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Sensitivity of arctic summer sea ice coverage to global warming forcing: towards reducing uncertainty in arctic climate change projections

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ABSTRACT

Substantial uncertainties have emerged in Arctic climate change projections by the fourth Intergovernmental Panel on Climate Change assessment report climate models. In particular, the models as a group considerably underestimate the recent accelerating sea ice reduction. To better understand the uncertainties, we evaluated sensitivities of summer sea ice coverage to global warming forcing in models and observations. The result suggests that the uncertainties result from the large range of sensitivities involved in the computation of sea ice mass balance by the climate models, specifically with the changes in sea ice area (SIA) ranging from 0.09×10^6 to -1.23×10^6 km^2 in response to 1.0 K increase of air temperature. The sensitivities also vary largely across ensemble members in the same model, indicating impacts of initial condition on evolution of feedback strength with model integrations. Through observationally constraining, the selected model runs by the sensitivity analysis well captured the observed changes in SIA and surface air temperatures and greatly reduced their future projection uncertainties to a certain range from the currently announced one. The projected ice-free summer Arctic Ocean may occur as early as in the late 2030s using a criterion of 80% SIA loss and the Arctic regional mean surface air temperature will be likely increased by 8.5 ± 2.5 °C in winter and 3.7 ± 0.9 °C in summer by the end of this century.

1. Introduction

Significantly decreasing Arctic sea ice coverage is the most prominent feature and an important indicator of recently observed global-warming-forced climate changes. Although the fourth Intergovernmental Panel on Climate Change assessment report (IPCC AR4)/phase 3 of the Coupled Model Intercomparison Project (CMIP3) models unanimously project continuing, accelerating retreat of Arctic sea ice coverage in the 21st century under various global warming scenarios, a large spread in the rate of sea ice area (SIA)/extent decline occurred across the models and model ensemble members (e.g. Zhang and Walsh, 2006; Holland et al., 2006). In particular, the models as a whole obviously did not capture or considerably underestimated the rapidly decreased sea ice cover in the latest decade and the extreme event of sea ice cover loss in summer 2007 (e.g. Stroeve et al., 2007; Comiso et al., 2008; Zhang et al., 2008).

To improve understanding of the origins of the uncertainties and to enhance credibility of future Arctic climate change assessment, we analyse sensitivities of sea ice cover to changes in surface air temperature (SAT) in the IPCC AR4/CMIP3 models and observations for the time period of 1979–2004 when the required observational data sets are available, and use observations as a constraint to reduce uncertainties. The afore-mentioned discrepancies between models and observations inevitably raise a question: Do the observed rapid changes result from global warming forcing or intrinsic natural variability? Distinguishing between these two contributing factors has been difficult (e.g. Zhang et al., 2008). On the other hand, the climate models are self-evolving systems. It is unreasonable to expect models exactly capture the amplitude and phase of observed changes if these changes are part of intrinsic natural variability. The analysis approach employed here is applicable to a combination of internal variability and forced climate change (Forster and Gregory, 2006), and avoids this difficulty.

2. Data and approach

This study uses the updated monthly sea ice concentration (SIC) derived from the passive microwave satellite data since 1979 (Comiso et al., 2008), SAT observations obtained from buoys, manned drifting stations, and meteorological land stations from 1979 to 2004 (Rigor et al., 2000), and the gridded fields of SIC, sea ice thickness (SIT) and SAT from the participating

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climate models (20 models and 43 ensemble members in total) for the IPCC AR4/CMIP3 over the Arctic Ocean and the adjacent marginal seas. We analysed the model data from both simulations of 20th century climate (20C3M) with observed anthropogenic or natural forcing and projections of 21st century climate under the prescribed IPCC Special Report on Emission Scenarios (SRES) (IPCC, 2000) A1B scenario. Most modelling centres have performed multimember ensembles of the simulations.

The model outputs were archived by the Program for Climate Model Diagnosis and Intercomparison (PCMDI, http://www-pcmdi.llnl.gov/about/index.php) at the Lawrence Livermore National Laboratory. Table 1 in Zhang and Walsh (2006) lists these models and briefly summarizes their key characteristics. Details can be found at http://www-pcmdi.llnl.gov/ipcc/model_documentation/ipcc_model_documentation.php and by following the embedded modelling centres' website links.

Climate sensitivity to global warming forcing has been widely examined in model simulations and observations to measure the size of response by different models and to different forcings in either global or regional domain (e.g. Hansen et al., 1997; Colman, 2003; Bony and Dufresne, 2005). Gregory et al. (2004) and Forster and Gregory (2006) proposed a new approach to diagnose a climate feedback term from modelling and observational data using a linear definition expressed by $N - Q = -Y\Delta T_s$, where the net downward heat flux imbalance of climate system N is related to the external radiative forcing Q, the averaged SAT change ΔT_s and the climate feedback or sensitivity term Y. This methodology is applicable to both a transient forced climate change and a combination of internal variability and forced climate change.

