A Model Ensemble Assessment of the Enhancement of Arctic Warming by Sea Ice Retreat

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Abstract

Five global climate models are used to estimate the local enhancement of Arctic warming attributable to sea ice retreat in B2-scenario greenhouse simulations. The models show a wide range of ice retreat, resulting in a corresponding range in the enhancement of warming. The enhancement is highly seasonal, varying locally from essentially zero in the summer to several degrees (°C) in the late autumn and early winter. Its magnitude increases with the threshold decline in ice concentration used to define retreat because higher thresholds better isolate the warming enhancement signal over ice retreat areas. A threshold of 20% ensures that all models in this study have enough ice retreat area to sample the enhancement because all start with ice concentrations at least that high over substantial northern hemisphere areas. All estimates are lower bounds because they do not account for advective effects.

1. Introduction

Global climate models have consistently indicated a polar amplification of greenhouse-driven warming, dating back to the earliest global model experiments of the 1970s (Manabe and Wetherald 1975) and continuing through the recent decade (e.g., ACIA 2004). A snow/ice albedo-temperature feedback triggered by an initial warming is among the factors that can contribute to a polar amplification of the near-surface warming. The decrease of surface albedo from 0.6–0.8 over snow-covered land or sea ice, to 0.1–0.3 over open ocean or bare land, will give strong leverage to an initial warming (or cooling) near the ice/snow margin, especially during spring and summer when insolation is strongest. This leverage suggests that an externally forced (e.g., greenhouse-gas driven) warming should be greatest over areas in which snow and ice disappear during the course of a climate change.

The 21st-century reduction of sea ice is substantial in most greenhouse-driven simulations of climate by global models, and the retreat of sea ice is known to play a substantial role in their globally-averaged warming response, e.g., Rind et al. (1995). The striking coherence of surface air temperature warming patterns over marginal ice zones observed in visualizations of the climate simulations used in the Arctic Climate Impact Assessment (ACIA 2004), suggests that direct enhancement of Arctic warming by sea ice retreat may be quantifiable in terms of the difference between the warming of surface air temperatures over northern hemisphere areas of

sea ice retreat and the warming over proximate areas. Insofar as such a differential warming is bound to be diluted by advection and perhaps other atmospheric processes, it represents a lower bound on the enhancement of warming by sea ice retreat. Nevertheless, this lower bound may serve as a starting point for quantitative assessments of the net contribution of local sea ice feedbacks to the polar amplification of greenhouse warming, and its calculation and analysis is the goal of this paper.

2. Models

The five models chosen for use in the ACIA are listed in Table 1. They are all well documented in the published literature and were run to the year 2100 using the moderate B2 greenhouse gas emissions scenario (IPCC 2000), which assumes medium growth (relative to the other harmonized climate change scenarios) in global population, GDP, energy use, etc. CO₂ concentrations in all simulations vary with time according to observationally-derived values during a spin-up covering at least the latter portion of the 20th century that culminates in a concentration of 370 ppm in the year 2000, and to the B2 scenario thereafter to the end of the 21st century where it reaches approximately 600 ppm. Thus, each model begins its B2-prescribed CO₂ forcing at the start of 2000, with ‘effective’ initial conditions for each being that model’s simulated climate (including sea ice) for that time. The CCC model results are actually averages over three members of an ensemble of simulations that differed only by slight perturbations of the initial conditions. The three ensemble members evolved much more similarly to each other than to the simulations by the other models. Because all five models are fully coupled atmosphere-ocean-ice models, sea ice is free to respond thermodynamically and dynamically to atmospheric and oceanic forcing. Over the 21st century all models show a contraction of northern hemisphere sea ice extent.

Table 1. The five global climate models

<i>Institute</i>	<i>Acronym</i>	<i>Reference</i>
Canadian Climate Centre for Modeling and Analysis	CCC	Flato et al. (2000)
Community Climate System Model, UCAR	CSM	Boville et al. (2001)
Geophysical Fluid Dynamics Laboratory, NOAA	GFD	Knutson et al. (1999)
Hadley Centre for Climate Prediction and Research, UK	HAD	Gordon et al. (2000)
Max-Planck Institute (ECMWF/Hamburg)	ECH	Roeckner et al. (1999)

