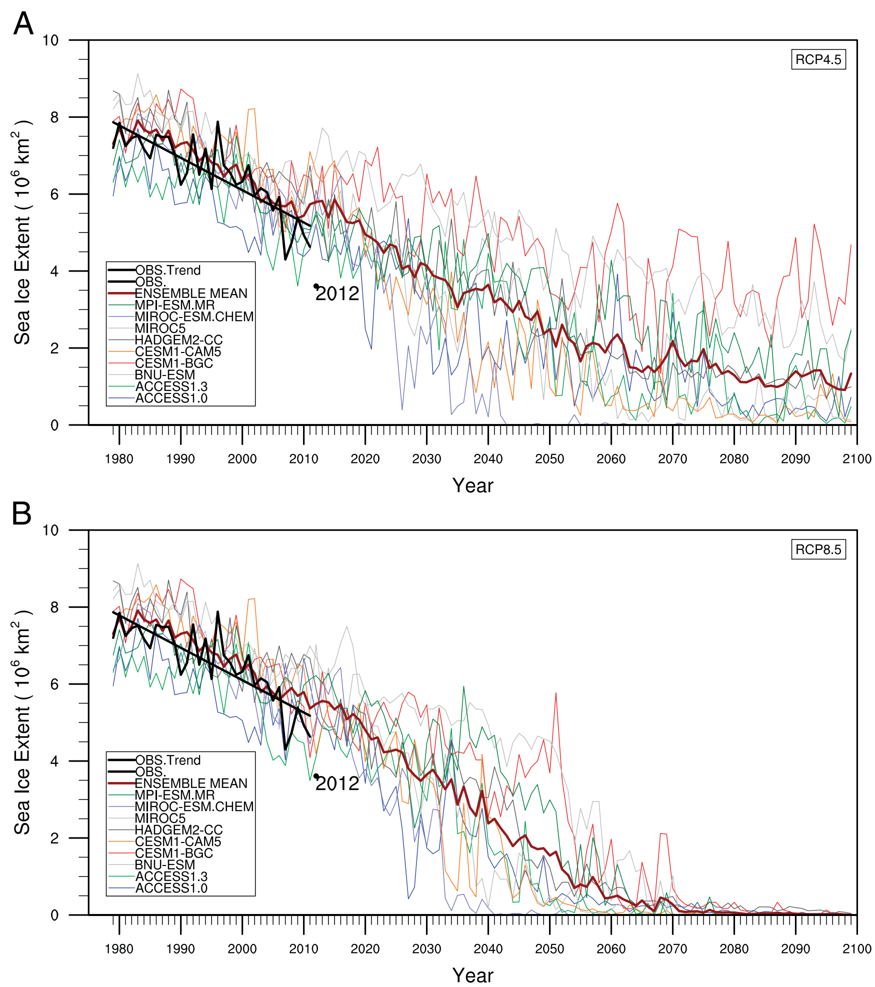

Fig. 3. Time-series of the simulated (colored lines) September sea ice extent from 1979 to 2100 for the nine selected models under the (*A*) RCP4.5 and (*B*) RCP8.5. The thick black line is the observations, the thick red line is the ensemble mean of the nine models, and the black circle is September sea ice extent in 2012.

of Arctic sea ice might be due to natural variability. Because there is substantial uncertainty about the relative roles of natural versus forced variability in the observed trend, the 30% threshold used here should be viewed as one from a range of choices, rather than as a definitive best answer. About one-third of the 30 CMIP5 models satisfy that requirement (Fig. 2*B*). The nine models that meet both the climatology and the trend criteria are Australian Community Climate and Earth-System Simulator (ACCESS1.0 and ACCESS1.3), Beijing Normal University Earth System Model (BNU-ESM), CESM1-BGC, CESM1-CAM5, Hadley Global Environment Model (HADGEM2-CC), Model for Interdisciplinary Research on Climate (MIROC5 and MIRO-ESM.CHEM), and MPI-ESM.MR. As shown in Fig. 2, the climatology and trend of September sea ice extent for the ensemble mean of the nine models for 1979–2011 are in good agreement with the observations. It should be noted that the trend of the ensemble mean of the nine models (and all 30 models) and the trend of the observations tend to diverge starting from 2007, especially when 2012 is considered.