The concept and approach of sensitivity analysis has been largely applied for various regions in low- and mid-latitudes, such as, sensitivity of tropical cloud radiative forcing to sea surface temperatures (Bony and Dufresne, 2005); and sensitivity of tropical outgoing long-wave radiation to sea surface temperatures (Lindzen and Choi, 2009). However, this analysis has not been well used for the Arctic region. Here, we employ this concept and approach to examine sensitivities of Arctic sea ice to global warming forcing in observations and IPCC AR4/CMIP3 models. The total sea ice mass imbalance over the polar cap represents an area-integrated net energy budget from surface exchanges with overlying atmosphere to the bottom oceanic heat flux, including natural and anthropogenic radiative forcing. We fit the overall sea ice volume anomalies ΔV_{ice} and the regionally averaged SAT anomalies ΔT_s to extract their response to forced climate change. The sea ice sensitivity to SAT associated with climate change is diagnosed through a regression relationship: $\Delta V_{\text{ice}} = -Y\Delta T_s$.

Sea ice volume is not a directly observed parameter, but SIA is an observed one and both the SIA and volume are inherently connected in physics and in model computations (Hibler, 1979). The scatter plot in Fig. 1 demonstrates these strong connections in the IPCC AR4/CMIP3 models. In the figure, the same symbol in the same colour represents the results from the same model runs. Although differences of SIA-volume diagrams emerge across different models, the annual and summer seasonal mean SIA and volume anomalies are tightly and positively correlated in the same model runs. The total SIA and volume anomalies are well fitted by a linear or quasi-linear function within each model or ensemble member. Therefore, we are able to use the changes in total SIA as a proxy indicator describing changes in total sea ice mass balance at the seasonal time scale in the following analysis; the above equation can be rewritten as $\Delta A_{\text{ice}} = -Y\Delta T_s$, where ΔA_{ice} is the total SIA anomaly.

Note that here we consider the total SIA over the entire polar cap. All sea ice dynamics associated with atmospheric and oceanic circulation forcings are internal processes. Contributions to changes in the total SIA by dynamic redistribution and throughflow via ocean passages or straits have been accordingly included. In addition, one may concern about wind-forced changes in the representation of sea ice in area and volume, such as ridging, in which SIA may decrease while volume might increase, leading to a negative correlation between area and

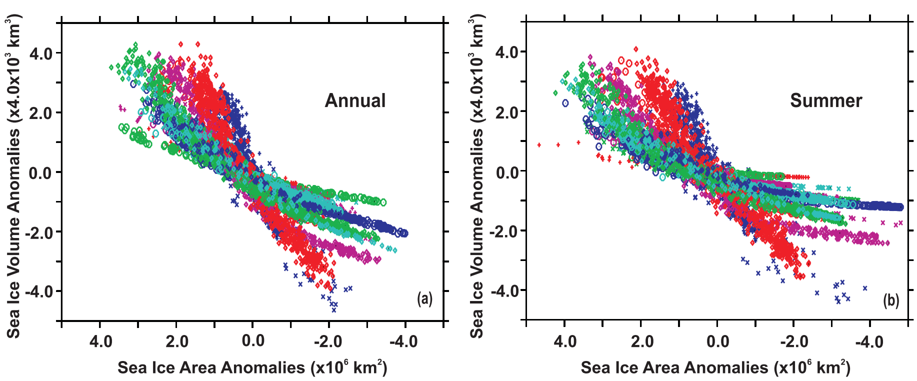

Fig. 1. Scatter plots of (a) annual mean and (b) summer seasonal mean SIA and sea ice volume anomalies from the IPCC AR4/CMIP3 climate models. The same symbol in the same colour represents a result from the same model runs, which indicates the annual and summer seasonal mean SIA and volume anomalies are highly and positively correlated.

volume. This process may appear at a short-time scale but does not occur in the annual and summer seasonal mean data, as illustrated by Fig. 1. In fact, during summer, reduced SIA enhances the energy absorption and hence warming over the Arctic through ice-albedo feedback and, in turn, results in a decrease in total volume. By the way, Fig. 1 shows that the slopes in a number of model runs become more flat when SIA and volume are much decreased. This reflects a circumstance in these model runs that sea ice thickness is thin and changes in sea ice volume are mainly influenced by the changes in SIA.

3. Results

3.1 Seasonality of summer SIA response to SAT change in observations

Changes in sea ice are not constant year-round. Observations and the IPCC AR4/CMIP3 model projections have shown a faster shrinkage of sea ice coverage in summer than in winter (e.g. Zhang and Walsh, 2006; Comiso et al., 2008). The fact of rapidly declined summer sea ice and the large diversity in model-projected rates of future summer sea ice decline have made the question of when the Arctic Ocean will become seasonally ice-free both a focal point of arguments in climate change studies and a critical issue for informed policy decision-making. Therefore, we focus on summer sea ice change in this study. We first examine seasonality of summer SIA response to SAT changes, that is, identify the season in which change in SAT is highly correlated with change in summer sea ice coverage, to lay the groundwork for the summer sea ice climate sensitivity analysis that follows.