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3. Methodology

The ‘raw’ data for this numerical experiment consists of time series of monthly-average records from 1990 to 2100 of two-dimensional (2-D) surface air temperature (hereafter denoted as “air temperature”) and sea ice concentration fields from all five ACIA models mapped onto a common global 2.5° grid. These are processed to obtain monthly time series of differential temperature anomaly (*DTA*), which are differences between air temperature changes from the models’ present-day (1990–2000) climatologies area-averaged over regions of sea ice retreat and over proximate ice-free areas. Calculation of *DTA* is made on a calendar-month basis for each of the five models. The first step for each model-month is to create temperature anomaly (*TA*) and ice concentration anomaly time series spanning the 2001–2100 period. *TA* is calculated by subtracting the 2-D 1990’s decadal mean air temperature from each 2-D record in the air temperature time series. Ice concentration anomaly time series are denoted by “*DC*” and are the percent difference in ice concentration from that model-month’s year-2000 record from each 2-D record in its ice concentration time series, such that positive values indicate a decrease in ice concentration from the year 2000. Ice concentration is calculated with respect to complete coverage (unity or 100%), and therefore so is *DC*. A grid point with a *DC* value of 0.2 has undergone a reduction of sea ice coverage equal to 20% of maximum possible (complete) coverage, not a 20% reduction with respect to the initial year 2000 coverage. A grid point is considered to have undergone retreat when its *DC* value exceeds an arbitrary threshold (hereafter referred to as “retreat threshold”). Higher retreat thresholds delimit less ice-retreat area because they require greater decreases in ice concentration in order for grid points to be considered to have undergone sea ice retreat.

The next step for each model-month is the synthesis of *TA* and *DC* information to create scalar time series of area-averaged temperature anomalies. Each 2-D record in the *DC* time series is used to construct a “mask” for area-weighted averaging of its contemporaneous 2-D record in the *TA* time series. Masks delimit ice-retreat area over which to average *TA* by selecting those grid cells for which the difference in concentration is greater than some retreat threshold. Area-weighted averages of *TA* calculated over Northern Hemisphere (NH) regions of sea ice retreat will hereafter be denoted by $\overline{TA}_{retreat}$, and the regions over which they are averaged will be referred to as “ice-retreat”. If $\overline{TA}_{retreat}$ values evaluated over ice-retreat regions are in any way influenced by the retreat of sea ice, then they will be dependent upon retreat threshold, i.e., greater average retreat over the averaging region means greater influence from the process of ice retreat on the area-averaged air temperature anomaly. It is important to assess the functional sensitivity of $\overline{TA}_{retreat}$ to variation in retreat threshold. Therefore, we calculate 101 separate $\overline{TA}_{retreat}$ time series by area-weighted averaging the *TA* time series over 101 different NH ice-retreat regions delimited by successive application of the monotonically-increasing thresholds (*DC*) $>0, \geq 1, \geq 2, \dots, \geq 98, \geq 99, \text{ and } =100$.

A “reference” scalar air temperature anomaly time series is constructed by area-weighted averaging *TA* over oceanic regions poleward of 50°N that are ice-free

Fig. 1. Hovmuller plot collating *DTA* time series calculated over full range of possible retreat thresholds (GFD-November)

ocean in that model-month’s year-2000 ice concentration field. This scalar air temperature anomaly time series will hereafter be denoted by $\overline{TA}_{no-ice}$, and the region over which it is averaged will be referred to as “ice-free”. Note that it is not dependent upon retreat threshold. The final step for each model-month entails calculation of 101 *DTA* scalar time series by subtraction of contemporaneous elements of the $\overline{TA}_{no-ice}$ time series from each of the 101 $\overline{TA}_{retreat}$ time series. Note that this means that *DTA* can vary with retreat threshold. Processing all model-months yields 60 *DTA* data sets (12 months x 5 models), each set comprised of 101 monthly-average *DTA* time series that functionally depend on time (τ) and retreat-threshold (*RT*), i.e.,

$$DTA(\tau, RT) = \overline{TA}_{retreat}(\tau, RT) - \overline{TA}_{no-ice}(\tau).$$

4. Results and Analysis

The entire GFD-November *DTA* data set is shown as a Hovmuller plot in Fig. 1 to illustrate *DTA* sensitivity to retreat threshold. Retreat threshold lies along the abscissa, and its 101 *DTA* time series are displayed in retreat-threshold order, each forming a column with contemporaneous elements horizontally synchronized. Note that the area of averaging decreases as the retreat threshold increases. The black region at high retreat thresholds indicates where the thresholds were so high that there was no area over which to average temperature anomaly. The ubiquity of *DTA* growth with retreat threshold throughout the record affirms the role of sea ice retreat in warming enhancement occurring over ice-retreat regions for this model-month. Although this GFD-November example is typical of NH winter patterns in all the models, the strength of the correlation does vary seasonally. Nevertheless, we can state unequivocally that when and where sea ice retreat enhances warming, and the magnitude of the warming increases with retreat threshold.

