The trends in summer Arctic sea ice extent are nonlinearly related to the mean sea ice state in CMIP5 models

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We examine the recent (1979-2010) and future (2011-2100) characteristics of the Arctic sea ice cover as simulated by 22 Earth system and general circulation models from the Coupled Model Intercomparison Project phase 5 (CMIP5). As was the case with CMIP3, a large inter-model spread persists in the simulated summer sea ice losses over the 21st century for a given forcing scenario. We identify a nonlinear relationship between the mean September sea ice extent (SSIE) and the trend in SSIE over the same climatic (∼30 yr) periods, characterized by an elevated rate of decline when the SSIE reaches ∼2-4 million km^2. From this point of view, all models evolve in a similar phase space but are currently located on different positions of resembling trajectories. Therefore, the current observed mean SSIE is, unlike the trends in SSIE (a statistic clearly sensitive to internal variability), a reasonable criterion to constain summer sea ice projections.

1. Introduction

The evolution of Arctic sea ice in the next decades is of particular economic, ecological and climatic relevance [ACIA, 2005], and the recent observed dramatic sea ice retreats in late summer (2005, 2007, 2008, 2011; Fetterer et al. [2012]) stress the urgent need for extracting reliable information from the abundant existing projections of Arctic sea ice. Here we examine the 21st century projections of Arctic sea ice from 22 Earth system and general circulation models (ESMs and GCMs) participating to the Coupled Model Intercomparison Project, phase 5 (CMIP5, `http://pcmdi3.llnl.gov/esgcet/home.htm`). All these models project a decline in summer Arctic sea ice extent over the next decades (Fig. 1).

Nonetheless, large uncertainties remain regarding the magnitude and timing of future changes in the sea ice cover. This was already underlined for CMIP3, the previous round of model intercomparison [see, e.g., Arzel et al., 2006; Zhang and Walsh, 2005], and several studies have proposed to reduce the spread in sea ice projections through model selection/weighting [Zhang and Walsh, 2005; Stroeve et al., 2007; Wang and Overland, 2009] or model recalibration on available observations [Boé et al., 2009; Mahlstein and Knutti, 2012]. Here we show that the CMIP5 simulations exhibit a similar, nonlinear link between the trend in September sea ice extent (SSIE) and the contemporary mean of SSIE throughout the 20th and 21st centuries and that this relationship can be invoked to effectively constrain summer sea ice projections from the baseline SSIE and other related quantities (e.g., the annual mean sea thickness).

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2. Model Output and Observational Data

Table 1 [Online Supplement] lists the 22 ESMs and GCMs used for this study, selected on the requirement that they archive sea ice fields up to 2100. Out of the existing climate forcing scenarios, we only retain two "representative concentration pathways" (RCPs, Moss et al. [2010]), RCP4.5 and RCP8.5, corresponding to a radiative forcing of +4.5 and +8.5 Wm^{-2} in 2100 relative to pre-industrial levels, respectively. Because of the much smaller population of available models under RCP2.6 and RCP6.0, these two other scenarios are not discused here.

For each simulation, three quantities have been derived from the monthly sea ice fields on the model native grid: the sea ice extent (the area of grid cells comprising at least 15% of ice), the mean sea ice thickness (the total sea ice volume divided by the area of the ocean above 65°N), and the thin ice extent (the extent of ice with mean grid cell thickness between 0.01 and 0.5 m). Working on the original grid is a well-founded choice, (1) because the grid is part of the model experimental design, and (2) because no ice is artificially created/removed due to interpolation onto a common grid, with a prescribed land-sea mask. However, as the area covered by ocean in the Arctic (> 65°N) is different on each model grid (∼1.8 million km^2 difference between the extremes), care must be taken when the output is analyzed. Here the term "CMIP5 model" refers to each of the 22 ESMs and GCMs listed in Table 1 [Online Supplement]; if a model comprises several members, then an equally-weighted average of these members is considered. The "multi-model mean" refers to the average across all CMIP5 models, with equal weight.