The ensemble mean of the nine models shows that under the RCP4.5, September sea ice extent decreases to ∼1.7 million km^2 (∼50% of the record low ice extent set on September 16, 2012) in the early 2060s, and then tends to level off toward the end of the 21st century (Fig. 3*A*). By contrast, under the RCP8.5, September sea ice extent drops to ∼1.7 million km^2 in the late 2040s and reaches the ice-free condition in 2054 (Fig. 3*B*). Using model selection based on four present sea ice characteristics, Massonnet et al. (19) estimated the year when the Arctic could become ice-free in summer is between 2041 and 2060 under the RCP8.5.

Fig. S3 shows the simulated spatial distribution of September ice concentration and thickness averaged for the nine models. During the present mean state (2007–2011), the ice edge forms an arc around the periphery of the Arctic Basin extending from north of Alaska to north of western Siberia (Fig. S3*B*), which is similar to the observations (Fig. S3*A*). The models show thick ice (>1.5 m, corresponding to ice that is more than 2 y old based on the relationship between the coregistered thickness and age data estimated from the Ice, Cloud, and Land Elevation Satellite, ref. 25) covering a large portion of the central Arctic Ocean (Fig. S3*D*). When the simulated September ice extent reaches ∼1.7 million km^2, the Arctic Ocean is a viable "open ocean" shipping route, and thick and multiyear ice can be found only in a tiny portion of the northern Canadian Archipelago (Fig. S3*E*).

Another approach for reducing the large spread of the projected timing of the September ice-free Arctic is through constrained estimation based on the relationship between present and future sea ice conditions derived from the intermodel spread (hereafter referred to as "constrained estimation"). This approach involves (*i*) exploring the relationship between the present and projected September sea ice extent for the 30 CMIP5 models and (*ii*) applying that relationship to the observed present condition to constrain the spread of the projected September sea ice extent during the 21st century. The rationale is that those models with excessive sea ice at present tend to retain ice for a relatively long period, whereas those with insufficient sea ice at present tend to lose ice relatively quickly.

Fig. 4 shows the simulated September sea ice extent averaged for 2007–2011 (referred to as the present mean state) versus the projected September sea ice extent by each CMIP5 model averaged for the 5-y window from 2018 to 2022 (referred to as the projected mean state). Each small black circle in Fig. 4 corresponds to one CMIP5 model. Indeed, under both the RCP4.5 and RCP8.5, the projected September sea ice extent is strongly associated with the simulated September sea ice extent in the present condition. Significant across-model correlations exist between the present and projected mean state (r = 0.93 for RCP4.5 and r = 0.95 for RCP8.5, >99% significance for both with the assumption that each model is an independent sample),

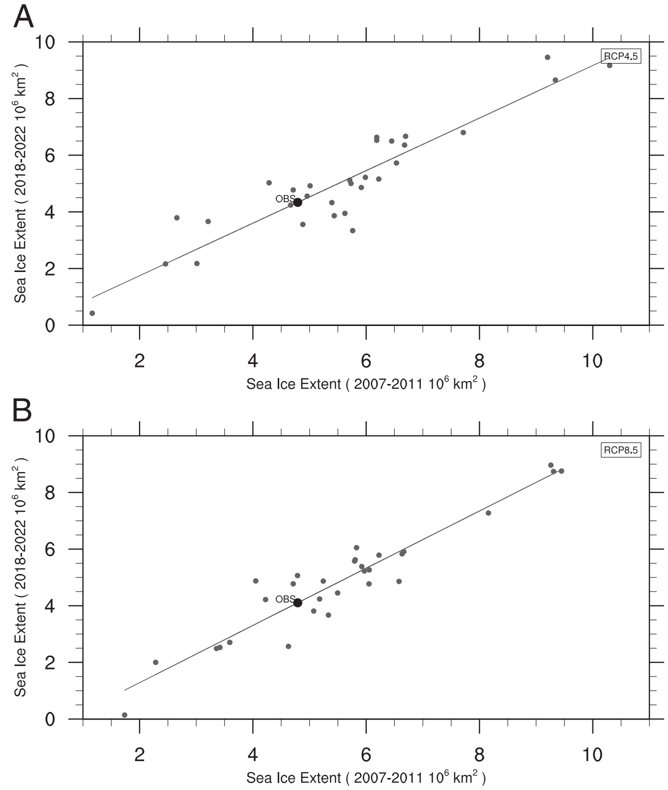

Fig. 4. Scatter plot of September sea ice extent in present mean state (2007–2011) versus September sea ice extent in the projected future state (2018–2022) simulated by 30 CMIP5 models (small circles) under the (*A*) RCP4.5 and (*B*) RCP8.5 (the observed present mean state is indicated with a large black circle).

confirming that the present condition is a good predictor of future condition. We calculate the regression coefficients between the present and projected mean state (solid lines in Fig. 4). The constrained estimation of September sea ice extent for 2018–2022 is then the intercept between the regression line and the observed present mean state (large black circle in Fig. 4).

