8. THE ROLE OF GLOBAL CLIMATE CHANGE IN THE EXTREME LOW SUMMER ARCTIC SEA ICE EXTENT IN 2012

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Introduction. Satellite observations reveal a record-breaking low September Arctic sea ice extent (ASIE) of 3.61 million km2 in 2012. Over the satellite period (1979–2012), September ASIE declined 49% compared to the 1979–2000 climatology of 7.04 million km2. The extreme low summer ASIE in 2012 continued the rapid downward trend seen in the early 21st century. The observed decline in ASIE has been attributed in large part to greenhouse gas forcing (Hegerl et al. 2007), and some climate models project that the Arctic Ocean will be ice free in summer within a few decades (Stroeve et al. 2012; Massonnet et al. 2012). Extrapolations of recent trends in ice volume would predict a nearly ice-free summer in less than a decade (e.g., Overland and Wang 2013). In this study, we compare both the observed September 2012 ASIE anomaly and the 2001–12 trend with model-simulated internal variability and response to climate forcings. We use Coupled Model Intercomparison Project Phase 5 (CMIP5) simulations (Taylor et al. 2012) to explore whether the observed summer 2012 ASIE anomaly and the 2001–12 trend can be explained as a response to anthropogenic and natural forcing and how they relate to the observed increase in global mean surface air temperature (SATgm).

Data and methods. Our observed September ASIE analysis for the satellite period 1979–2012 uses the National Snow and Ice Data Center (NSIDC) sea ice index (Fetterer et al. 2009) and observed September SAT_{gm} data is from the NCEP/NCAR Reanalysis (Kalnay et al. 1996). The model outputs from the CMIP5 archive combine 20th century All-Forcing (anthropogenic and natural combined) simulations with the representative concentration pathway (RCP) 4.5 future emission scenario experiments for years beyond 2005. We selected 19 CMIP5 models, with 88 All-Forcing ensemble members, requiring each model have at least three RCP4.5 ensemble members and 100 years of preindustrial control run. For observations and models, ASIE is defined as total Northern Hemisphere marine area with sea ice concentrations of at least 15%.

Both observed and modeled ASIE and SAT_{gm} anomalies are referenced to means for 1979–2000, a relatively stable period for ASIE and the same period used by NSIDC. Long-term drifts in the preindustrial control runs of each model were subtracted from all experiments. To derive the range of internal variability for each model, we drew 1000 random samples of 34-year segments from the detrended preindustrial control simulation and derived the anomalies using the first 22-year average as the climatology, as was done with observations. We then calculated the 5th to 95th percentile ranges ($PR_{5\text{-}95}$) of the anomalies and trends from the 1000 random samples. The $PR_{5\text{-}95}$ of the multimodel distribution was constructed using 19 000 samples—1000 from each of the 19 control simulations. The $PR_{5\text{-}95}$ of the multimodel distribution of forced response was constructed by adding random samples from each model's control simulation to that model's ensemble mean from the forced (All-Forcing historical/RCP4.5) experiments. This methodology is similar to that in Knutson et al. (2013) for surface temperature. Thus, the total distribution represents the uncertainties due to both the difference in the models' ensemble-mean forced response and the internal variability of each model.

If the observed anomaly or trend (for either ASIE or SAT_{gm}) lies below the $PR_{5\text{-}95}$ of the multimodel distribution of internal (control run) variability alone, we classify the observed trend/anomaly as "detectable"; if it is both detectable and within the $PR_{5\text{-}95}$ of the multimodel distribution of the forced response, we interpret it as "detectable and consistent with All-Forcing runs"; if the trend/anomaly is detectable but below the $PR_{5\text{-}95}$ of the All-Forcing runs, we interpret it as "detectable and significantly stronger than the models' ensemble All-Forcing response."