Observations of sea ice extent are taken from the National Snow and Ice Data Center (NSIDC) sea ice index [Fetterer et al., 2012]. The data is provided as monthly values calculated on the NSIDC grid, with the same 15% cutoff definition as that described in the previous paragraph. We perform the comparison to observations over the 1979-2010 reference period. For that purpose, we have extended the 1979-2005 available CMIP5 sea ice output from the historical simulations with the 2006-2010 fields under RCP4.5. At such short time scales and so early in the 21st century, the choice of the scenario to complete the 1979-2005 time series is of no particular importance.

3. Results

3.1. 1979-2010 Overview

Summary statistics of the Arctic sea ice extent as simulated by the 22 CMIP5 models and their members are shown in Fig. 2 for the 1979-2010 reference period. We make the distinction between the climatological mean state (x-axis) and the linear trend (y-axis) over that period. The multi-model mean compares well with the observed September and March Arctic sea ice extents (x-axis). The distribution of the extents among CMIP5 models is roughly symmetric about the multi-model mean in both months, but the width of the distribution is substantial (7 million km^2) and has not narrowed since CMIP3 [Parkinson et al., 2006].

In both months, the CMIP5 multi-model mean underestimates the observed trend (y-axis in Fig. 2). However the distribution of the modeled trends spans the observations, and hence, the models cannot be considered inconsistent with the observed trend. The same is true for CMIP3 models for the 1979-2006 period as shown by Stroeve et al. [2007]. It is worth noting that the SSIE trend of the multi-model mean for 1979-2006 is considerably higher in the CMIP5 models compared to CMIP3 models (not shown here), suggesting that model improvements have caused models to have greater sea ice decline in September. Actually, the trend –as a statistic from a distribution– appears much less stable than the mean state: in Fig. 2, the different members of the same models (e.g. MPI-ESM-LR, CCSM4, CSIRO-Mk3-6-0) are clustered in terms of mean (x-axis), but scattered in terms of trend (y-axis). In addition, the SSIE trends are very sensitive to the end points of the period [Kay et al., 2011]. It is therefore not prudent to conclude that the models under-represent observed trends, as a much larger number of members for each model (or a longer observational period) would be needed to test the hypothesis that observed trends are statistically different from the modeled ones.

3.2. 21st Century Summer Projections

In the course of the 21st century, the CMIP5 models simulate a widespread response of the sea ice cover to the prescribed radiative forcings, as illustrated with the SSIE projections (Fig. 1). One way to address, understand and possibly narrow this spread is to study the evolution of sea ice characteristics as a function of the present-day state. With the CMIP3 data set, Arzel et al. [2006] showed that the summer mean 1981-2000 extent influences the relative (i.e. in %) but not the absolute changes in SSIE. However, this is a concern, since a relationship can be found by construction: the correlation between X and $\Delta X/X$ can be non-zero even if X and ΔX are actually decorrelated. Besides, they found no relationship between the 1981-2000 mean sea ice thickness and future SSIE changes. On the other hand, Holland et al. [2008] found that the baseline thickness of ice is well correlated with the SSIE throughout the 21st century. Using the CMIP2 data set, Flato [2004] –yet using annual mean values of Arctic sea ice extent– reported that the initial extent does not strongly impact future changes in sea ice extent; this is consistent with the hypothesis that, if such relationships exist, they may be seasonally-dependent [Bitz et al., 2012]. Boé et al. [2010] found interesting links between current trends in SSIE and future SSIE changes, but again they worked with relative values.

With the CMIP5 data set, it appears that, as long as the 22 models are considered, the absolute SSIE changes (for example, 2040-2060 mean SSIE minus 1979-2010 mean SSIE) are not systematically related to the model 1979-2010 state (not shown here). This makes sense, since these changes are calculated between common time windows over which models are in very different states. For example, over 2040-2060, some models are already at (near) ice-free, equilibrium conditions while some others are at near present-day levels and still on the track of ice loss (Fig. 1). We will get back to this issue in section 4.