Repeating the same constrained estimation procedure described above, we calculate the across-model correlations and regression coefficients based on the scatter plots of the simulated September sea ice extent averaged for 2007–2011 and the projected September sea ice extent averaged for the 5-y sliding windows extending to the end of the 21st century for the 30 CMIP5 models. For example, the first 5-y window starts from 2013 to 2017 centered on 2015, and the last 5-y window is 2095–2099 centered on 2097. As shown in Fig. 5, under both the RCP4.5 and RCP8.5, the across-model correlations are persistently high, ∼0.9–0.95 at the beginning (2013–2017, >99 significance) and then gradually decreasing to ∼0.65–0.7 for the RCP4.5 and RCP8.5 at the end of the 21st century (2095–2099, >99 significance). This result further confirms that the evolution of September sea ice extent through the 21st century is closely associated with the magnitude of the present condition in the CMIP5 simulations. Note that the relationship (correlation/regression) between present and future September sea ice extent is also robust even if the length of the period is defined as a 10-y window or 33-y window (the entire observational period, 1979–2011).

In a recent study, Massonnet et al. (19) found a generally weak relationship between the present mean of sea ice extent and future anomalies (defined as departures from the present mean or trends, which removes the model's climatological bias). Here

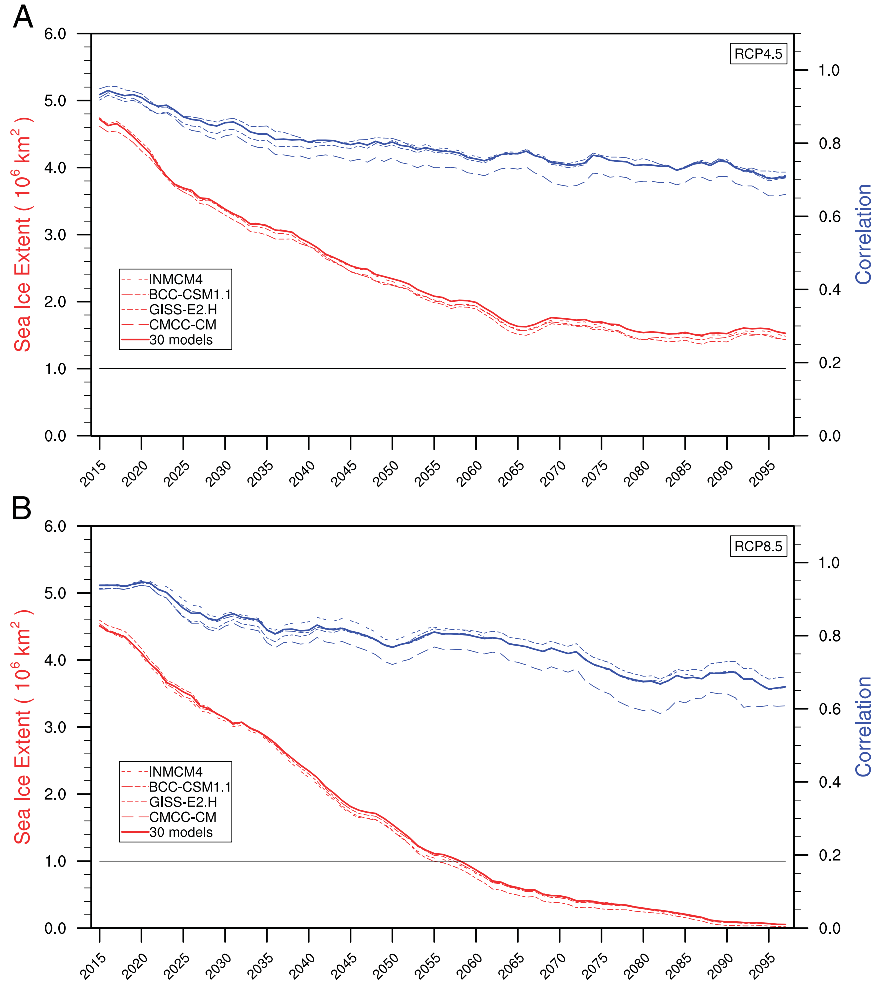

Fig. 5. The evolution of the correlation (blue lines) and constrained estimation of September sea ice extent (red lines) based on the relationship between the simulated September sea ice extent averaged for 2007–2011 and the projected September sea ice extent averaged for the 5-y sliding windows under the (*A*) RCP4.5 and (*B*) RCP8.5.

our analysis comparing the present mean sea ice extent to the future mean sea ice extent throughout the 21st century shows a strong relationship, in part because those models with excessive sea ice at present tend to retain ice for a relatively long period, whereas those with insufficient sea ice at present tend to lose ice relatively quickly. Note that the trend biases simulated by the models are even larger than the climatological biases simulated by the models (Fig. 2). We believe that both the Massonnet approach and our approach have merit.

The constrained estimation of September sea ice extent for each 5-y sliding window is calculated as the intercept between the regression line and the observed present mean state (2007–2011). Here we use the averaged September sea ice extent observed during 2007–2011 as the initial condition, because much lower sea ice extent has appeared from 2007 onward. Fig. 5 shows the evolution of the constrained estimation of September sea ice extent. Under the RCP4.5, the Arctic Ocean does not reach the ice-free state (below 1 million km^2) during the 21st century. September sea ice extent decreases to ~1.7 million km^2 in the early 2060s and then tends to