A sea ice free summer Arctic within 30 years: An update from CMIP5 models

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[1] Three years ago we proposed that the summer Arctic would be nearly sea ice free by the 2030s; "nearly" is interpreted as sea ice extent less than 1.0 million km^2. We consider this estimate to be still valid based on projections of updated climate models (CMIP5) and observational data. Similar to previous models (CMIP3), CMIP5 still shows a wide spread in hindcast and projected sea ice loss among different models. Further, there is no consensus in the scientific literature for the cause of such a spread in results for CMIP3 and CMIP5. While CMIP5 model mean sea ice extents are closer to observations than CMIP3, the rates of sea ice reduction in most model runs are slow relative to recent observations. All CMIP5 models do show loss of sea ice due to increased anthropogenic forcing relative to pre-industrial control runs. Applying the same technique of model selection and extrapolation approach to CMIP5 as we used in our previous paper, the interval range for a nearly sea ice free Arctic is 14 to 36 years, with a median value of 28 years. Relative to a 2007 baseline, this suggests a nearly sea ice free Arctic in the 2030s. **Citation:** Wang, M., and J. E. Overland (2012), A sea ice free summer Arctic within 30 years: An update from CMIP5 models, *Geophys. Res. Lett.*, *39*, L18501, doi:10.1029/2012GL052868.

1. Introduction

[2] The fast changing Arctic in the recent decade has drawn much attention as an indicator of local and global climate change, particularly after the unexpected drop of summer sea ice extent in 2007. From 2007 to 2011 summer sea ice extent has remained low relative to its climatology (1980–2005), but variable. Sea ice extent, defined as the area where the ice concentration is greater than 15% in a grid box, has been below 5.0 million km^2 in four of the last five years (http://nsidc.org/data/g02135.html), the lowest values during the satellite era beginning in 1979. The current low coverage of multi-year Arctic sea ice [*Kwok and Untersteiner*, 2011] and the projected loss of summer sea ice extent represent social, climatological and ecological threats and economic opportunities [*Arctic Monitoring and Assessment Programme*, 2011; *Overland et al.*, 2011b]. These potential opportunities and threats make urgent the answer to the question: When will the Arctic be nearly sea ice free during summer? It is of interest to provide reasonable projections for summer Arctic sea ice conditions based on current limited information.

[3] Coupled global climate models (CGCMs) are the major objective tools available to provide future climate projections based on physical laws that control the circulation and thermodynamics of the atmosphere, ocean, land and sea ice. Three years ago, based on a sub-group of CGCMs simulation results submitted to the third phase of the Coupled Model Intercomparison Project (CMIP3), we suggested that the summer Arctic may be nearly sea ice free by the 2030s [*Wang and Overland*, 2009] (hereinafter WO2009). "Nearly" is interpreted as sea ice extent less than 1.0 million km^2, the same criterion used in WO2009. Recently, modeling groups around the world have improved their CGCMs and made their results available to the wider scientific community through the archive at The Program for Climate Model Diagnosis and Intercomparison (PCMDI) at the Lawrence Livermore National Laboratory. This constitutes the fifth phase of the Coupled Model Intercomparison Project (CMIP5). From the PCMDI archive and through direct communication with modeling centers we obtained sea ice simulations from 32 models (auxiliary material, Table S1).[1] We analyze results from a subset of 23 models which have simulations for at least two emissions scenarios.

[4] During the CMIP3 experiments, the models ran simulations under three main emissions scenarios, B1, A1B and A2. We found that projected trajectories of the Arctic summer sea ice extent had little difference before 2050 between A1B and A2 emissions scenarios, which were used in our previous analysis. In the new CMIP5 experiments, different emissions scenarios were used, described as "representative concentration pathways" (RCPs) [*Moss et al.*, 2010]. In the current study we concentrate on two: RCP8.5 and RCP4.5. These two emissions scenarios correspond to a high and medium radiative forcing of +8.5 and +4.5 Wm^{-2} in 2100 relative to pre-industrial levels. A business as usual economic projection implies a greater than RCP4.5 emission scenario.