To clarify the role of the initial state on the SSIE evolution, and to account for the fact that the CMIP5 model population has very contrasted characteristics at any particular time, we propose to analyze this data set from a slightly different perspective. Let Y_i be the year after 1979 where the CMIP5 model i reaches a fixed SSIE for the first time, say 4 million km^2 for RCP4.5 and 1 million km^2 for RCP8.5. Across the CMIP5 models, the Y_i's correlate significantly ($p < 0.05$) with different characteristics of the sea ice state over 1979-2010: the thin ice extent in September (correlation: -0.66 for RCP4.5, -0.56 for RCP8.5), the annual mean ice thickness (0.72 and 0.73), the mean SSIE (0.86 and 0.76), the amplitude of the seasonal cycle of ice extent (-0.60 and -0.53), and the trends in SSIE (0.48 and 0.61). These relationships indicate that CMIP5 models tend to reach a given summer sea ice extent earlier when the following –not necessarily independent– conditions hold: (i) the extent of thin (<0.5 m) ice is larger in September, (ii) the ice is thinner in the annual mean, (iii) the baseline SSIE is lower, (iv) the amplitude of the climatological cycle of sea ice extent is larger and, to a lesser extent, (v) they have higher present-day September sea ice loss trends. These results confirm previous studies [e.g., Boé et al., 2009; Holland et al., 2008] but the relationships are expressed on the basis of common SSIE, and not fixed time periods.

Beyond the fact that some of these criteria can be used to constrain the timing of future SSIE evolution (see next section), one of them raises a particular interest: the SSIE itself. Indeed, as shown in the previous paragraph, the time taken for SSIE to reach a given extent is, on the one hand, well correlated with the initial extent. This occurs because the CMIP5 simulations have nearly the same long-term trend in SSIE as they approach ice-free conditions. As an example, under RCP8.5, the SSIE trends from 1979 up to the year when ice-free (1 million km^2) conditions are reached, is $-799 \pm 182 \times 10^3$km^2/decade (mean of the CMIP5±1 std). On the other hand, the trends are weaker and more scattered over the 1979-2010 period as discussed in section 3.1 and shown in Fig. 2 ($-552 \pm 328 \times 10^3$km^2/decade). The trends are more uniform over the longer period because at some point each simulation experiences a rapid loss of SSIE that dominates over the longer period. Such an event occurs in all CMIP5 models and manifests as a marked minimum of the running trend during the 21st century (Fig. Online Supplement). While the timing of this minimum varies between 2000 and 2100 in the CMIP5 ensemble, it is related to the mean SSIE: in Fig. 3, we show the trajectories of SSIE in a phase space diagram (SSIE against its time derivative, i.e., its trend) in the case of RCP8.5. In these plots, the time is thus an implicit variable. All models follow a similar trajectory: they start from the right (relatively high mean SSIE at the beginning of the simulation), then move leftwards as the mean SSIE decreases. Then they all experience a vase-shaped trajectory as the mean SSIE decreases further to ice-free conditions. Interestingly, the 1979-2010 position of each CMIP5 model on this trajectory (colored crosses in Fig. 3) is different: for example, BCC-CSM1.1, CanESM2 and GISS-E2-R are already near the minimum, while EC-EARTH and CCSM4 have not reached it yet. Under RCP4.5, similar trajectories exist, but are less marked for models that do not reach ice-free conditions by 2100 (not shown here).

4. Discussion and Conclusions

We show that the trend in SSIE is, on climatic time scales, nonlinearly related to the contemporary mean SSIE (Fig.

3). This nonlinearity is further evidenced by the behavior of the multi-model mean in Fig. 3: it also experiences a minimum of trend, but this event is much more smoothed in time and much less pronounced in magnitude than any individual CMIP5 model. The existence of such a nonlinear dependence has important implications. (1) Under the assumption that the CMIP5 models reflect the reality, the real SSIE follows a trajectory similar to those depicted in Fig. 3. Nonetheless, we only have one snapshot at our disposal (black dots on the figure), and not a full trajectory. (2) The CMIP5 models are capable of achieving observed 1979-2010 SSIE trends (-0.80×10^6 km^2/10yr, the horizontal black lines on the figure), but they often make it later than the 1979-2010 period, when their mean SSIE is lower. (3) We have a more precise explanation as to why there is no systematic relationship between the 1979-2010 SSIE and SSIE absolute changes between this period and another time period (for example 2030-2061) later in the 21st century. Indeed, these changes are by definition proportional to the trends between the two time periods; thus the relationship can be positive or negative depending on the present and future locations of the models on their trajectory.