Figure 2a shows a lag correlation analysis between summer (August–October) SIA anomaly and the Arctic regionally averaged SAT from the previous October to present September during 1979–2004. The changes in regionally averaged SAT can be considered to be a consequence of external forcing combined with integrative internal climate system feedback processes. Significant seasonal variations appear in the correlation of summer SIA changes with SAT anomalies. The summer SIA is strongly correlated with SAT in the melting season, rather than in the freezing season. This could be accounted for by a continuing net negative surface heat budget during the freezing season despite the strength of the global warming effect, allowing sea ice coverage to be retained over the entire Arctic Ocean. This may also imply that the effect of thermodynamics dominates that of dynamic redistribution in determining the overall summer sea ice coverage. We therefore elect to use the melting season SAT in the summer sea ice sensitivity analysis below.

3.2 Climate Sensitivity Diagnosis

For diagnosing the summer sea ice climate sensitivity term Y, we compute summer SIA and the melting season (April–September) regionally averaged SAT from observational data and from all model ensemble members/runs of the 20C3M and A1B simulations for 1979–2004 (Figs. 2b and c). The observed and simulated melting season SATs show a general upward trend, consistent with global warming trends. When comparing observational with simulation results we found a cold bias in a large number of model ensemble members, causing a considerable underestimation of SAT increase for this period. Both observed and simulated summer SIA exhibited a downward trend. However, unlike for SAT trends, these models either overestimated or underestimated summer SIA changes.

The inconsistent biases between simulated SAT and SIA relative to their observational counterparts indicates that SIA responds differently to SAT changes in different model runs. This inspired us to examine climate sensitivities of sea ice to SAT changes in observations and in model simulations. For this purpose, we created a scatter plot of summer SIA anomalies versus regionally averaged SAT anomalies, including all IPCC AR4/CMIP3 model ensemble runs and observations (Fig. 3). To compute the SIA and SAT anomalies, we first calculated their time-mean values in the observations and in each model simulation from 1979 to 2004 and then subtracted these mean values year-by-year from the original SIA and SAT time series. For detecting global-warming-forced changes, the ensemble-mean approach is generally employed, by which changes due to internal variability cancel out each other (e.g. Zhang and Walsh, 2006). Therefore, we first examine the overall relationship between summer SIA and SAT anomalies in all model runs.

Generally, these two parameters are well correlated in both observations and model outputs (Fig. 3): as SAT increases, summer SIA decreases. Compared with observations, model results are quite diverse; this is similar to comparison between observed and simulated rates of sea ice change (Zhang and Walsh, 2006). We used a linear regression analysis to identify the climate sensitivity terms in the observations (Y_{obs}) and the model outputs (Y_{mod}), which are quantified as $Y_{obs} = 0.56 \times 10^6\,km^2\,K^{-1}$ and $Y_{mod} = 0.43 \times 10^6\,km^2\,K^{-1}$. The climate sensitivity terms in the observations and the model outputs are significantly different as revealed by the significance testing through the Monte Carlo simulations, in which we conducted 1000 times of regression analysis with the scrambled sea ice anomaly data. The maximum climate sensitivity term in the Monte Carlo simulations $Y_{mod\,(Monte\,Carlo)} = 0.11 \times 10^6\,km^2\,K^{-1}$ is far below those in the original model data and the observations, indicating the identified climate sensitivity term above is unique and its difference from the observational one is not produced by random noises. Therefore, the overall modelled SIA change is less sensitive to a given SAT change than are observations, providing a physical insight into the statement by Stroeve et al. (2007) that observed sea ice change is faster than that projected by IPCC AR4/CMIP3 models as a whole.

Looking more closely at Fig. 3, we can readily find model simulation results that either underestimate or overestimate the