[5] In this study we address the following questions: 1) Do the newer versions of climate models show improvement in their sea ice simulations? 2) What is a suggested timing of future summer Arctic sea ice loss based on a combination of model projections, known sea ice and ocean feedbacks [*Overland et al.*, 2011b; *Stroeve et al.*, 2012b], and recent observations? There are several CMIP5 sea ice evaluation papers in the literature or in review [*Pavlova et al.*, 2011; *Stroeve et al.*, 2012a; F. Massonnet et al., The trends in summer Arctic sea ice extent are nonlinearly related to the mean sea ice state in CMIP5 models, submitted to *The*

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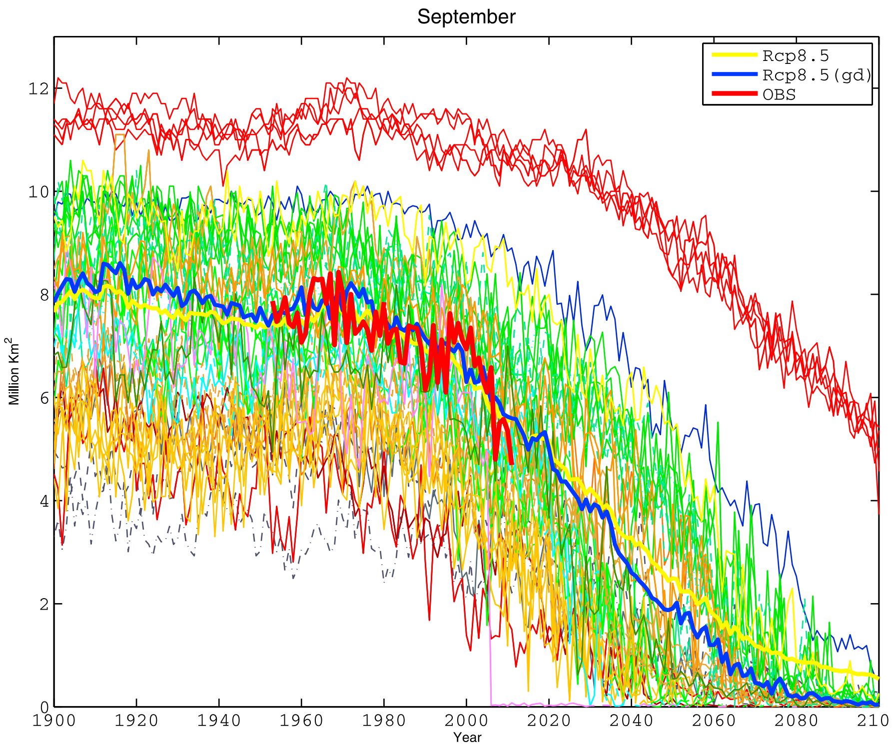

Figure 1. September Arctic sea ice extent from CMIP5 models for historical and RCP8.5 runs. Each thin colored line represents one ensemble member. Thick colored lines are the ensemble mean of all members (yellow), and ensemble means from seven selected models (blue), The thick red line is based on observations (HadleyISST_ice) as adjusted by Meier before 1979. Units are million square kilometers.

Cryosphere, 2012]. The set of papers add credibility to the model evaluation process as they have similar conclusions on the utility of CMIP5 even though different subsets of models were used and there were differences in interpolation approaches and comparison techniques.

2. Observational Data and Model Output

[6] Sea ice extent is often defined as the area with ice concentration equal or greater than 15% of a grid cell. There are several observational sea ice data available. The most commonly referenced is the National Snow and Ice Data Center (NSIDC) sea ice index [*Fetterer et al.*, 2002] (updated 2009). NSIDC products are based on satellite data from the Scanning Multichannel Microwave Radiometer (SMMR) and Special Sensor Microwave/Imager (SSM/I) instruments. The gridded spatial resolution is around 25 km. In the present study we use the HadISST_ice sea ice concentration analysis, which was made more homogeneous by compensating satellite microwave based sea ice concentrations for the impact of surface melt effects on retrievals in the Arctic [*Rayner et al.*, 2003]. We use the Hadley sea ice analysis as an observational constraint for comparing model simulations based on: 1) it has a spatial resolution ($\sim$1 $\times$ 1 degree) similar to that of most models, 2) it is a gridded product and therefore we can avoid errors introduced due to interpolation process, and 3) it provides contrast to approaches used by other CMIP5 sea ice evaluation studies. It has been suggested that the HadleyISST_ice analysis may overestimate the sea ice extent before 1979 based on comparison with ESMR microwave data from 1972–1978 [*Stroeve et al.*, 2012a; W. Meier, personal communication, 2012]. We therefore show the Meier's adjusted Hadley "observed" time series for 1953–1978 and the original Hadley analysis thereafter as the observed curves in our Figures 1 and 2 (thick red lines). Because our climatology period for observation/model comparisons was 1981–2005, treatment of the pre-1979 period does not affect our analysis.

