Arctic sea ice decline: Faster than forecast

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Received 15 February 2007; accepted 26 March 2007; published 1 May 2007.

[1] From 1953 to 2006, Arctic sea ice extent at the end of the melt season in September has declined sharply. All models participating in the Intergovernmental Panel on Climate Change Fourth Assessment Report (IPCC AR4) show declining Arctic ice cover over this period. However, depending on the time window for analysis, none or very few individual model simulations show trends comparable to observations. If the multi-model ensemble mean time series provides a true representation of forced change by greenhouse gas (GHG) loading, 33–38% of the observed September trend from 1953–2006 is externally forced, growing to 47–57% from 1979–2006. Given evidence that as a group, the models underestimate the GHG response, the externally forced component may be larger. While both observed and modeled Antarctic winter trends are small, comparisons for summer are confounded by generally poor model performance. **Citation:** Stroeve, J., M. M. Holland, W. Meier, T. Scambos, and M. Serreze (2007), Arctic sea ice decline: Faster than forecast, *Geophys. Res. Lett.*, *34*, L09501, doi:10.1029/2007GL029703.

1. Introduction

[2] Climate models are in near universal agreement that Arctic sea ice extent will decline through the 21st century in response to atmospheric greenhouse gas (GHG) loading [*Zhang and Walsh*, 2006]. Through fostering large heat fluxes to the atmosphere, delayed autumn and winter ice growth will promote increases in surface air temperature (SAT) over the Arctic Ocean that are outsized compared to the globe as a whole [*Holland and Bitz*, 2003]. Ice loss will also likely influence mid-latitude patterns of atmospheric circulation and precipitation [e.g., *Sewall and Sloan*, 2004].

[3] From 1953–2006, Arctic sea ice extent at the end of the summer melt season in September has declined at a rate of −7.8%/decade. Over the period of modern satellite observations (1979–2006) the trend is even larger (−9.1% per decade). Trends for March (the climatological maximum ice extent), while much smaller, are also downward, at −1.8% and −2.9%/decade over these two time periods.

[4] Although it is tempting to attribute these statistically significant (99% level) trends to GHG loading, the observed sea ice record has strong imprints of natural variability. An overall rise in SATs over the Arctic Ocean is consistent with ice loss [*Comiso*, 2003], but rates of change depend strongly on season, the time period analyzed, as well as the data set employed [*Serreze and Francis*, 2006]. Variability in the Northern Annular Mode (NAM) and other atmospheric patterns has played a role through impacts on ice circulation [e.g., *Rigor and Wallace*, 2004], as have changes in oceanic heat transport [*Polykov et al.*, 2005; *Shimada et al.*, 2006]. However, a role of GHG loading finds strong support in the recent study of *Zhang and Walsh* [2006]. They show that from 1979–1999 the multi-model mean annual trend from models participating in the Intergovernmental Panel on Climate Change Fourth Assessment Report (IPCC AR4) is downward, as are trends from most individual models.

[5] This paper makes three points: (1) if the IPCC AR4 multi-model mean time series properly reflect the response to GHG loading, then both natural variability and forced change have been strong players in the observed September and March trends, with the latter becoming more dominant during 1979–2006; (2) given evidence that that the IPCC models as a group are too conservative regarding their GHG response, the GHG imprint may be larger; and (3) there is more consistency between models and observations regarding much smaller sea ice trends in the Antarctic.

2. Data and Observations

[6] Gridded fields of observed and modeled sea ice concentration were used to derive comparative time series of sea ice extent (summing the area of all grid cells with at least 15% ice concentration) for September and March, representing the climatological minimum and maximum extent in the Arctic and vice versa in the Antarctic.