Results. The observed September ASIE in 2012 (Fig. 8.1a,c) was an extreme low anomaly (-3.41 million km^2) for the 34-year record. This anomaly was much lower than the simulated multimodel ensemble mean anomaly for 2012 of -1.5 million km^2 and even lies below the $PR_{5\text{-}95}$ of the multimodel distribution of both internal variability (-1.0 million km^2) and forced response (-2.9 million km^2). Hence the ASIE anomaly is detectable and significantly stronger than the ensemble All-Forcing response. Meanwhile the observed September SAT_{gm} anomaly of 0.55 K in 2012

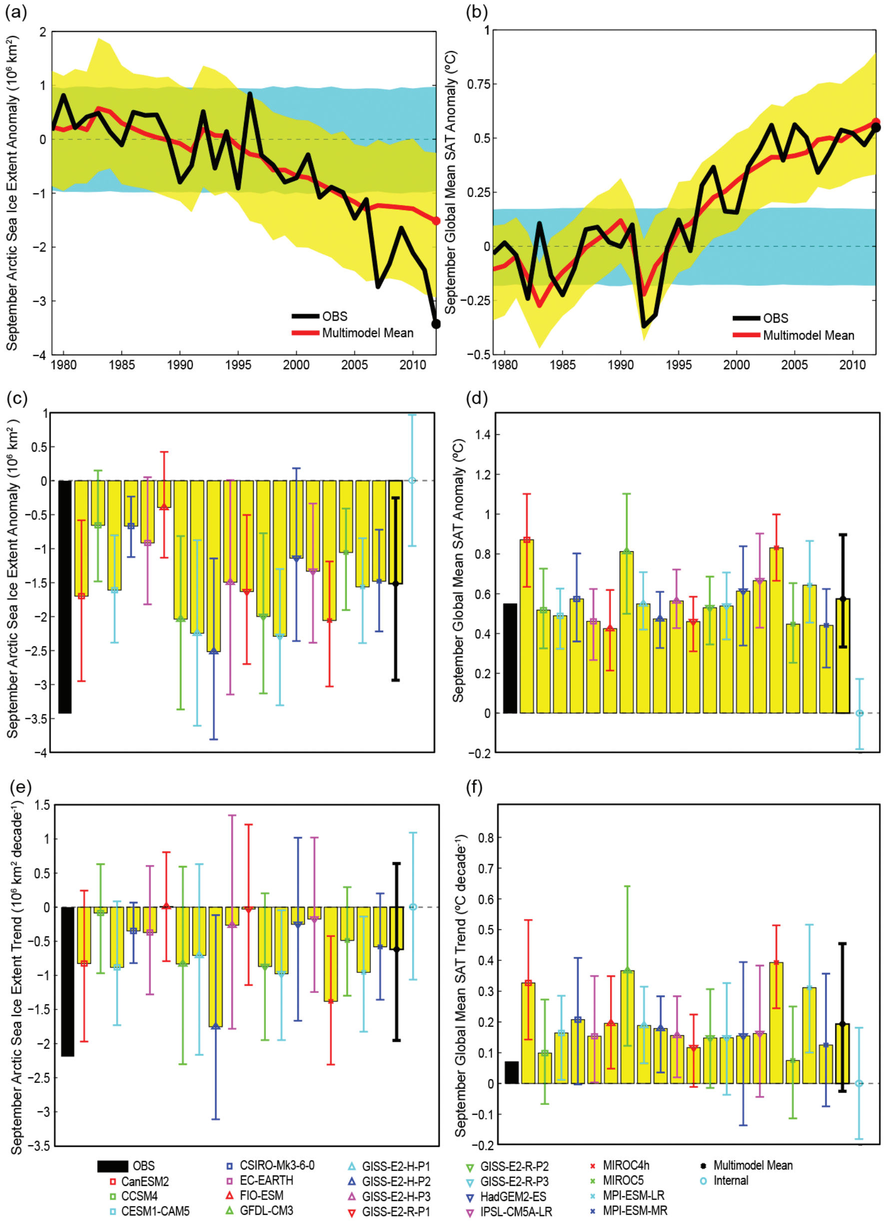

Fig. 8.1. (a) September Arctic sea ice extent (ASIE) anomalies. (b) September global mean surface air temperature (SAT_{gm}) anomalies. In (a) and (b) the thick black lines are observations, and the thick red lines are multimodel ensemble mean from 19 CMIP5 models (All-Forcing historical simulations through 2005 combined with RCP4.5 projections for the period after 2005). The yellow shading is the 5th to 95th percentile range (PR_{5-95}) of the multimodel distribution of forced response. The cyan shading is the PR_{5-95} of internal variability constructed from the detrended multimodel control simulations. (c) September ASIE anomaly for the year 2012. (d) September SAT_{gm} anomaly for the year 2012. (e) September ASIE trend for the period 2001–12. (f) September SAT_{gm} trend for the period 2001–12. In (c)–(f), the black bars are the observations. The yellow bars with color error bars are ensemble means from 19 CMIP5 models and the PRs_{5-95} of internal variability constructed from each model's control simulation. The yellow bars with the thick black error bars are the multimodel ensemble means and the PRs_{5-95} of the multimodel distributions of forced response. The stand-alone cyan error bars without yellow data bars depict the PRs_{5-95} of internal variability constructed from multimodel control simulations. All anomalies are relative to the climatology for 1979–2000.

(relative to 1979–2000) is not warmer than the peaks in 2003 and 2005 but matches well with the CMIP5 multimodel ensemble mean and is detectable and consistent with the models' All-Forcing response (Fig. 8.1b,d).

The observed summer ASIE declined precipitously and diverged from the simulated multimodel ensemble mean in the early 21st century (Fig. 8.1a). The observed decline trend of September ASIE over the period 2001–12 (-2.2 million km^2 $decade^{-1}$), is detectable but significantly more rapid than the CMIP5 All-Forcing ensemble-mean trend of -0.6 million km^2 $decade^{-1}$ (Fig. 8.1e). Meanwhile, the observed warming trend of September SAT_{gm} over the same period (0.07 K $decade^{-1}$) is much less than the CMIP5 ensemble-mean trend (0.19 K $decade^{-1}$), and is not detectable compared to internal variability; however, it is not significantly different from the All-Forcing response (Fig. 8.1f). The observed September ASIE decline trend for 2001–12 is more rapid than the ensemble mean trend in any of the 19 CMIP5 models, while the observed September SAT_{gm} warming trend over the same period is *less* than the ensemble mean trend in any of the same 19 models (Fig. 8.1e,f). The PRs_{5-95} for the All-Forcing responses (Fig. 8.1c-f) do not include the uncertainty in each model's ensemble mean caused by the model's limited number of available ensemble members—an issue discussed in more detail in Knutson et al. (2013).