All calendar-monthly *DTA* time series with retreat thresholds of 20% are collated for each model as Hovmuller plots, so that each vertical column of data in these plots is a *DTA* time series extracted from a plot similar to Fig. 1. This threshold is chosen for illustration because all models experienced concentrations of at least 20% over substantial areas, while the areas of (for

Fig. 2. Hovmuller plots collating all calendar-month time series of *DTA* (20% retreat threshold) for the CCC and CSM models. Both panels use the Fig. 1 Celsius colorbar.

example) 50% and 80% ice retreat were small in the early decades for some of the models. Figure 2 contains two of these ‘calendar-monthly’ Hovmuller plots of *DTA* from the models most and least responsive to warming enhancement by sea ice retreat: the CCC model in panel (a) and the CSM model in panel (b). These two models, and the three not presented, all show a seasonal modulation of *DTA*, i.e., they sustain a seasonal cycle of warming enhancement with substantive warming by sea ice retreat (of ice-retreat areas relative to ice-free areas) during winter and negligible warming during summer.

This signal occurs throughout the *DTA* data, including the earliest years of the 21st century when CO₂ concentration was still close to its year 2000 value, due to sea ice retreat associated with interannual variation in the position of the polar ice edge (with respect to the reference fields). Therefore the first several years of the *DTA* data may perhaps be viewed as being representative of a seasonally modulated signal in quasi-dynamic equilibrium, i.e., not undergoing systematic changes other than from the seasonal cycle, prior to response to the B2-scenario greenhouse gas forcing. The time

Fig. 3. Model-composite difference between decadal means (2090's–1990's) of surface air temperature area-averaged over (red) region of ice-free ocean poleward of 50°N and (blue) region of NH ice retreat at threshold of 20%

dependent response (inclusive of all feedback mechanisms) of the CCC model manifests as a nonlinear (with respect to the seasonal cycle) amplification of warming enhancement that is most intense during late autumn and early winter. Contrarily, the CSM model has no discernable centennial trend. The other three models' responses lie somewhere in between, with clearly defined warming enhancement increasing over time similar to that of the CCC model, but with smaller magnitudes and modest phase differences.

The CCC model started the B2 portion of the run with too little sea ice, and the CSM model with too much, with respect to validated satellite observations of sea ice extent made during the early years of the 21st century. The CCC model then proceeded incurring the most sea ice retreat of any of the models, and CSM the least, through to the end of the runs in 2100. One explanation for the growth in warming enhancement experienced by the four models with the greatest sea ice retreat is that average ice concentration in the retreat region decreases with time, intensifying the influence of local retreat-related feedback processes. We conclude that the wide range of sea ice retreat observed in the ensemble of models directly corresponds with a wide range of warming enhancement by sea ice retreat. An ancillary point is that a realistically simulated seasonal cycle of sea ice distribution at the commencement of any GCM greenhouse gas forcing scenario (e.g., B2) is essential to a realistic simulation of greenhouse warming in the Arctic, because any estimates of warming in the Arctic include enhancements by sea ice retreat, which in turn is sensitive to the initial distribution of sea ice. This is consistent with the conclusion by Meehl and Washington (1990) that adequate representation of “the seasonal cycle is critical in the ice-albedo feedback process”.

Ensemble averages of model results tend to provide more realistic estimates than those from any single model, and a composite ‘calendar-monthly’ Hovmuller can be calculated by simple averaging of the 20% retreat threshold *DTA* data from all five models, i.e., those in

Fig. 2 and the three not shown. However, the regularity of the composite seasonal cycle and its amplification over time is similar to that of the CCC model. More can be learned by comparison of the relative magnitudes of the two components of composite DTA: composite $\overline{TA}_{\text{retreat}}$ and composite $\overline{TA}_{\text{no-ice}}$, so seasonal averages of the 2090's decadal mean of both are displayed in Fig. 3. The areas over which averaging was performed to obtain the values in Fig. 3 are regions of sea ice retreat from 2000 at a 20% retreat threshold (blue bars) and oceanic regions poleward of 50° N that were free of sea ice in 2000 (red bars).

Surface air temperatures show increases in both regions during all seasons. The increases are larger during fall, winter, and spring, and very slightly less during summer, over areas of sea ice retreat than over ice-free areas. The winter maxima and summer minima signify the seasonality of warming, with that over ice retreat areas being much more pronounced. The weaker variation over ice-free areas may be due at least in part to advective leakage of heat from ice-retreat areas. The experiment design ensures that ice retreat (inclusive of all possible feedbacks and processes) is a leading reason for differences between the areas, and warming over ice-retreat areas is by definition local. Therefore we conclude that enhancement of warming by sea ice retreat is highly seasonal, varying locally from essentially zero in the summer to 4–7 degrees (°C) in the late autumn and early winter.