[7] Observations for the Arctic make use of a blended record described by *Meier et al.* [2007] spanning 1953–2006. The primary source is the Hadley Centre sea ice and sea surface temperature data set (HadlSST) [*Rayner et al.*, 2003]. Prior to 1979, estimates of sea ice concentration are based on early satellite observations, aircraft and ship reports. After 1979, reliance is placed on satellite passive microwave observations using the NASA Team sea ice algorithm [*Cavalieri et al.*, 1996] and augmented by *Fetterer and Knowles* [2004]. A significant inconsistency occurs between 1996 and 1997 when the Had1SST developers switched to a different source for sea ice concentration. To improve consistency, values for 1997–2006 were reprocessed using updated sea ice concentrations based on the NASA team algorithm. In the Antarctic, use is made of a combined passive microwave record starting in 1973 [see *Cavalieri et al.*, 2003] adjusted to match the ongoing record through 2006.

[8] IPCC AR4 simulations are available from the Program for Climate Model Diagnosis and Intercomparison (PCMDI, available at http://www-pcmdi.llnl.gov/about/index.php). All simulations apply external forcings over

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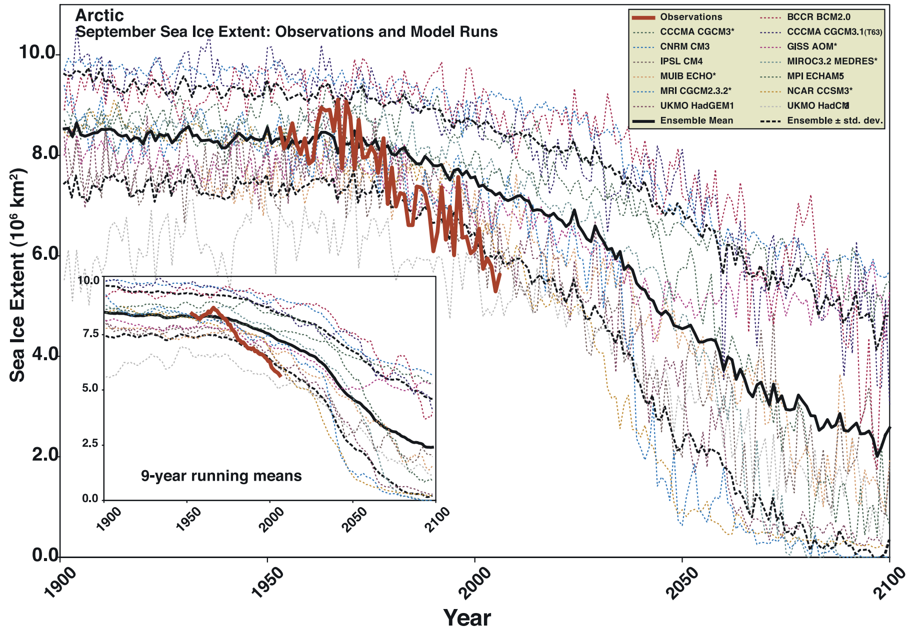

Figure 1. Arctic September sea ice extent ($\times$ 10^6 km^2) from observations (thick red line) and 13 IPCC AR4 climate models, together with the multi-model ensemble mean (solid black line) and standard deviation (dotted black line). Models with more than one ensemble member are indicated with an asterisk. Inset shows 9-year running means.

the 20th and 21st centuries. The 20th century integrations specify forcings based on observed records and offline chemical transport models. Different centers use different external forcings over the 20th century. They all include changing greenhouse gas concentrations, but may also include variations in solar input, volcanic forcing and ozone concentrations. To compare model hindcasts with projections through the 21st century, we employ runs with 21st century forcings based on the SRES A1B "business as usual" scenario, where CO_2 is projected to reach 720 ppm by 2100 (compared to approximately 370 ppm in 2000).

[9] Of the 18 models examined for the Arctic and 15 for the Antarctic, we focus on those with mean ice extent within 20% of observations (from 1953–1995 for the Arctic, and 1973–1995 for the Antarctic). This screening resulted in 13 and 18 models for the September and March Arctic comparisons, respectively. For Antarctica, 12 models were used for September and only 5 for March. Some models have more than one ensemble member which are used to generate the ensemble mean for that particular model. A multi-model ensemble mean and its inter-model standard deviation are computed. We also summarize Arctic September trends for three time periods, and the range between different ensemble members. All trends are reported as % per decade.

