GEOPHYSICAL RESEARCH LETTERS, VOL. 31, L06209, doi:10.1029/2003GL019133, 2004

Disappearing Arctic sea ice reduces available water in the American west

Jacob O. Sewall and Lisa Cirbus Sloan

Earth Sciences Department, University of California, Santa Cruz, California, USA

Received 21 November 2003; revised 3 February 2004; accepted 26 February 2004; published 24 March 2004.

[1] Recent decreases in Arctic sea ice cover and the probability of continued decreases have raised the question of how reduced Arctic sea ice cover will influence extrapolar climate. Using a fully coupled earth system model, we generate one possible future Arctic sea ice distribution. We use this "future" sea ice distribution and the corresponding sea surface temperatures (SSTs) to run a fixed SST and ice concentration experiment with the goal of determining direct climate responses to the reduction in Arctic sea ice that is projected to occur in the next 50 years. Our results indicate that future reductions in Arctic sea ice cover could significantly reduce available water in the American west and highlight the fact that the most severe impacts of future climate change will likely be at a regional scale. *INDEX TERMS:* 1620 Global Change: Climate dynamics (3309); 1803 Hydrology: Anthropogenic effects; 1812 Hydrology: Drought; 3354 Meteorology and Atmospheric Dynamics: Precipitation (1854). **Citation:** Sewall, J. O., and L. C. Sloan (2004), Disappearing Arctic sea ice reduces available water in the American west, *Geophys. Res. Lett.*, *31*, L06209, doi:10.1029/2003GL019133.

1. Introduction

[2] Recent studies indicate that Arctic sea ice has thinned and decreased in extent over the last century [*Johannessen et al.*, 1999; *Rothrock et al.*, 1999; *Hilmer and Lemke*, 2000; *Comiso*, 2002, 2003] and that future greenhouse warming could further reduce Arctic ice cover [*McPhee et al.*, 1998; *Zhang et al.*, 2000; *Weatherly and Arblaster*, 2001]. Reduced Arctic sea ice could drive extrapolar climate change via complex feedback responses and possibly affect large population centers. The most effective tool for investigating the direct extrapolar climate response to reduced Arctic sea ice cover and concentration is a global climate model run with user specified sea surface temperatures (SSTs) and ice concentrations. Such an experiment will remove feedbacks due to other climate forcing factors and provide information on the direct climate impact of reduced Arctic sea ice. While we do not know precisely what future Arctic sea ice concentrations or SSTs will be, there are general projections of how far Arctic ice cover will decline in the future [e.g., *Comiso*, 2002]. Using the National Center for Atmospheric Research (NCAR) Community Climate System Model (CCSM 1) [*Boville et al.*, 2001], we generate one potential future (~2050) Arctic ice cover and SST distribution. We use these projected ice cover and SST boundary conditions to force a fixed SST experiment and investigate the direct, extrapolar climate responses to reduced Arctic sea ice. Extrapolar responses to our reduced Arctic sea ice were regional in nature. Here we present the surprising result that decreased Arctic sea ice causes drying of western North America.

2. Methods

[3] While the reality of future climate change will involve the interaction of many climate forcing factors, we wish to investigate the climate response to only one forcing factor, reduced Arctic sea ice and the correspondingly warmer Arctic SSTs. We, therefore, must have a "dataset" of reduced Arctic ice cover and warmer SSTs. *Comiso* [2002] presents one possible distribution of 2050 minimum season ice concentrations based on projections of recent negative trends in minimum season ice concentration. However, as *Comiso*'s [2002] projection is for a single season and our model experiment requires monthly varying ice concentrations, we use a fully coupled earth system model to generate a monthly varying Arctic sea ice climatology using Comiso's projection as a minimum season tie point. The coupled model we use is the NCAR CCSM1 [*Boville et al.*, 2001], which consists of component models for the atmosphere, ocean, land, and sea ice. We presume that a future reduction in Arctic sea ice will be forced by an increased heat flux to the Arctic surface. While we do not know the source of the increased heat flux to the Arctic, we know that if sea ice-cover decreases, this heat flux must exist. We, therefore, borrow from the concept of flux corrections and, in our model, "correct" the sensible heat flux to the Arctic (regions north of 60°N) until the sea ice component model produces minimum season ice concentrations that approach *Comiso*'s [2002] projections for the year 2050. As the actual source of this increased future heat flux is unknown, we simplify our correction process by "correcting" the sensible heat flux from only one component model, the atmosphere. We "correct" the atmospheric sensible heat flux to both the ice and ocean component models.