5. Conclusions

This study has provided a preliminary assessment of the local enhancement of warming attributable to sea ice retreat in greenhouse simulations by five global climate models. Although the estimates presented here are lower bounds because they do not include advective effects, they provide a base upon which more comprehensive evaluations of sea-ice-albedo-temperature feedbacks can build. The main findings are the following:

- Sea ice retreat doesn't always enhance warming (e.g., summer), but when it does the magnitude of enhancement increases with the threshold used to define retreat because higher thresholds better isolate the warming enhancement signal over ice retreat areas.
- The models show a wide range of sea ice retreat, resulting in a corresponding range in the enhancement of warming by sea ice retreat. The model with minimal ice retreat not only provides little area for sampling of enhanced warming, but it also shows a weak sea ice signal irrespective of the threshold used to define retreat.
- The enhancement of warming by sea ice retreat is highly seasonal, varying *locally* from essentially zero in the summer to several degrees (°C) in the late autumn and early winter, when it is so strong that it clearly delineates areas of sea ice retreat.

The major challenge to an assessment of this type is to account for the "leakage" of the enhanced warming

that results from advection of the additional heat gained over newly ice-free ocean areas. Since some of this heat has already warmed areas that did not experience sea ice retreat in the model simulations, the sea ice contribution to the warming is underestimated by the methodology used here. Model experiments are planned with CCSM3 with advective fluxes evaluated across the boundaries between sea-ice-retreat areas and other areas, providing a means for the assessment of the full impact of sea ice retreat on the temperature of the Arctic. The results will be placed into a broader context of feedbacks (e.g., Alexeev 2003).

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References

- ACIA, 2004: *Impacts of a Warming Climate*, Cambridge University Press, Cambridge, U.K., 140 pp.
- Alexeev, V. A., 2003: Sensitivity to CO₂ doubling of an atmospheric GCM coupled to an oceanic mixed layer: a linear analysis. *Clim. Dyn.*, **20**, 775–787.
- Boville, B. A., J. T. Kiehl, P. T. Rasch and F. O. Bryan, 2001: Improvements in the NCAR CSM-1 for transient climate simulations. *J. Climate*, **14**, 164–179.
- Flato, G., G. J. Boer, W. G. Lee, N. A. McFarlane, D. Ramsden, M. C. Reader and A. J. Weaver, 2000: The Canadian Centre for Climate Modeling and Analysis global coupled model and its climate. *Clim. Dyn.*, **16**, 451–468.
- Gordon, C., C. Cooper, C. A. Senior, H. T. Banks, J. M. Gregory, T. C. Johns, J. F. B. Mitchell and R. A. Wood, 2000: The simulation of SST, sea ice extents and ocean heat transports in a version of the Hadley Centre coupled model without flux adjustments. *Clim. Dyn.*, **16**, 147–168.
- IPCC, 2000: *Special report on emission scenarios*: A special report of Working Group III of the Intergovernmental Panel on Climate Change (N. J. Nakicenovic and R. Swart, Eds.), Cambridge University Press, Cambridge, U.K., 599 pp.
- Knutson, T. R., T. L. Delworth, K. W. Dixon and R. J. Stouffer, 1999: Model assessment of regional surface temperature trends (1949–1997). *J. Geophys. Res.*, **104**, 30981–30996.
- Manabe, S., and R. T. Wetherald, 1975: The effects of doubling the CO₂ concentration on the climate of a general circulation model. *J. Atmos. Sci.*, **32**, 3–15.
- Meehl, G. A., and W. M. Washington, 1990: CO₂ climate sensitivity and snow-sea-ice albedo parameterization in an atmospheric GCM coupled to a mixed-layer ocean model. *Climate Change*, **16**, 283–306.
- Rind, D., R. Healy, C. Parkinson, and D. Martinson, 1995: The role of sea ice in 2 × CO₂ climate sensitivity. part 1: The total influence of sea ice thickness and extent. *J. Climate*, **8**, 449–463.
- Roegner, E., L. Bengtsson, J. Feichter, J. Lebevelde and H. Rodhe, 1999: Transient climate change simulations with a coupled atmosphere-ocean GCM using the tropospheric sulfur cycle. *J. Climate*, **12**, 3004–3012.

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