3. Comparisons for the Arctic

[10] Figure 1 shows September sea ice extent ($\times$ 10^6 km^2) from observations and the screened IPCC AR4 models while Table 1 summarizes trends. The observed trend from 1953–2006 is -7.8 ± 0.6 %/decade, three times larger than the multi-model mean trend of -2.5 ± 0.2%/decade. More striking is that none of the models or their individual ensemble members have trends as large as observed for this period. The largest negative trend from any individual model run is -5.4 ± 0.4 %/decade (an ensemble member from NCAR CCSM3).

[11] For the shorter, yet more reliable period of observations based on modern satellite records (1979–2006), both the observed (-9.1 ± 1.5%/decade) and multi-model mean trend (-4.3 ± 0.3%/decade) are larger, but there is again a strong mismatch, and trends from only 5 of 29 individual ensemble runs (from only two models: NCAR CCSM3, UKMO HadGEM1) are comparable to observations. Over the last 11 years (1995–2006), observed and multi-model mean trends are even larger at -17.9 ± 5.9 %/decade and -6.6 ± 0.6 %/decade, respectively, and only 6 individual ensemble members (from NCAR CCSM3, GISS AOM3, and MIUB ECHO) are within 20% of the observed trend.

[12] March trends are not as dramatic (Figure 2), but the modeled values are again smaller. Over 1953–2006, the multi-model mean of -0.6 ± 0.1%/decade is one third of the observed value of -1.8 ± 0.1%/decade and only two simulations (CCCMA GCM3, UKMO HadGEM1) have trends within 20% of observations. Over the satellite era, the observed trend grows to -2.9 ± 0.3%/decade, over twice the model mean value of -1.2 ± 0.2%/decade. Trends from 5 out of 18 models are within 20% of observations, and some show increasing ice extent.

[13] To summarize, there is qualitative agreement between observations and models regarding an overall decline in September ice extent. This points to an imprint of GHG loading [*Zhang and Walsh*, 2006]. Since both observed and modeled September trends have become larger in more recent years, it appears that GHG imprints are growing. Simulations run with pre-industrial GHG concentrations do not produce the magnitude of September trends just discussed.

[14] As expected, observed and modeled March trends are much smaller. In the early stages of a GHG-driven

Table 1. September Ice Extent Trends and Standard Deviations from IPCC AR4 Models and Observations for 1953–2006, 1979–2006, and 1995–2006[a]

IPCC Model ID	Trend 1953–2006, % dec^{-1}	Trend 1979–2006, % dec^{-1}	Trend 1995–2006, % dec^{-1}
BCCR BCM2.0	−0.47 ± 0.35	−2.16 ± 0.89	−2.80 ± 3.92
CCCMACGCM 3	−1.79 ± 0.21	−1.85 ± 0.54	−1.87 ± 2.27
Ensemble mean Range	−2.86, −0.89	−2.53, −1.27	−2.74, −0.30
CCCMA CGCM3.1 (T63)	−2.50 ± 0.25	−2.47 ± 0.64	−4.72 ± 2.54
CNRM CM3	−3.18 ± 0.44	−4.03 ± 1.36	−12.56 ± 4.51
GISS AOM	−2.82 ± 0.36	−4.13 ± 1.17	−5.97 ± 3.43
Ensemble mean Range	−2.94, −2.70	−5.74, −2.49	−10.97, −1.10
IPSL CM4	−4.50 ± 0.63	−7.74 ± 1.51	−8.06 ± 7.15
MIROC3.2 MED	−2.21 ± 0.29	−3.07 ± 0.65	−5.03 ± 1.80
Ensemble mean Range	−2.91, −1.77	−6.04, −1.03	−8.11, ± 0.39
MIUB ECHO	−1.53 ± 0.47	−5.11 ± 1.21	−11.79 ± 2.90
Ensemble mean Range	−1.84, −1.00	−7.18, −3.49	−13.96, −7.96
MPI ECHAM5	−0.82 ± 0.30	−3.25 ± 0.69	−2.68 ± 1.53
Ensemble mean Range	−1.01, −0.64	−4.24, −2.27	−2.72, −2.64
MRI CGCM2.3.2	−1.41 ± 0.19	−1.70 ± 0.66	+6.95 ± 1.89
Ensemble mean Range	−1.65, −1.08	−1.76, −1.65	+4.98, +8.12
NCAR CCSM3	−3.96 ± 0.32	−7.24 ± 0.86	−19.12 ± 1.33
Ensemble mean Range	−5.44, −2.52	−10.84, −2.65	−28.29, −10.66
UKMO HadGEM	−4.85 ± 0.63	−9.03 ± 1.42	−9.66 ± 6.24
UKMO HadCM3	−4.77 ± 0.60	−5.82 ± 1.70	−19.37 ± 6.30
Multi-model Ensemble mean	−2.55 ± 0.16	−4.26 ± 0.25	−6.65 ± 0.59
Satellite/in situ observations	−7.77 ± 0.60	−9.12 ± 1.54	−17.91 ± 5.98