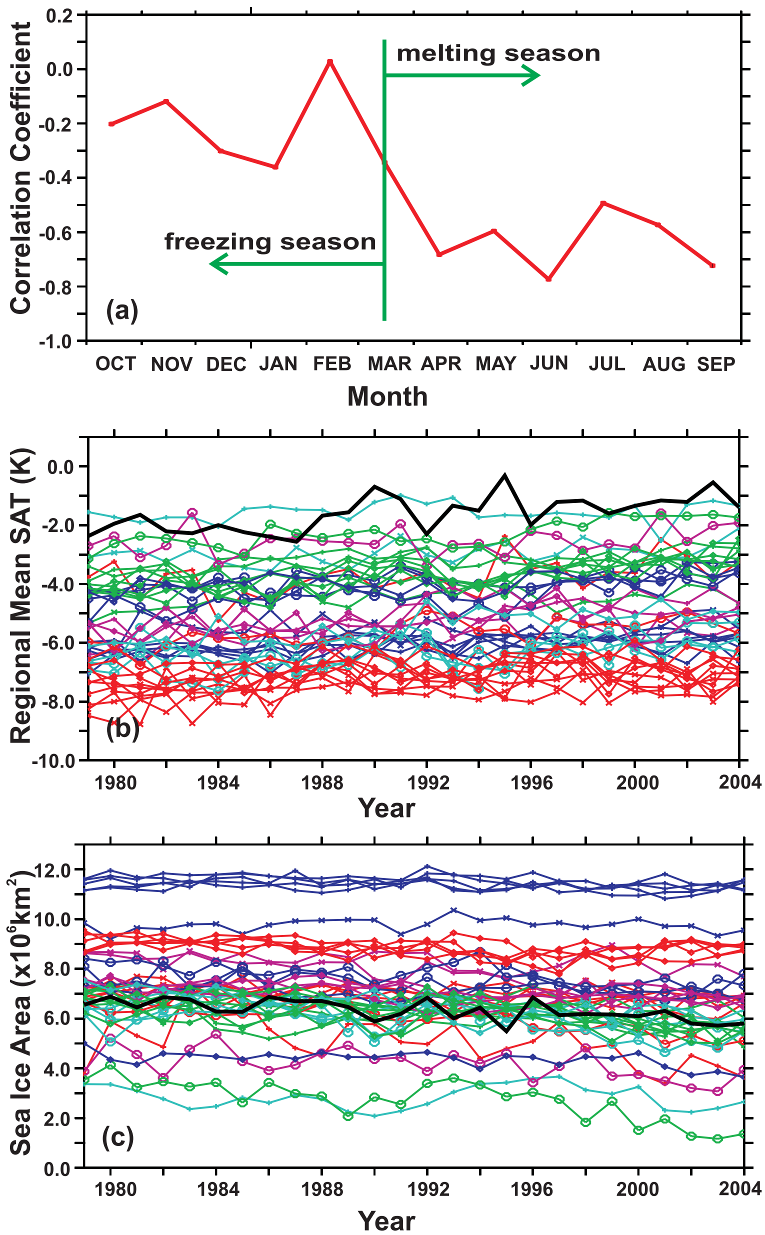

Fig. 2. (a) Lag-correlation coefficients of SIA and Arctic regionally averaged SAT from observations; (b) Arctic regionally averaged summer SAT and (c) summer SIA from observations (in black) and IPCC AR4/CMIP3 model simulations (in colours) during 1979–2004.

sensitivity term diagnosed in observations. To further understand this, we deconstruct the information shown in Fig. 3 to examine the sensitivity of each individual model ensemble run (Fig. 4). The sensitivity terms Y_{mod} range from -0.09×10^6 to 1.23 $\times$ 10^6 km^2 K^{-1}, indicating that some model runs project larger and others project smaller SIA changes in response to the same SAT changes; a few model runs show no clear relationship between SIA and SAT. The uncertainty measured by the standard deviation of the sensitivity terms Y_{mod} also varies across the model and the model ensemble members. Model run errors are obviously larger than observed.

It is worthwhile to note that different ensemble members of the same model demonstrate different sensitivities, perhaps implying that perturbed initial conditions could trigger different developments of feedback strength in model simulations. This actually can be inferred from the fact that the perturbed initial conditions not only impact the phase but also cause the large differences in amplitudes and long-term trends of the simulated SIA time series across the ensemble members of the same models. This can also be observed in the diversified ensemble simulations by using the same model in Alexander et al. (2004, fig. 13), where the 500-mb geopotential height responses to prescribed sea ice forcing are different not only in magnitude but also in sign. Impact of initial conditions on feedback loops in the models deserves a further investigation in additional studies.

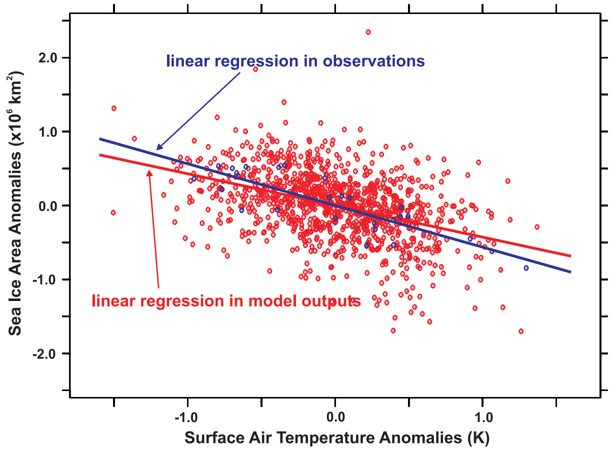

Fig. 3. Scatter plot and linear regression of summer SIA and SAT anomalies for all 43 model runs (red) and observations (blue). The SIA and SAT anomalies are computed from 1979 to 2004 when observational data are available. The anomalies are relative to the climatological mean for the same time period.