[7] Among 32 models that provided their sea ice simulations for various scenarios (Table S1), 23 of them submitted projections with at least two emissions scenarios (RCP4.5 and RCP8.5). There was a total of 49 (RCP4.5) and 50 (RCP8.5) ensemble members for each emission scenarios. Seven models only submitted a single run. We limit the contribution from any single model to no more than 5 ensemble members and do not average the individual ensembles members from any single model. Thus we maximized the available number of ensemble members but avoid extra weight from any single model.

[8] Unlike the CMIP3 model archives, several CMIP5 models provide their simulation results on their original model grid instead of interpolating them to a common latitude/longitude grid. This creates ambiguity in comparing results among different models. Since these models each have their own grid, we interpolate the ice concentration from model grids to a 0.5 $\times$ 1.0 degree lat/lon grid before sea ice extent is computed. In this way, model results were compared in a consistently manner. The interpolated lat/lon grid is also close to the Hadley sea ice analysis resolution. We noticed that there are differences in the calculated sea ice extent based on model versus interpolated grids. Taking the CCSM4 model as an example, the averaged sea ice extent is about 0.6 million km^2 more for September when calculated

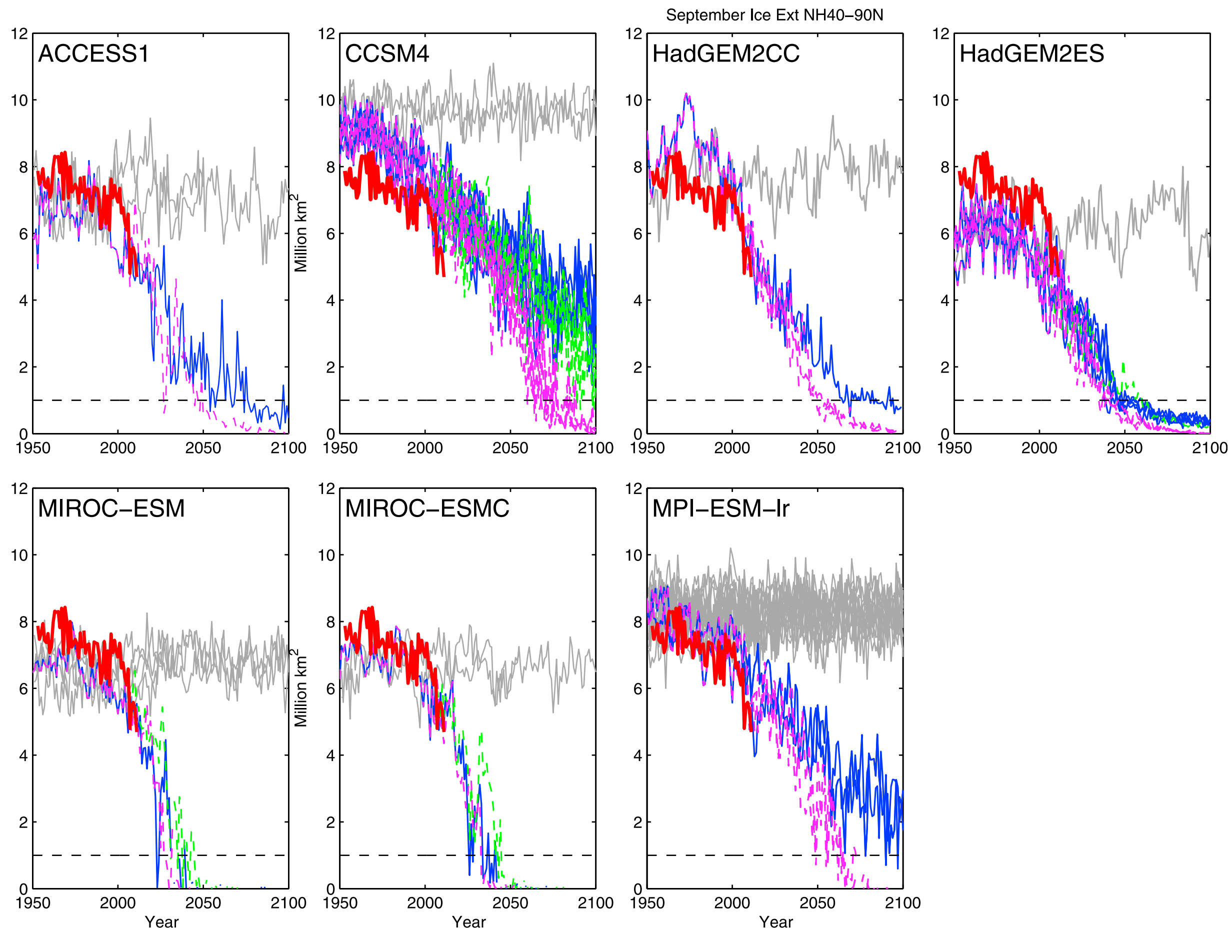

Figure 2. Time series of September sea ice extent from seven selected models for historical, RCP4.5 (blue), RCP6.0 (green) and RCP8.5 (magenta) runs. Thin grey lines are from the corresponding control runs (piControl) in 150 yr blocks.

on a lat/lon grid compared with that calculated on its original model grid. As supplied models have different underlying grids and different amounts of interpolation to a lat/lon grid, we could not systematically assess the potential overall uncertainties caused by the interpolation process across the set of models.

3. Results