[a]September ice extent trends (%/decade). Results are only given for models with September ice extent within 20% of observations from 1953–1995. When more than one ensemble member was available for a particular model, the range in trends is also given.

warming, ice extent should still recover in the cold season, albeit with thinner ice. With only a small externally-forced trend in extent, effects of internal variability will be especially strong. Indeed, some models actually show increasing ice extent over the observational record. Only with continued GHG loading through the 21st century do all models show declining March ice extent. Nevertheless, the results for September, and to a lesser extent March, indicate decay of the ice cover is proceeding more rapidly than expected based on the model simulations.

4. Synthesis

[15] One interpretation of these results is that the observed September trend is a statistically rare event and imprints of natural variability strongly dominate over any

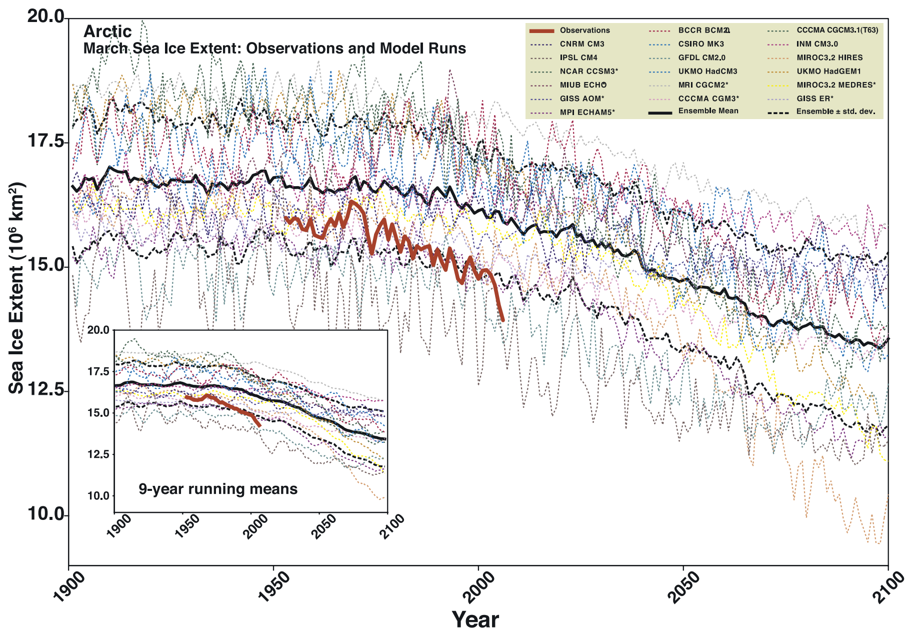

Figure 2. Arctic March sea ice extent ($\times$ 10^6 km^2) from observations (thick red line) and 18 IPCC AR4 climate models together with the multi-model ensemble mean (solid black line) and standard deviation (dotted black line). Models with more than one ensemble member are indicated with an asterisk. Inset shows 9-year running means.