3.3 *observationally constrained projections of future climate changes*

A post-IPCC-AR4 effort seeks to reduce uncertainty and enhance credibility of future climate change projections through exploiting the existing model outputs. Statistical analysis was used to rank the IPCC AR4/CMIP3 models on the basis of differences between observed and modelled SAT over Alaska and other selected geographic domains (Walsh et al., 2008) and Arctic sea ice (Wang and Overland, 2009). The analysis presented here indicates that although the models as a group underestimate reality, individual model run results fall on both sides of observations. Therefore, in an additional step we used the physically based climate sensitivity information to select a subset of model runs to improve projections of future changes in both Arctic sea ice coverage and SAT.

We selected model runs that fell within the 99% observational confidence interval of 0.42×10^6 to 0.70×10^6 km^2 K^{-1}. The selected subset of model runs includes CNRM-CM3, GFDL-CM2.1, IPSL-CM4, MIROC3.2(medres)/run2, ECHAM5/MPI-OM/run3, CCSM3/run6 and UKMO- HadGEM1. Each of the first three and the last models has only one run; the rest have

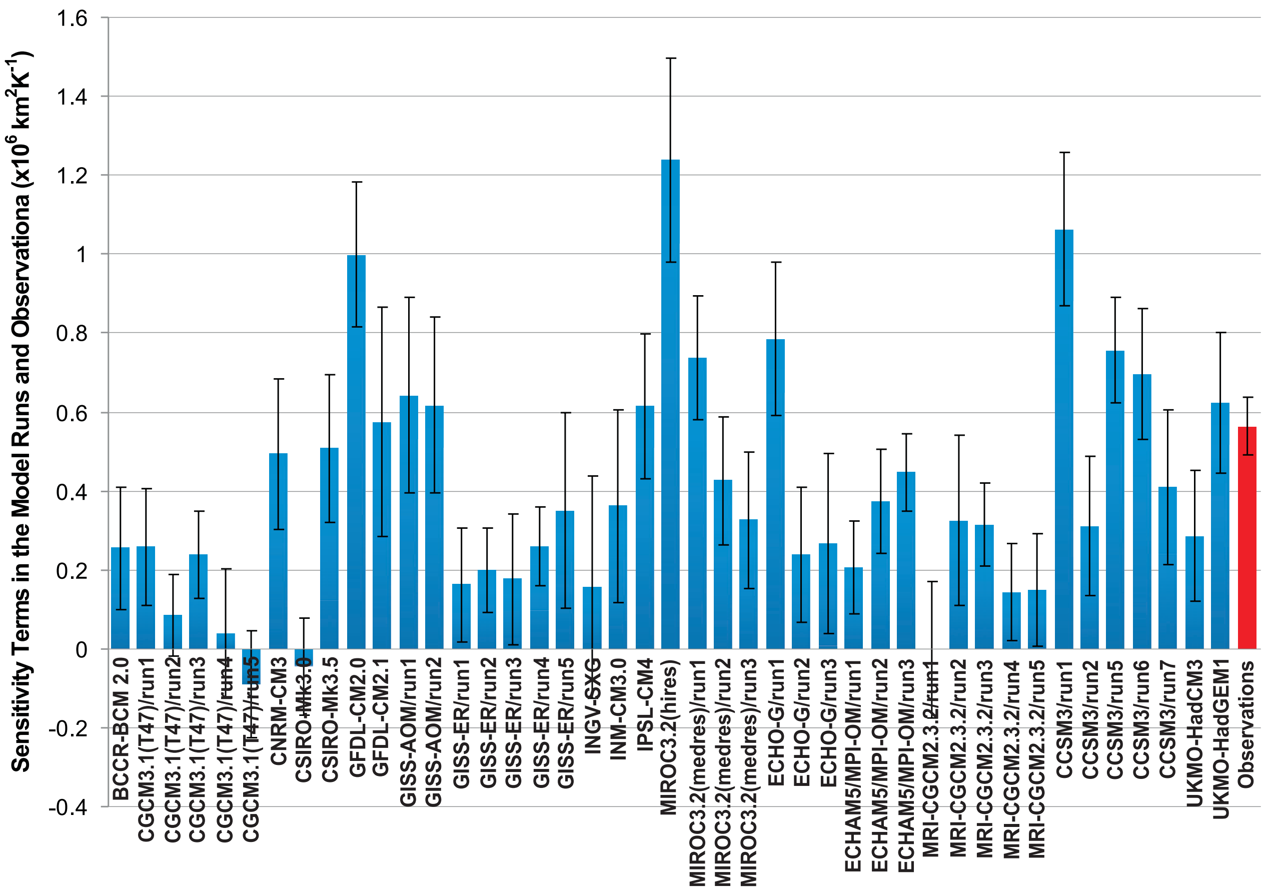

Fig. 4. Diagnosed sensitivity term for all model runs (blue) and observations (red) with standard deviations shown by the vertical lines in each column.

multiple runs in the data archive. All selected models employ a sophisticated treatment of sea ice physics by using viscous-plastic or elastic-viscous-plastic rheology and thickness distribution. Notably, the selected model simulations capture occurrence of rapid change episodes (Holland et al., 2006); such episodes have recently been manifested in reality (e.g. Comiso et al., 2008; Zhang et al., 2008). Interestingly, new versions of the same models (e.g. GFDL-CM2.1 versus GFDL-CM2.0, UKMO-HadGEM1 versus UKMO-HadCM3) perform better than their predecessors, suggesting that improved physics is essential for reducing uncertainty.