Figure 8.2 shows the joint plots of September ASIE and SAT_{gm} for the 2012 anomalies and the 2001–12 trends. For 2012, the observed September ASIE anomaly lies outside the multimodel $PR_{5\text{-}95}$ for the All-Forcing experiments, although the observed September SAT_{gm} anomaly is consistent with All-Forcing experiments (Fig. 8.2a). The observed September ASIE decline trend for 2001–12 is so rapid that it lies outside the multimodel $PR_{5\text{-}95}$ of the All-Forcing runs, but the observed September SAT_{gm} warming trend for the same period is so small that it is not detectable (Fig. 8.2b). The above findings raise the question as to why such a rapid decline in the summer ASIE occurred at the same time as the relatively "flat" trend in the SAT_{gm}.

The discrepancy between observations and multimodel simulations of both 2012 and the early 21st century trend (Fig. 8.2a,b) suggests several possibilities: (i) most CMIP5 models may underestimate the polar amplification of temperature change and the decrease of summer ASIE in the response to a given forcing; (ii) internal variability of summer ASIE may be underestimated by the models; (iii) there may be important errors/omissions in forcings used in the models that can directly or indirectly affect summer ASIE; or (iv) the observations represent an extreme, rare scenario, i.e., outside the $PR_{5\text{-}95}$. Concerning the second possibility, a previous study (Winton 2011) suggested that substantial natural variability is necessary to reconcile models with observations. For example, if the amplitude of the internal variability in all 19 control simulations is increased by 25%, then the observed September ASIE decline trend for 2001–12 will fall within the multimodel $PR_{5\text{-}95}$ of the All-Forcing runs. If the internal variability of ASIE is increasing due to the lower base state values (e.g., Goosse et al. 2009), our use of preindustrial control runs may lead to a systematic underestimation of the present levels of internal variability. Concerning the fourth possibility, we plotted all 19 000 random samples of summer ASIE trends, including those outside the models' $PRs_{5\text{-}95}$ of either internal variability or forced response, as dots in Fig. 8.2. The observed summer ASIE trend in the early 21st century is not outside of this model range, indicating that it can possibly be explained as an extreme, rare scenario in either the "pure internal variability" case (cyan dots) or the "forced plus internal variability" case (orange dots; Fig. 8.2b). ASIE anomalies for 2012 remain outside the complete (19 000-member) sample of internal variability.