effect of GHG loading. In this line of reasoning, one could argue that the sample of model simulations is too small for any of the models to capture the magnitude of the observed trend. If instead we accept that the suite of simulations is a representative sample, an alternative conclusion is that as a group, the models are deficient in their response to anthropogenic forcing.

[16] Some support for the first interpretation, particularly in terms of the strong mismatch between modeled and observed trends over the last 11 years, comes from impacts of the strong positive state of the winter NAM during 1989–1995 (highest in over 100 years). Altered wind patterns flushed much of the Arctic Ocean's store of thick ice into the Atlantic via Fram Strait. While the NAM has subsequently regressed back to a more neutral phase, this episode left the Arctic with thinner ice, more apt to melt in summer, contributing to sharply lower September ice extent in recent years [*Rigor and Wallace*, 2004]. Atmospheric variability in the post-positive NAM era has also favored ice loss [*Maslanik et al.*, 2007] as have changes in Atlantic heat inflow [*Polyakov et al.*, 2005] and the transport of Pacific-derived waters [*Shimada et al.*, 2006]. Assuming these processes reflect natural variability, it is likely that in their absence, the September trend would be smaller than observed.

[17] However, the observed September trend from 1953–2001 of -6.9 ± 0.7%/decade, which eliminates the extremely large ice losses of the last four years, remains much larger than the multi-model mean of -2.2 ± 0.2%/decade and larger than that for any of the individual ensemble members (the largest being -4.3 ± 0.5%/decade). Nevertheless, it seems the more general rise of the winter NAM from the 1960s into the mid-1990s has also contributed to declining ice extent [*Rigor et al.*, 2002].

[18] Regarding the second interpretation, while IPCC AR4 models incorporate many improvements compared to their predecessors, shortcomings remain. Modes of atmospheric variability like the NAM are represented with questionable fidelity. While some studies suggest anthropogenic forcing may favor a positive NAM mode [e.g., *Gillett et al.*, 2003], there is evidence that climate models underestimate NAM-like variability [e.g., *Gillett*, 2005; *Stenchikov et al.*, 2006]. Most models do not parameterize a sub-grid scale ice thickness distribution, which is important for sea ice-related feedbacks [*Holland et al.*, 2006a]. Ocean circulation and vertical structure are often poorly represented [e.g., *Tremblay et al.*, 2007]. Ice-albedo feedback and oceanic heat flux are implicated as critical factors that may cause abrupt reductions in the future Arctic summer ice cover [*Holland et al.*, 2006b]. Notably, the two models that best match observations over the satellite record incorporate relatively sophisticated sea ice models (e.g., with a sub-grid scale ice thickness distribution) [*McLaren et al.*, 2006; *Meehl et al.*, 2006].

[19] If we assume the September time series from the multi-model ensemble mean over the period 1953–2006 allows for a correct depiction of the externally forced trend, we can estimate the forced component of the observed trend. As one estimate, we divide the multi-model mean trend by the observed trend. As another, we compute anomalies of the multi-model mean time-series for each year with respect to 1953, subtract these from the observed time series, and then re-compute the trend from the adjusted observations. These calculations indicate that 33% to 38% of the observed trend is externally forced. The same calculations for the satellite era (1979–2006) point to larger forced contributions of 47% and 57%. Calculations for March indicate that 34 to 39% and 45 to 52% of the trend is externally forced from 1953–2006 and 1979–2006, respectively. However, if the models as a group under-represent the GHG response the forced components must be larger.