[4] Sensible heat flux between the atmosphere, ocean, and ice component models can be generally formulated as:

$$Q_{sen} = \rho_a c_p^a C_H W_{10}(Ta - \theta_1), \qquad (1)$$

where Q_{sen} is the sensible heat flux, ρ_a is the air density, c_p^a is the specific heat of air, C_H is the transfer coefficient for heat, T_a is the 2 m air temperature, θ_1 is the surface temperature, and W_{10} is the wind speed at 10 m and equals $(U_{10}^2 + V_{10}^2)^{1/2}$ where U_{10} and V_{10} are the zonal and meridional winds at 10 m.

0094-8276/04/2003GL019133$05.00

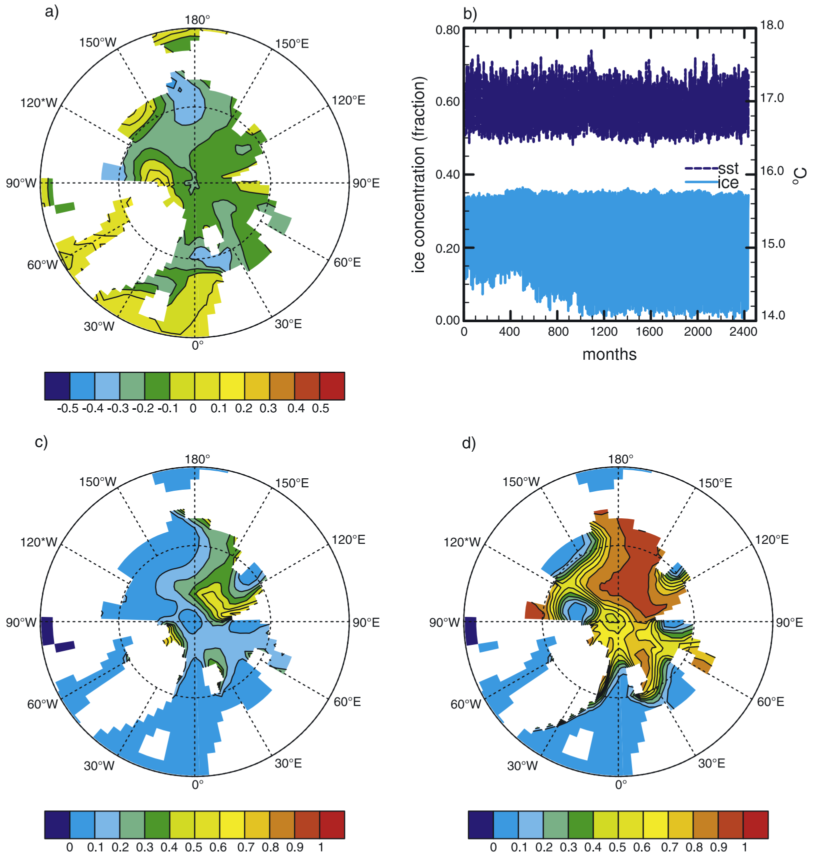

Figure 1. a) Annual average Arctic ice concentration difference (fraction) (SSTGEN-SSTINIT). b) Model time in months vs. SSTGEN Northern Hemisphere annual average ice concentration (fraction, left axis) and SSTGEN global average SST (°C, right axis). c) FARC minimum ice concentration (fraction) (July, August, September average). d) MARC minimum ice concentration (fraction) (July, August, September average).

[5] Our additional heat flux is applied as a correction to T_a prior to the calculation of Q_{sen}. In Arctic regions, values of T_a below freezing are increased to just above freezing.

[6] Because we do not know the magnitude of the increased heat flux necessary to decrease Arctic sea ice cover to projected 2050 values, we must determine that value empirically. We make slight adjustments to T_a until we achieve a minimum season ice-cover distribution that is consistent with projected distributions.