The evolution of the sea ice cover characteristics over the 21st century is related to the 1979-2010 conditions in the CMIP5 models, as we showed in section 3.2. Here we offer a new point of view that reinforces the importance of the current (1979-2010) SSIE on the timing as when the Arctic could become ice-free during summertime. Assuming that the real trajectory will resemble that of the 22 models, a requirement for models to correctly simulate the timing of possible near ice-free conditions in the Arctic (say, < 1 million km^2) is to start, in 1979-2010, from the correct location on their own trajectory. Given the very limited amount of available information on the real sea ice cover (the black dots on Fig. 3), one has to use a robust statistic to work with in the perspective of narrowing uncertainties. Constraining the models on their ability to simulate the 1979-2010 SSIE trend only (i.e., comparing the colored crosses with the horizontal line on Fig. 3) would be a poor choice, because (1) the curves of Fig. 3 are multi-valued, i.e., identical trends are achieved for different mean states, and (2) the imprint of internal variability is so large onto this statistic [Overland et al., 2011] that models could be dismissed for wrong reasons. Referring back to Fig. 2b, we find evidence of this signature of internal variability: over 1979-2010, the simulated trends can differ from a factor of greater than 2 (GISS-E2-R, CSIRO-Mk3.6.0) or even have different signs (MPI-ESM-LR). From a climatic point of view, the real, observed trend is also a single realization from a climatic distribution and we would need, for each CMIP5 model, a very large number of members (say, >10) to properly assess their simulated trends; this is not the case with the present experimental setup (Table 1, Online Supplement). Instead, the only information on the mean SSIE provides a reasonable constraint on the projections (i.e., comparing the colored crosses with the vertical black line on Fig. 3) because it guarantees that the initial position of the model on its trajectory is correct.

The elevated rate of decline present in the CMIP5 simulations throughout the 21st century (Fig. 3) cannot be caused by the prescribed climate forcing since all these events occur at different times. Instead, it occurs when the SSIE is roughly between 2 and 4 million km^2. In a previous study, Goosse et al. [2009] showed that the variance in detrended SSIE is also dependent on the mean SSIE in the Arctic for various climate models, with a peak at comparable SSIE (between 2 and 4 million km^2). In our case, the elevated rates of summer sea ice decline probably stems from the fact that (1) wider areas of open ocean in the Arctic basin at such low values of the SSIE promote the emergence of more physical ocean-sea ice processes that are less marked if the Arctic basin is saturated in summer [Goosse et al., 2009], and (2) the ice gets thinner in the course of the 21st century, and open water forms at higher rates in this case [Holland et al., 2006]. When ice-free conditions are eventually reached, there is by definition no interannual variability (the $(0, 0)$ coordinates in Fig. 3). This boundary condition in the phase space gives the trajectories their vase-shaped appearance.

We propose that the uncertainties in 21st century projections of SSIE can effectively be reduced by considering the mean state of each model, i.e. its 1979-2010 mean SSIE as the starting point of the trajectories up to ice-free conditions, but also the amplitude of the seasonal cycle of ice extent, annual average thickness and thin ice extent (section 3.2). Out of these four criteria, the last two are certainly the most difficult to use given the limited available records but, as we show in the next example, they are all potentially relevant. For the sake of simplicity, we retain here only the models with a reasonable sea ice extent, i.e., we only select models that simulate the SSIE and amplitude of the sea ice extent seasonal cycle (note that this amplitude is in fact related to thin ice extent, they correlate at 0.68 ($p < 0.05$)) within 20% of the observations (the numerical value of 20 % is arbitrary, but identical to that of Stroeve et al. [2007] and Wang and Overland [2009]). 8 CMIP5 models (CCSM4, GFDL-CM3, INM-CM4, IPSL-CM5A-LR, IPSL-CM5A-MR, MIROC-ESM, MIROC-ESM-CHEM and MPI-ESM-LR) satisfy the requirements; under RCP8.5 (resp. RCP4.5), their SSIE remains below 1 million km^2 for 5 consecutive years between 2033 (resp. 2031) for the earlier, MIROC-ESM, and 2077 (resp. not before 2100) for the later, CCSM4. Now we note that, out of these models, MIROC-ESM is the one with the thinnest ice and CCSM4 with the thickest ice cover in annual mean (not shown here). This indicates that a further model selection through ice thickness assessment could be applied, as it would narrow the time window that we propose in our simple examination. Very interestingly, exactly the same 8 particular models are retained if the same selection procedure is conducted over 1979-2006. Now suppose we choose another criterion for model selection and retain the models based on their SSIE trends only (again, only those whose trends are within 20% of the observations): then 6 models would be selected when the assessment is conducted over 1979-2010; over 1979-2006, 3 models would be selected, only 2 of which were also part of the first subset (1979-2010). Again, this reinforces the idea that the trends (in opposition to the mean state) are very sensitive statistics, and a small change in the experimental setup can lead to very different conclusions.