Figures 5a and b display 20th and 21st century summer minimum SIA anomalies simulated and projected by all model runs and by the selected subset of model runs, respectively. Comparison of these two figures indicates that the observationally constrained selection of the subset tremendously reduced the spread of future sea ice cover change projections and well captured the observed SIA fluctuations and trends. The extreme event of sea ice cover loss in summer 2007 also well falls into the simulated range of changes. This is different from the conclusion by Stroeve et al. (2007). The reason could be that Stroeve et al. focused on the ensemble mean of all models runs, while we analysed each individual runs. The ensemble mean of the subset suggests the Arctic Ocean will likely become nearly ice-free in summer around 2037–2065, when 80% of the present-day SIA will be lost and only a million square kilometres will remain around the Canadian Archipelago. The criterion of one million square kilometres is the same as the value chosen by Wang and Overland (2009). It is worthwhile to mention here that the timing for Arctic to become ice-free sensitively depends on choice

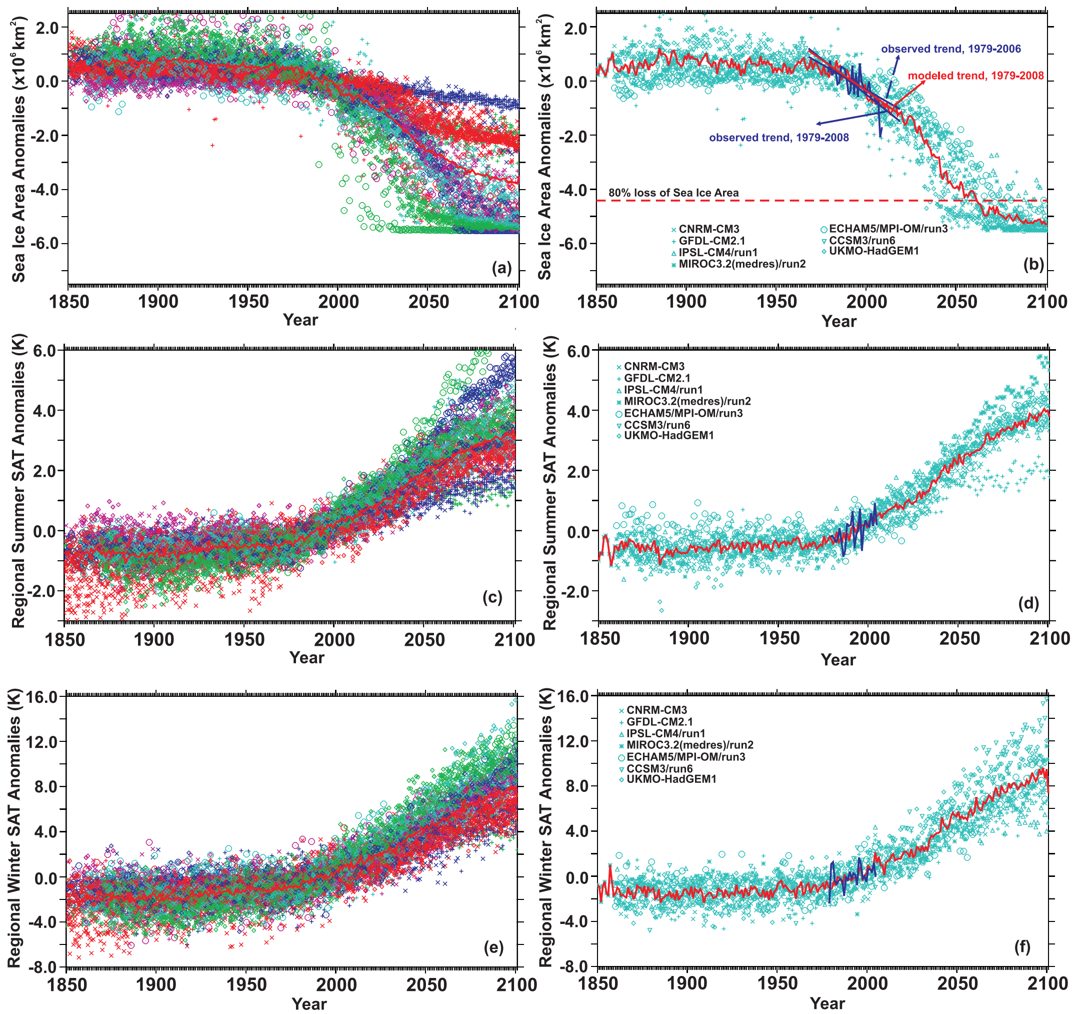

Fig. 5. Sea ice area anomalies in (a) all model runs and (b) the selected subset of model runs; summer SAT anomalies in (c) all model runs and (d) the selected subset of model runs; and winter SAT anomalies in (e) all model runs and (f) the selected subset of model runs. The anomalies are adjusted by the 1979–2004 climatologies. The red and blue lines represent the multimodel-ensemble mean and observations, respectively. The different symbol in different colour represents a result from different model runs.