[9] When the simulated sea ice extents from these 23 available CMIP5 models are evaluated together, we found that models results had a wide spread in simulating the summer Arctic sea ice extent for September for hindcasts and under emission scenario RCP 8.5 (Figure 1). The spread among the models is similar to CMIP3 results [*Zhang and Walsh*, 2006; *Stroeve et al.*, 2007; WO2009]. The mean of all models (yellow line) is near the observations (thick red line) for the 1981–2005 period. This contrasts with the CMIP3 results where the model mean overestimated sea ice extent for this period [WO2009; *Pavlova et al.*, 2011]. The CMIP5 mean is close to observations before 1980 and above observations at the end of the observational record. In the RCP4.5 scenario (not shown) many models show sea ice remaining at more than 2 million km^2 at the end of 21st century [*Stroeve et al.*, 2012a].

[10] To reduce this spread, we recommend removal of models that cannot simulate the present day climate. This is a reasonable but not sufficient approach [see *Overland et al.*, 2011a]. To be consistent with our previous study (WO2009), we use the same selection criteria to cull the models, i.e., we require the model simulated mean and seasonal cycle of the sea ice extent to be within 20% when compared with the observational mean climatology (1981–2005). The 1981–2005 period was chosen because it overlaps with satellite observation period and 2005 is the last year of the models' historical simulation period. The 20% bounds were used in our previous study, and the approach has been accepted by others [*Zhang*, 2010]. Seven models have satisfactory performance in both categories: ACCESS1, CCSM4, HadGEM2-CC, HadGEM-ES, MIROC-ESM, MIROC-ESM-CHEM, and MPI-ESM-LR. The trajectory of the ensemble mean from the seven selected models is shown in blue (RCP8.5) in Figure 1, indicating that sea ice declines faster after 2030 for the mean of the seven culled models than in the mean of all models. This is similar to what was found in WO2009.

[11] The projection of future sea ice conditions from these seven selected models show that the decline of sea ice can only happen when external forcings from anthropogenic sources are included in the model simulations. All the CMIP5 Control runs show no sign of ice decline in any given 150 years (Figure 2, grey lines) in contrast to the projections under different emissions scenarios (blue for RCP4.5, green for RCP6.0 and magenta for RCP8.5). The attribution of sea ice loss due to anthropogenic forcing based on model studies