In our study, we started from the principle that none of the available CMIP5 models should be dismissed prior to the analysis, as it is sometimes the case [e.g., Arzel et al., 2006]. From the large and widespread population of the CMIP5 models, we have (1) found relationships that make the current sea ice state a fair predictor of the future evolution of the sea ice cover, and (2) identified a nonlinear relationship between the trends and the mean of the SSIE, reinforcing the importance of the mean state. We have constrained the date of possible disappearance of summer Arctic sea ice as simulated by the CMIP5 models (this date depending also on the forcing scenario that is considered) on this basis, although we acknowledge that the sea ice cover is also sensitive to other factors, e.g., the near-surface global or Arctic air temperature [Mahlstein and Knutti, 2012; Zhang, 2010] or the meridional oceanic heat flux [Mahlstein and Knutti, 2011]. We consider therefore that simulating a correct mean sea ice state over 1979-2010 is a necessary condition to reasonably anticipate future sea ice evolution, as it has a clear influence on the variability and response of the sea ice cover.

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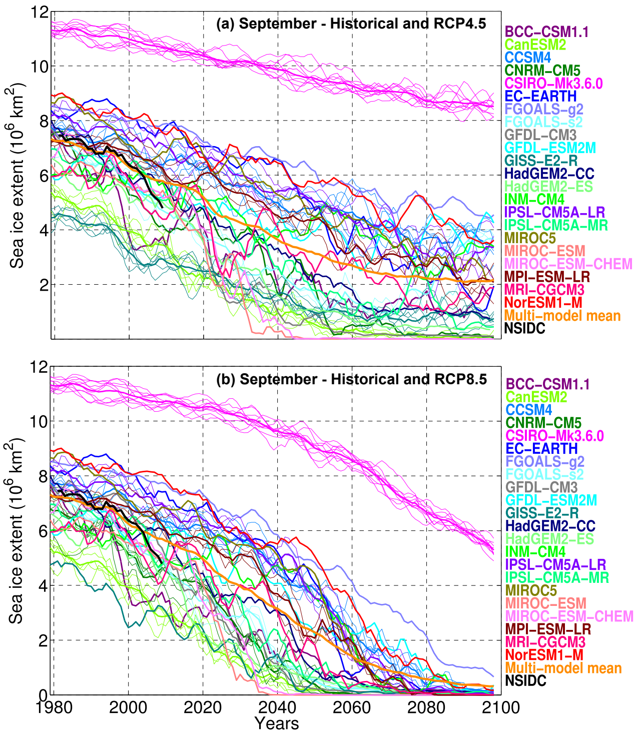

Figure 1. September Arctic sea ice extent (5-yr running mean) as simulated by 22 CMIP5 models. The historical runs are merged with the RCPs (representative concentration pathways [Moss et al., 2010]) 4.5 (a) and 8.5 (b) runs. Members of a same model, if any, are represented by thin lines. Individual models (or the mean of all their members, if any) are represented by thick lines. The multi-model mean (equal weight for each model) is depicted by the thick orange line. Observations [Fetterer et al., 2012] are shown as the thick black line.