of a criterion. When choosing a criterion of 90% of loss of the present-day SIA, the projected ice-free summer Arctic Ocean may occur in 2050–2072. Projection of decadal-scale changes has recently drawn much attention. This subset indicates a summer minimum SIA of $3.9 \times 10^6\,\text{km}^2$ during 2020–2030, an approximate 28.4% reduction below the 1979–2004 mean.

As discussed above, overall model sensitivity is weaker than real-world sensitivity, and the sea ice cover change projected by the models as a group is slower than the observed change (Stroeve et al., 2007). The subset of selected model runs demonstrates an obvious improvement comparing with all model runs as a group. The former shows a decreasing rate of SIA at $-0.48 \times 10^6\,\text{km}^2$ per decade, while the latter at $-0.32 \times 10^6\,\text{km}^2$ per decade for the time period of 1979–2008. We further examined this issue and found that the subset of selected model runs captures, or with just slight overestimates of, the SIA declining trend shown in the 1979–2006 observations (Fig. 5b). The extreme 2007 decrease in SIA slightly increases the observed SIA declining trend (Fig. 5b). However, global-warming forcing obviously cannot be solely responsible for this greatly decreased SIA. An extreme shift in the atmospheric circulation spatial pattern plays a pivotal role (Zhang et al., 2008). If this shift is partially a manifestation of natural variability, it is reasonable to expect the SIA declining trend to weaken. In fact, sea ice cover did not continue to plummet in 2008 and a slight recovery tendency has been observed since then. The sensitivity-constrained projection of global-warming-forced sea ice changes in this study does not depend on the single year's event in 2007.

Changes in SIA and SAT are interactively tied together through surface energy budgets. In particular, the observed SAT during 1979–2004 has been included in the sensitivity above, providing a constraint on the modelled SAT. Therefore, along with the new projection of sea ice change, we also assess SAT changes by using the same subset of model runs. The uncertainty of SAT anomalies projected by this subset is also substantially reduced (Figs. 5d and f) compared to projections by all model runs (Figs. 5c and e). The regional mean SAT is projected to increase $8.5 \pm 2.5\,^\circ\text{C}$ in winter and $3.7 \pm 0.9\,^\circ\text{C}$ in summer by the end of this century. These increases would be $2.2 \pm 0.7\,^\circ\text{C}$ ($4.9 \pm 1.1\,^\circ\text{C}$) in winter and $1.0 \pm 0.4\,^\circ\text{C}$ ($2.2 \pm 0.5^\circ\text{C}$) in summer around 2020–2030 (2040–2050), greater than is indicated in all model ensemble means.

4. Concluding remarks

Substantial uncertainties exist in the IPCC AR4/CMIP3 model simulated and projected climate changes in response to greenhouse-gas-emissions forcing (Solomon et al., 2007), among which the changes in sea ice coverage demonstrate a large spread (e.g. Holland et al., 2006; Zhang and Walsh, 2006; Stroeve et al., 2007). To understand the origin of the uncertainties, we applied the climate sensitivity analysis concept and approach (e.g. Gregory et al., 2004; Bony and Dufresne, 2005; Forster and Gregory, 2006) to diagnose summer sea ice cover sensitivity to changes in Arctic regional SAT in model runs and observations. The results provide a physical insight into model uncertainties, compared with statistical comparison and analysis, suggesting that much uncertainty results from the large range of climate sensitivities involved in the computation of sea ice mass balance and feedback processes in the climate models, and providing a new approach for evaluating model performance and reducing uncertainties of model-based future Arctic climate change assessments.

An ongoing post-IPCC-AR4 effort seeks to reduce model uncertainties and enhance credibility of climate change projections through, for example, selecting a subset of models (e.g. Walsh et al., 2008; Wang and Overland, 2009). We used the derived sensitivity from observations to constrain the selection of a subset of model runs, including CNRM-CM3, GFDL-CM2.1, IPSL-CM4, MIROC3.2(medres)/run2, ECHAM5/MPI-OM/run3, CCSM3/run6 and UKMO- HadGEM1. All models included in the subset employ a sophisticated treatment of sea ice physics and capture rapid changes episodes. The subset clearly demonstrates a substantial reduction of model output spread and captures the observed SIA declining trend subject to a modulation by natural variability; the extreme event of sea ice cover loss in summer of 2007 also fall into the range of changes simulated by the subset. The Arctic Ocean is projected to be ice-free in summer between 2037 and 2065, and the regional mean SAT will be likely increased by 8.5 and 3.7 °C in winter and summer by the end of this century under the A1B global warming scenario. Sensitivity analysis here may have important implication for enhancing Arctic climate predictability.