[7] As previously noted, we conducted our research with the NCAR CCSM1 [*Boville et al.*, 2001] at a spectral resolution of T31 (~3.75° lat × 3.75° lon). We initialized our fully coupled experiment (henceforth known as SSTGEN) from an equilibrated modern scenario [*Otto-Bliesner et al.*, 2002] (henceforth known as SSTINIT). Over the course of 150 model years we adjusted our "corrected" T_a values until an adequate reduction in sea ice cover was achieved. The final "corrected" T_a values that correspond to an adequate ice -cover reduction are 1°C for calculation of fluxes to the ice component model and 2°C for the calculation of fluxes to the ocean component model; these values are only used in the calculation of fluxes to regions north of 60°N. Comparisons between SSTGEN and SSTINIT indicate that our "corrected" T_a values are equivalent to adding an additional annual heat flux of 200–225 W/m^2 over the high Arctic. This flux is sufficient to produce a significant reduction in Arctic ice cover (Figure 1a), particularly in the summer, but perturbs the residual at the top of the model by only 0.145 W/m^2 when SSTGEN is compared to SSTINIT. After we stabilized our T_a values, we integrated SSTGEN for an additional 54 years to ensure there were no trends in Arctic ice cover or SSTs. Although we recognize that our SSTGEN experiment was not run for sufficient time to equilibrate the deep ocean, we are satisfied that the lack of a trend in either SSTs or sea ice concentration indicates surface equilibrium (Figure 1b). We, therefore, believe that the SST and ice concentration distributions in SSTGEN represent reasonable surface forcing boundary conditions for investigating direct climate responses to reduced Arctic sea ice.

[8] Our imposed flux "correction" resulted in SSTGEN having, in general, a 20% decrease in annual averaged ice concentration (Figure 1a) and a 1 m decrease in annual averaged ice thickness (not shown) over most of the Arctic Ocean as compared to SSTINIT. There were regions of greater change with SSTGEN having up to a 6 m reduction in annual average ice thickness (not shown) north of the Bering Strait and a 20–40% reduction in ice concentration in the same region (Figure 1a). Annual averaged ice concentration was also reduced in SSTGEN by 20–50% in the Norwegian, Greenland, and Barents seas when compared to SSTINIT. Finally, SSTGEN exhibited a notable increase in both annual averaged ice concentration and thickness when compared with SSTINIT between Greenland and Baffin Island (ice thickness up to 1 m [not shown] and concentration 0–20% (Figure 1a)).

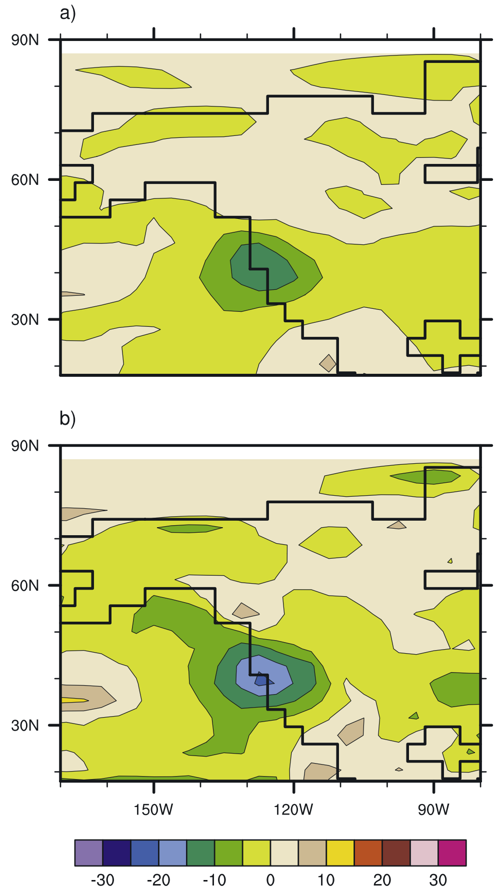

Figure 2. Cumulative precipitation difference (FARC-MARC) (cm) over western North America. a) December January, February average. b) Annual average.

[9] We extracted the final 50 years of both SSTGEN and SSTINIT and created 50-year means of monthly SST and ice fraction. These monthly means were combined into two monthly varying, spatially detailed SST and ice fraction datasets. One dataset contains SSTINIT (modern) SSTs and ice fractions. The second dataset contains SSTGEN (projected future) SSTs and ice fractions. Using these two SST and ice fraction data sets, we initialize two fixed SST and ice fraction experiments; ice thicknesses were model specified constant values of 2.5 m (Northern Hemisphere) and 1.0 m (Southern Hemisphere). The model we use is the NCAR CCSM1 [*Boville et al.*, 2001] at T31 spectral resolution. The experiment forced with SSTGEN SSTs and ice fractions is henceforth known as FARC (Future ARctic Case). The control experiment, forced with SSTINIT SSTs and ice fractions, is henceforth known as MARC (Modern ARctic Case). Both cases were initialized from the same year of SSTINIT that SSTGEN was initialized from and both cases were run for 60 years. We averaged the final 50 years of each case for analysis.