[20] The residual time series for individual simulations after removing the multi model-mean trend include a combination of each simulation's natural variability and departures in GHG sensitivity with respect to the multi-model mean. The larger downward residual trends will tend to include those simulations especially sensitive to GHG loading that (by chance) are paired with a downward trend associated with natural variability. Since none of the negative residual trends from 1953–2006 are comparable to that from the observations after removing the forced component, this implies that natural variability in the models is underestimated. However, this again assumes that the multi-model ensemble mean time series correctly represents the GHG response.

[21] It is useful at this point to turn briefly to the Antarctic. In contrast to the Arctic, Antarctic ice extent has shown little change. The observed September (end of austral winter) trend from 1973–2006 is essentially zero. The corresponding March trend is -1.7 ± -2.3%/decade, but given the high variability in the Antarctic March extent, the trend is not statistically significant.

[22] This is consistent with the notion that surface heat in the southern ocean is rapidly removed from the surface, and hence does not readily influence the ice cover. Deeper water in the southern ocean is observed to be warming [*Gille*, 2002], but the majority of the sea ice is in contact with a near-surface cold-water layer formed by the interaction of a katabatic outflow from the continent with coastal water. Where warmer, deeper water is brought near the surface, near the western Antarctic Peninsula, there is a significant downward trend in sea ice extent [*Martinson*, 2005; *Zwally et al.*, 2002]. It is likely that stratospheric cooling from springtime ozone depletion favors the positive phase of the Southern Annular Mode (SAM), promoting a cooler climate over most of the coastline but warming over the Antarctic Peninsula [*Thompson and Solomon*, 2002]. Some IPCC-AR4 models simulate this positive trend in the SAM [e.g., *Raphael and Holland*, 2005].

[23] The multi-model mean for September from 1973–2006 is also small at -1.8 ± 0.2 %/decade, (almost identical to the trend over 1900 to 2100) and modeled trends range widely, with 3 of 12 showing increasing ice extent during the satellite era. While one might argue that the large scatter in the modeled March trends (-6.5%/decade to 0.1%/decade) is broadly consistent with the insignificant observed trend, only the 5 of the 15 models passed the initial performance screening described earlier. The appropriate conclusion is that there are strong shortcomings in the ability of most models to simulate March Antarctic ice extent.

5. Conclusions

[24] Observations indicate a downward trend in September Arctic sea ice extent from 1953–2006 that is larger than any of the IPCC AR4 simulations, and current summer minima

are approximately 30 years ahead of the ensemble mean model forecast. However, the multi-model mean downward trend is still substantial. If this trend is a true representation of forced change by greenhouse gas loading, we conclude that 33–38% of the observed trend is externally forced. For the more recent period 1979–2006, and despite apparent strong impacts of natural processes, these estimates rise to 47–57%. To the extent that the evidence presented here supports the contention that the model GHG response is too weak, the externally forced component may be larger. Either way, it appears that impacts of GHG loading on Arctic sea ice in September are strong, and growing, and have also impacted March ice extent. By contrast, while both observed and modeled Antarctic winter trends are small, few models give reasonable assessments of Antarctic summer ice extent.

[25] The IPCC AR4 models indicate with the "business as usual" SRES A1B scenario, an essentially ice-free Arctic Ocean in September (less than 1.0×10^6 km^2) may be realized anywhere from 2050 to well beyond 2100. However, if the models as a group underestimate the impacts of GHG loading, this transition to a new Arctic state is more likely to occur well within this century. The Arctic has often been viewed as a region where the effects of GHG loading will be manifested early on, especially through loss of sea ice. The sensitivity of this region may well be greater than the models suggest.

[26] **Acknowledgments.** We acknowledge the modeling groups for providing their data for analysis, PCMDI for collecting and archiving model output, and the JSC/CLIVAR Working Group on Coupled Modeling for organizing model data analysis activity. The multi-model data archive is supported by the Office of Science, U.S. Department of Energy. This work was funded under NASA contracts NNG06GB26G, NNG04GH04G, and NSF grants ARC-0229651, OPP-0242125, and ARC-0531040.

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