Among the 19 CMIP5 models, the GISS-E2-H-P2 model simulated the largest 2012 summer ASIE reduction and the largest decreasing trend for 2001–12 (Fig. 8.1c,e). However, this model has unrealistically low climatological summer ASIE (4.0

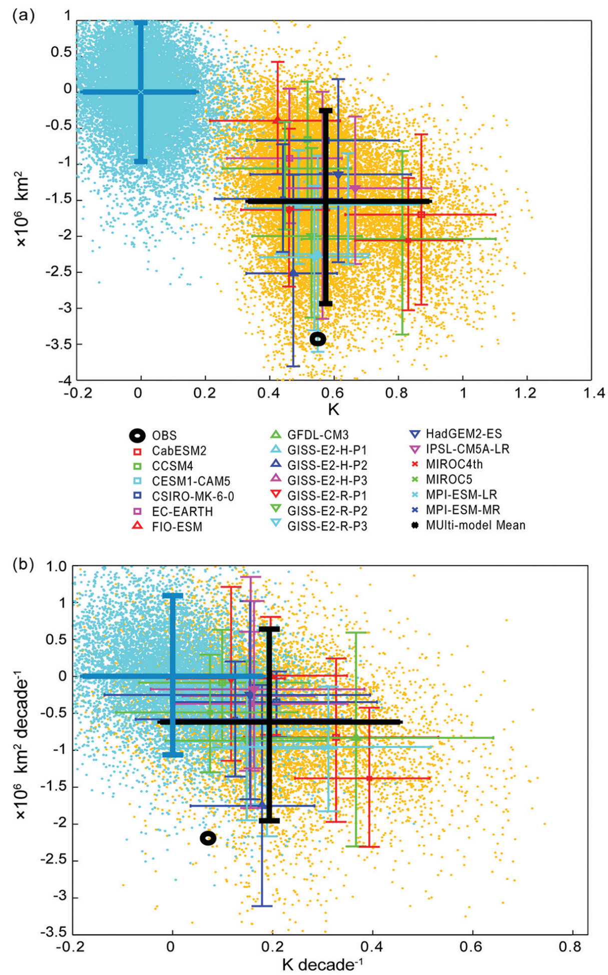

Fig. 8.2. (a) Anomalies of September sea ice extent (ASIE) versus September global mean surface air temperature (SAT_{gm}) for the year 2012 and (b) trends of September ASIE versus September SAT_{gm} for the period 2001–12 in observation (OBS) and 19 CMIP5 models. The thin color error bars are the $PRs_{5\text{-}95}$ in ASIE and SAT_{gm} respectively for each CMIP5 model. The thick black cross and error bars are multimodel ensemble mean and the $PRs_{5\text{-}95}$ of multimodel distributions of forced response. The thick blue error bars are the $PRs_{5\text{-}95}$ of multimodel distributions of internal variability. The orange scatter dots are 19 000 random samples of multimodel distributions of forced response in both ASIE and SAT_{gm}, sampled together. The cyan scatter dots are 19 000 random samples of internal variability in both ASIE and SAT_{gm} constructed from multimodel control simulations, sampled together. All anomalies are relative to the climatology of 1979–2000.

million km^2) for the reference period 1979–2000, compared to observations (~7.0 million km^2).

Conclusions. Comparisons between observations and 19 CMIP5 models reveal that the 2012 ASIE anomaly and the rapid decline of ASIE in the early 21st century are very rare occurrences in the context of these models and their responses to anthropogenic and natural forcing combined. The observed 2012 record low in ASIE is extremely unlikely to have occurred due to internal climate variability alone, according to the models, i.e., and has a much greater likelihood of occurrence in the "forced plus internal variability" scenario. The 2012 anomaly is significantly stronger than the multimodel's mean response to both anthropogenic and natural forcing combined. In addition, the observed September ASIE decline trend for 2001–12 is much more rapid than in the previous decades and even lies outside of the $PR_{5\text{-}95}$ of the multimodel distribution of forced responses, despite the observed September SAT_{gm} warming trend for the same period being smaller than in the previous two decades.