3. Results and Analyses

[10] Although the imposed changes in ice thickness and concentration were reasonably uniform over all seasons, the extrapolar climate responses were most extreme in the northern hemisphere winter season (December, January, and February; DJF) and particularly interesting over North America. Consequently, the remainder of the results we present will be for DJF unless otherwise noted and focused predominantly on North America. All discussed differences are significant at the 95% confidence level based on the t-test of *Chervin and Schneider* [1976].

[11] As was mentioned previously, the most interesting extrapolar climate response to reduced Arctic sea ice cover is a significant drying of western North America; cumulative winter precipitation in FARC is up to 15 cm (~30%) less than that in MARC from southern British Columbia south to the Gulf of California and inland as far as the Rocky Mountains (Figure 2a). The greatest change is found along the west coast and decreases inland to ~5 cm (17%) less winter precipitation once the Rocky Mountains are reached. Evaporation minus precipitation (E-P) also reflects this drying trend with FARC having a 0.5–2 mm/day (up to 50%) increase in E-P over coastal western North America (not shown).

[12] The drying of western North America is directly linked to other changes in the climate system. The 500 mb geopotential height off the west coast of North America is higher in FARC by up to 0.4 hectometers when compared to MARC (Figure 3b). This increased geopotential height alters the path of winter storms and causes them to track slightly north of their path in MARC (Figures 3c and 3d). As much of western North America receives the majority of its precipitation during the winter months, this shift in winter stormtracks results in an annual decrease in cumulative precipitation of up to 25 cm (up to 30%) (Figure 2b) for this region when FARC is compared to MARC. The change in winter storm tracks is also reflected in an increase in annual average cumulative precipitation of up to 10 cm over northern British Columbia and southern Alaska (Figure 2b).

[13] While we are confident in the causal relationship between reduced precipitation, changing stormtracks and increased 500 mb geopotential height off the west coast of North America, the association between these responses and changing Arctic ice cover is not as clear. Our results suggest that the changes in, and offshore of, western North America are linked to changes in winter ice cover of the Greenland, Norwegian, Barents, and Kara Seas (not shown). Ice cover in this region is reduced by up to 50% in FARC and the increased open water results in a substantial change in outgoing energy (up to 80 W/m^2; not shown). This increase in energy passed from the ocean to the atmosphere results in a substantial positive anomaly in 850 mb temperatures (up to 4°C) over the Greenland, Norwegian, Barents and Kara Seas (Figure 3a). Increased 850 mb temperatures in FARC drive a large, positive 500 mb geopotential height anomaly in this same location (Figure 3b). We hypothesize that this 500 mb geopotential height increase south of the Barents and Kara Seas perturbs the planetary wave pattern and contributes to the increased 500 mb geopotential heights offshore of western North America and, thus, decreased precipitation in this same region.

[14] The impact that a small shift in winter stormtracks has on annual average precipitation in western North America highlights the inherent fragility of a water budget based heavily on precipitation in one season.