flatten out toward the end of the 21st century. By contrast, under the RCP8.5, September sea ice extent drops to ~1.7 million km^2 in the mid 2040s and the first 5-y window showing the ice-free Arctic is 2056–2060 (centered on 2058). To measure uncertainty associated with model outliers that might unduly influence the correlation, we further repeat the procedure, including the correlation analysis and constrained estimation, by removing the model with the most and least September sea ice extent climatology [Centro Euro-Mediterraneo sui Cambiamenti Climatici Climate Model (CMCC-CM) and Goddard Institute for Space Studies ModelE/Hycom (GISS-E2.H), Fig. 2*A*], and trend [Beijing Climate Center Climate System Model (BCC-CSM1.1) and Institute of Numerical Mathematics Climate Model (INMCM4), Fig. 2*B*]. The resulting correlations (blue thin lines in Fig. 5) and constrained estimations (red thin lines in Fig. 5) are in good agreement with those based on all 30 models.

A recent study found that the observed linear trend in Arctic sea ice extent from 1979 onward is primarily attributed to the linear increase in atmospheric CO_2 concentration (26). We therefore extrapolate the time series of the observed September sea ice extent into the future using the linear regression based on the linear trend for 1979–2011. It yields September sea ice extent below 1 million km^2 in 2061. Interestingly, our projections based on the two different approaches (i.e., model selection and constrained estimation) under the RCP8.5 give similar ice-free timing (the mid and late 2050s).

Discussion

Using model selection (removing the outlier models that fall outside a range of criteria using the observations) and constrained estimation (constraining the model biases and estimation using a statistical fit with the observations), we effectively reduce the spread projected by CMIP5 models in timing for the September ice-free Arctic from 2011 to 2098 down to 2054–2058 for the high-emission scenario (RCP8.5). In reality, increased maritime activities in the Arctic Ocean and substantial climate impacts have been emerging in the Arctic Ocean in advance of the ice-free state (6, 13).

The role of natural variability in the recent dramatic decline remains a critical research question (27). Moreover, as the extent of multiyear sea ice decreases, and the warm layer of Atlantic and Pacific origin water increases (28), further efforts are needed to improve understanding of the role of penetration of solar radiation in sea ice, vertical advective heat flux from the warm layer of Atlantic and Pacific origin water to the surface mixed layer, and/or poleward oceanic and atmospheric heat transports, leading to correct representations of the heat source for the ice melt. These processes may lead to a nonlinear reduction of Arctic sea ice. Better representations of these processes and the multidecadal modes of natural internal variability are critical for accurate prediction of how sea ice might change in the coming decades.

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