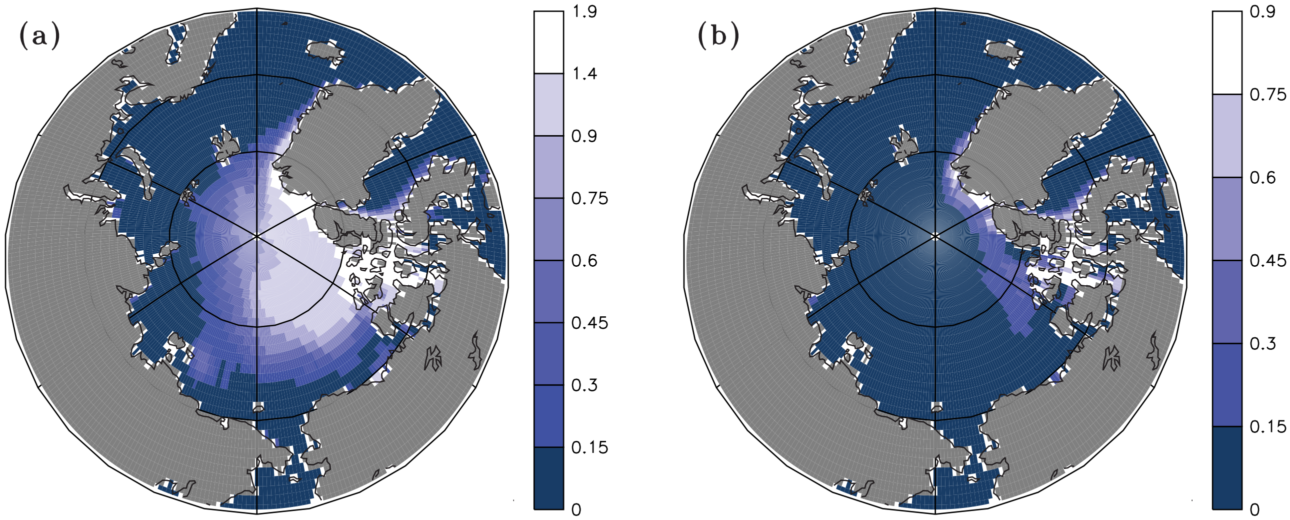

Figure 3. Mean September sea ice thickness averaged over seven selected models (a) at present and (b) by the time Arctic is nearly sea ice free. Note the scale differences between Figures 3a and 3b. Units are in m.

is further supported by the observational study of *Notz and Marotzke* [2012].

[12] If we consider 1.0 million km^2 as the summer ice free condition (the horizontal dashed line crossing the colored lines in Figure 2), then under the RCP8.5 scenario (magenta lines in Figure 2) this condition will be reached by the ensemble members of the seven selected models by ~2040–2060.

[13] Figure 3 shows the mean summer sea ice thickness from the seven selected models for current conditions and for the time when the Arctic is nearly sea ice free. Currently, modeled sea ice more than 2 m thick is found in the central Arctic near Canadian Archipelago. By the time when the Arctic is nearly sea ice free, this same region becomes a sea ice refuge, similar to results from WO2009.

4. Discussion

[14] The range of September estimated sea ice extents for the late 20th century from CMIP5 models of roughly 4–10 million km^2, and similar to CMIP3, is rather discouraging. Further there is no consensus in the causes for the spread. *Kwok* [2011] notes a shift in location of the Beaufort Sea high pressure in models which produces considerable uncertainties in sea ice decline. *Eisenman et al.* [2007] note differences in cloud cover between the models and sensitivity to downward radiation. *Ridley et al.* [2007], *Boé et al.* [2009], and *Zhang* [2010] note different sensitivity of sea ice loss to global temperatures and sea ice mass balance. *Overland et al.* [2011b] and *Stroeve et al.* [2012b] suggest that accelerated sea ice loss is due to multiple mutually supporting air, ice, and ocean processes, which are not well represented in coarse resolution GCMs. Thus we conclude following the guidance of the IPCC on treatment of uncertainties: while all models show a loss of sea ice extent in the 21st century, the consistency among models on the future trajectory of sea ice loss is low, and the agreement on the physical causes for the differences is also low.

[15] Internal variability, as shown by the range of results from the limited number of ensemble members for the same model, makes it difficult to compare observed and model trends [*Kay et al.*, 2011]. Further, both NSIDC (not shown) and HadleyISST_ice "observations" show a visual break in the slope of the trend of sea ice extent near 1996. For the 18 ensemble members of the seven selected models the median trend value for 1996–2011 is -1.0×10^6 km^2 decade^{-1} compared to the Hadley observed trend of -1.7×10^6 km^2 decade^{-1}. Although the range of ensemble member model trends does bracket the observation, the smaller value of the median model trend suggests that we continue to use the similar extrapolation approach for estimating an expected value of future sea ice loss timing as in WO2009, and make an earlier timing adjustment to the direct model projections. Our method calculates the time interval for sea ice extent to be reduced from a nominal current observed value of 4.5 million km^2 to 1.0 million km^2 for all ensemble members of the seven selected models under RCP8.5 scenario (Figure 4). This time interval range is 14 to 36 years, with a median value of 28 years. Relative to a 2007 baseline, a future nearly sea ice free summer is centered in the 2030s, consistent with the estimate obtained based on six selected CMIP3 models (WO2009).

5. Conclusion

[16] Along with other authors [*Pavlova et al.*, 2011; *Stroeve et al.*, 2012a], we review the sea ice projections available from CMIP5. Our second goal was to make a suggestion for the timing of a future nearly sea ice free summer Arctic (i.e. less than 1 million km^2) based on a combination of model projections and recent observations.