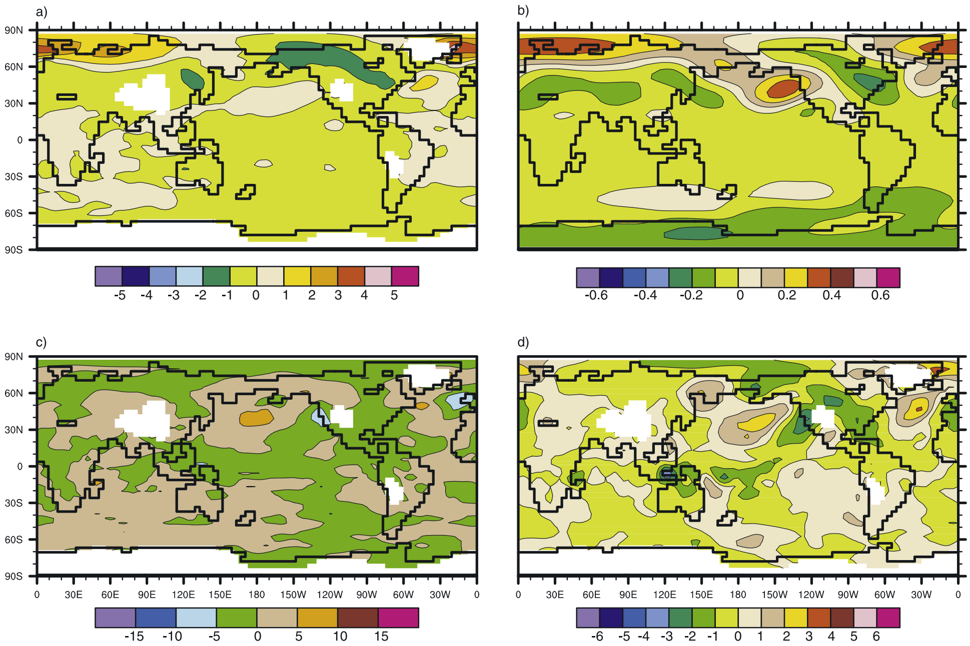

Figure 3. December, January, February average differences (FARC-MARC). a) 850 mb temperature (°C), b) 500 mb geopotential height (hectometers), c) 850 mb eddy kinetic energy (m^2/s^2), d) 850 mb meridional heat transport (K m/s × 100).

The dependence on winter storm precipitation to provide water for much of western North America renders this region especially vulnerable to changes in the planetary wave pattern and, consequently, storm tracks, both of which appear to be sensitive to minor perturbations in the climate system.

4. Conclusions

[15] Using one possible future Arctic SST and sea ice extent distribution, we examined the direct climate response to reduced Arctic sea ice thickness and concentration. One of the more interesting responses to this change in sea ice cover is a significant drying of western North America, a region that already struggles with limited water resources. As a reduction in Arctic sea ice has already begun, and is expected to continue as a result of increases in greenhouse gas concentrations, these results highlight the possibility that the amount of available water in western North America could be reduced in the 21st century. An additional cause for concern is that our modeled responses show only the consequences of a reduction in the Arctic sea ice, they do not include the overall warming that western North America could expect as greenhouse gases increase. Certainly an increase in surface temperature would enhance evaporation, thus exacerbating the water crisis in western North America. As the largest impact of our imposed future climate forcing is regional in nature, further work investigating future climate impacts should incorporate regional scale modeling of climatically sensitive areas. Also, this regional response highlights the facts that the impacts of future climate change may be difficult to predict in both location and magnitude and a small change in one location can produce a significant impact at a distant location.

[16] **Acknowledgments.** JOS and LCS thank NSF (OPP0116941) and NCAR for financial and computational support. JOS also thanks NDSEG for graduate fellowship support.

References

Boville, B. A., J. T. Kiehl, P. J. Rasch, and F. O. Bryan (2001), Improvements to the NCAR CSM-1 for transient climate simulations, *J. Clim.*, *14*, 164–179.

Chervin, R. M., and S. H. Schneider (1976), Determining statistical significance of climate experiments with general circulation models, *J. Atmos. Sci.*, *33*, 405–412.

Comiso, J. C. (2002), A rapidly declining perennial sea ice cover in the Arctic, *Geophys. Res. Lett.*, *29*(20), 1956, doi:10.1029/2002GL015650.

Comiso, J. C. (2003), Warming trends in the Arctic from clear sky satellite observations, *J. Clim.*, *16*, 3498–3510.

Hilmer, M., and P. Lemke (2000), On the decrease of Arctic sea ice volume, *Geophys. Res. Lett.*, *27*, 3751–3754.

Johannessen, O. M., E. V. Shalina, and M. W. Miles (1999), Satellite evidence for an Arctic sea ice cover in transformation, *Science*, *286*, 1937–1939.

McPhee, M. G., T. P. Stanton, J. H. Morison, and D. G. Martinson (1998), Freshening of the upper ocean in the Arctic: Is perennial sea ice disappearing?, *Geophys. Res. Lett.*, *25*, 1729–1732.

Otto-Bliesner, B. L., E. C. Brady, and C. Shields (2002), Late Cretaceous ocean: Coupled simulations with the National Center for Atmospheric Research Climate System Model, *J. Geophys. Res.*, *107*(D2), 4019, doi:10.1029/2001JD000821.

Rothrock, D. A., Y. Yu, and G. A. Maykut (1999), Thinning of the Arctic sea-ice cover, *Geophys. Res. Lett.*, *26*, 3469–3472.

Weatherly, J. W., and J. M. Arblaster (2001), Sea ice and climate in 20th- and 21st-century simulations with a global atmosphere-ocean-ice model, *Ann. Glaciol.*, *33*, 521–524.

Zhang, J. L., D. Rothrock, and M. Steele (2000), Recent changes in Arctic sea ice: The interplay between ice dynamics and thermodynamics, *J. Clim.*, *13*, 3099–3114.

J. O. Sewall and L. C. Sloan, Earth Sciences Department, University of California, Santa Cruz, 1156 High Street, Santa Cruz, CA 95064, USA. (jsewall@es.ucsc.edu)