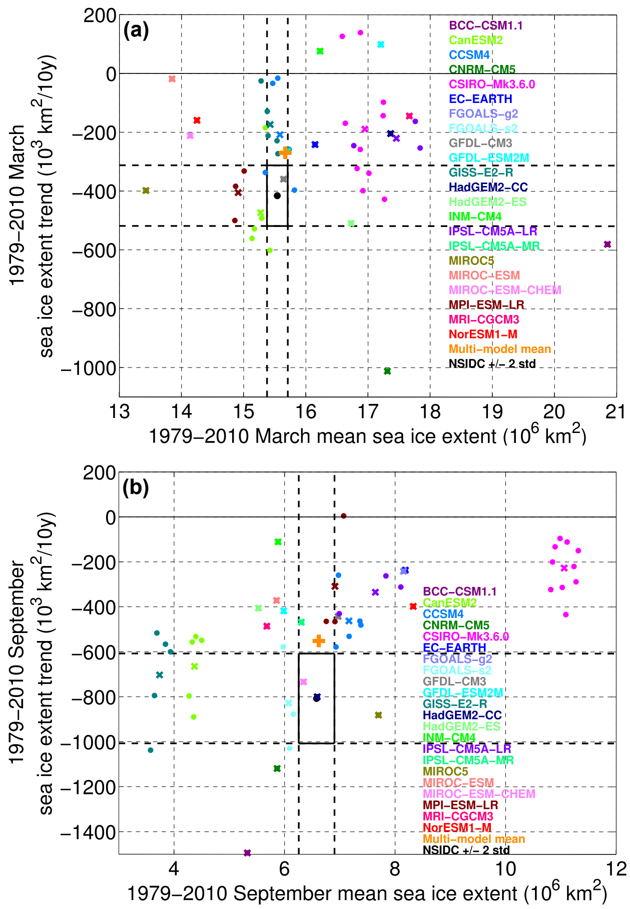

Figure 2. 1979-2010 mean of (x-axis) and trend in (y-axis) the September (a) and March (b) Arctic sea ice extent, as simulated by the CMIP5 models and their members. Members of a same model (if any) are represented by dots (•). Individual models (or the mean of all their members, if any) are represented by crosses (×). The multi-model mean is depicted as the orange plus (+). Observations [Fetterer et al., 2012] are shown as the black dot, with $\pm 2\sigma$ windows of to the mean and trend estimates (dashed lines).

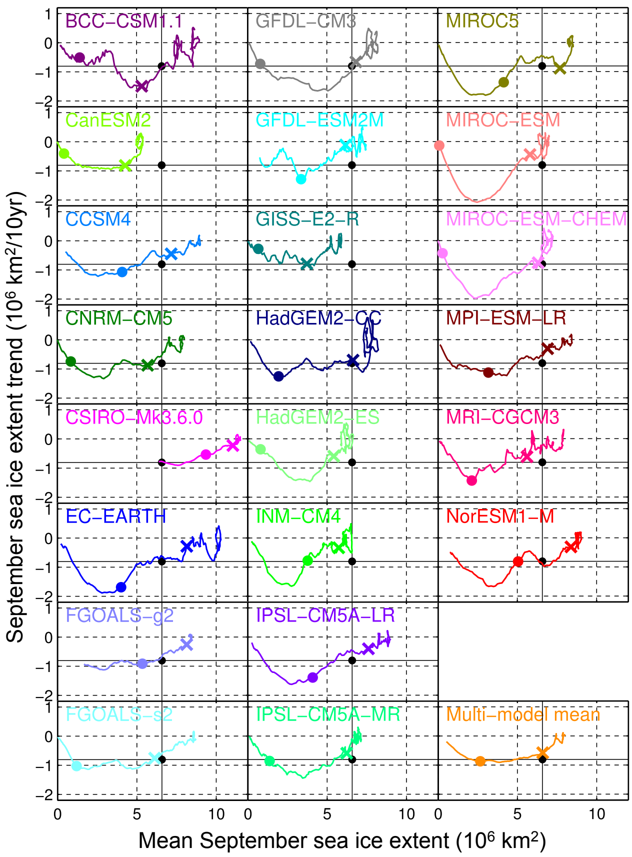

Figure 3. Phase space of the SSIE as simulated by the CMIP5 models: the mean SSIE over consecutive 32-yr periods from 1850 to 2100 (x-axis) are plotted against the SSIE linear trends over the corresponding periods. The colored crosses indicate the current (1979-2010) position of the model on its trajectory. The colored dots are the model position over 2030-2061. The black dots show the current (1979-2010) state of the observed Arctic SSIE in this phase space. The reader can visualize a dynamic version of this figure at `http://www.astr.ucl.ac.be/users/fmasson/CMIP5.gif` (also available as Online Supplement).