[17] Based upon the observed rapid loss of multi-year sea ice in recent years [*Kwok and Untersteiner*, 2011; *Comiso*, 2012], the multiple mutually supporting air, ice, and ocean processes impacting sea ice loss [*Overland et al.*, 2011b; *Stroeve et al.*, 2012b], and the slow trend from the CMIP5 models, we consider that the models provide only an outer limit for the timing of such loss. While there is improved agreement between model mean and recently observed sea ice extent in CMIP5 relative to CMIP3, and larger downward trends in CMIP5 [*Pavlova et al.*, 2011], the range of future sea ice trajectories in models remains large. This suggests that more attention should be paid to the physics and results

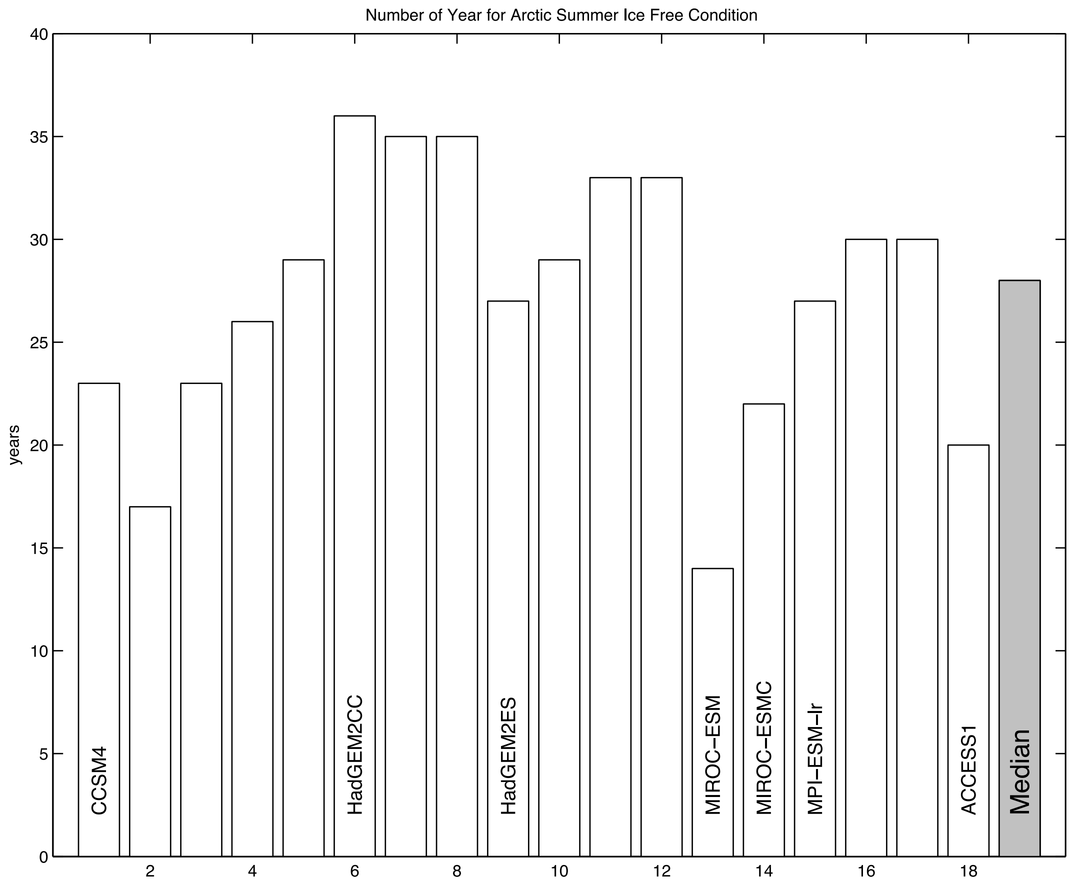

Figure 4. Estimated time for a nearly sea ice free summer Arctic to be reached (from 4.5 to 1.0 M km^2) based on individual ensemble members from the seven models that simulated current mean and seasonal cycle of sea ice in reasonable agreement with observations. The right grey bar is the median value.

of individual models. For the seven selected CMIP5 models based on observed mean and magnitude of seasonal cycle and our extrapolation approach (Figure 4), the interval range for a nearly sea ice free Arctic is 14 to 36 years, with a median value of 28 years, i.e. relative to 2007 a loss in the 2030s, consistent with the previous estimate we obtained based on six selected CMIP3 models (WO2009).

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