In this study, we evaluated an overall sensitivity of summer sea ice changes to the Arctic regional mean SAT in each individual model run and compared them with observations. To get an in-depth insight into the large spread of the sensitivities across the multi-model ensemble members, we need to untangle sea ice energy budget terms to examine their climate sensitivity, and analyse evolutions of associated feedback strength with model integration. Meanwhile, models may have different capabilities in simulating various spectra of variability or oscillations. It would be worthwhile to evaluate impacts of these differences on the overall sensitivity. In particular, the relatively short analysis time period of the climate sensitivity from 1979 to 2004 may fail resolve entire cycle of some low-frequency variability, bringing about uncertainties to the ratio of SIA to SAT. With an increase in available data length, uncertainties of SIA sensitivity to changes in SAT could be further narrowed for an improved sensitivity evaluation. Finally, although this study focuses on the greenhouse-forcing scenario A1B, the findings are probably valid for or the approach can straightforwardly be extended to other scenarios, for example, B1, A2. All of these would be interesting follow-up work to do after the present study.

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References

Alexander, M., Bhatt, U. S., Walsh, J. E., Timlin, M. S., Miller, J. S. and co-authors. 2004. The atmospheric response to realistic Arctic sea ice anomalies in an AGCM during winter. *J. Clim*. **17**, 890–905.

Bony, S. and Dufresne, J. L. 2005. Marine boundary layer clouds at the heart of tropical cloud feedback uncertainties in climate models. *Geophys. Res. Lett.* **32**, L20806, doi:10.1029/2005GL023851.

Colman, R. 2003. A comparison of climate feedbacks in general circulation models. *Clim. Dyn.* **20**, 865–873.

Comiso, J. C., Parkinson, C. L., Gersten, R. and Stock, L. 2008. Accelerated decline in the Arctic sea ice cover. *Geophys. Res. Lett.* **35**, L01703, doi:10.1029/2007GL031972.

Forster, P. M. D. and Gregory, J. M. 2006. The climate sensitivity and its components diagnosed from earth radiation. *J. Clim.* **19**, 39–52.

Gregory, J. M., Ingram, W. J., Palmer, M. A., Jones, G. S., Stott, P. A. and co-authors. 2004. A new method for diagnosing radiative forcing and climate sensitivity. *Geophys. Res. Lett*. **31**, L03205, doi:10.1029/2003GL018747.

Hansen, J., Sato, M. and Rueby, R. 1997. Radiative forcing and climate response. *J. Geophys. Res.* **104**, 30997–31022.

Hibler, W. D. 1979. A dynamic thermodynamic sea ice model. *J. Phys. Oceanogr.* **9**, 815–846.

Holland, M. M., Bitz, C. M. and Tremblay, B. 2006 Future abrupt reductions in the summer Arctic sea ice. *Geophys. Res. Lett.* **33**, L23503, doi:10.1029/2006GL028024.

Lindzen, R. S. and Choi, Y. S. 2009. On the determination of climate feedbacks from ERBE data. *Geophys. Res. Lett.* **36**, L16705, doi:10.1029/2009GL039628.

Rigor, I., Colony, R and Martin, S. 2000. Variations in surface air temperature observations in the Arctic, 1979–1997. *J. Clim.* **13**, 896–914.

Solomon, S., Qin, D., Manning, M., Marquis, M., Averyt, K. and co-authors. 2007. *The Physical Basis of Climate Change*. Cambridge University Press, New York, USA.

Stroeve, J., Holland, M. M., Meier, W., Scambos, T. and Serreze, M. 2007. Arctic sea ice decline: faster than forecast. *Geophys. Res. Lett.* **34**, L09501, doi:10.1029/2007GL029703.R

Walsh, J. E., Chapman, W., Romanovsky, V., Christensen, J. H. and Stendel, M. 2008. Global climate model performance over Alaska and Greenland. *J. Clim.* **21**, 6156–6174.

Wang, M. and Overland, J. E. 2009. A sea ice free summer Arctic within 30 years?. *Geophys. Res. Lett.* **36**, L07502, doi:10.1029/2009GL037820.

Zhang, X. and Walsh, J. E. 2006. Toward a seasonally ice-covered Arctic Ocean: scenarios from the IPCC AR4 model simulations. *J. Clim.* **19**, 1730–1747.

Zhang, X., Sorteberg, A., Zhang, J., Gerdes, R. and Comiso, J. C. 2008. Recent radical shifts of atmospheric circulations and rapid changes in Arctic climate system. *Geophys. Res. Lett.* **35**, L22701, doi:10.1029/2008GL035607.