Amplified Arctic climate change: What does surface albedo feedback have to do with it?

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[1] A group of twelve IPCC fourth assessment report (AR4) climate models have Arctic (60N–90N) warmings that are, on average, 1.9 times greater than their global warmings at the time of CO_2 doubling in 1%/year CO_2 increase experiments. Forcings and feedbacks that impact the warming response are estimated for both Arctic and global regions based on standard model diagnostics. Fitting a zero-dimensional energy balance model to each region, an expression is derived that gives the Arctic amplification as a function of these forcings and feedbacks. Contributing to Arctic amplification are the Arctic-global differences in surface albedo feedback (SAF), longwave feedback and the net top-of-atmosphere flux forcing (the sum of the surface flux and the atmospheric heat transport convergence). The doubled CO_2 forcing and non-SAF shortwave feedback oppose Arctic amplification. SAF is shown to be a contributing, but not a dominating, factor in the simulated Arctic amplification and its intermodel variation.

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1. Introduction

[2] Polar amplification of CO_2 forced warming is a common feature of climate change simulations. In transient simulations, southern hemisphere warming is retarded by the large heat uptake of the Southern Ocean, leaving the Arctic as the global location with the largest warming. This aspect of the global warming pattern has often been linked to surface albedo feedback (SAF) – the extra absorption of shortwave radiation as ice melts and the surface becomes less reflective. It is the goal of this paper to place the SAF in the context of other feedbacks and forcings that affect Arctic amplification.

[3] Important work on this topic was done by *Hall* [2004] who showed, by disabling SAF in the GFDL climate model, that it accounts for part but not all of the polar amplification. *Vavrus* [2004] performed similar experiments with the GENESIS2 climate model to evaluate the role of cloud changes under doubled CO_2. He found that the cloud fraction changes enhanced the warming at all latitudes but by a fractionally greater amount in the Arctic, therefore enhancing Arctic amplification. The high-latitude response to increased CO_2 was found to be quite variable amongst the group of 15 CMIP climate models studied by *Holland and Bitz* [2003]. Using correlations, they identified a number of processes that contributed to the variation of Arctic amplification amongst the models. They found that models with larger increases in ocean heat transport, larger increases in cloud cover, and thinner control climate sea ice tended to have larger Arctic amplification. They proposed that thinner sea ice would lead to an increased ice-albedo feedback. However, *Flato and CMIP Modelling Groups* [2004] found that in the Southern Hemisphere, thinner ice was associated with reduced warming in the CMIP models. In the Southern Hemisphere, *Flato and CMIP Modelling Groups* [2004] found some tendency for models with more extensive ice to produce greater warming while in the Northern Hemisphere there was a tendency toward the opposite relationship. These studies emphasize the complexity of Arctic amplification and the multiplicity of processes that contribute to it.

[4] In this paper the conventional energy balance method of global climate sensitivity analysis is applied to both global and Arctic regions. Two forcings and three feedbacks are diagnosed in each region. A comparison is then made of the impact of differences in the forcings and feedbacks between the two regions on the Arctic amplification. The simulations analyzed come from the archive of climate model results made for the IPCC fourth assessment report (AR4). The twelve AR4 models used here were chosen because they supplied the necessary data to calculate the SAF using a method developed by *Winton* [2005b]. Details on the twelve models and the SAF analysis method are given by *Winton* [2005a].

2. Method

[5] A zero-dimensional energy balance model allows us to quantify the role of specific forcings and feedbacks in temperature sensitivity. The top-of-atmosphere forcings, F_i, and feedbacks, f_j, combine to form an expression for the surface air temperature change, ΔT:

$$\Delta T = -\frac{\sum F_i}{\sum f_j} \quad (1)$$

The sign of the f_j corresponds to the sign of the feedback – negative f_j reduce the magnitude of the response. Positive F_i correspond to forcings that increase the temperature. The forcings and feedbacks together partition the perturbation radiative energy balance at the top of the atmosphere. This energy balance has three components that sum to zero: shortwave, longwave, and net flux. There is some discretion in choosing to interpret a given perturbation flux as a forcing or a feedback – feedbacks are distinguished by having a direct or indirect connection to surface temperature.

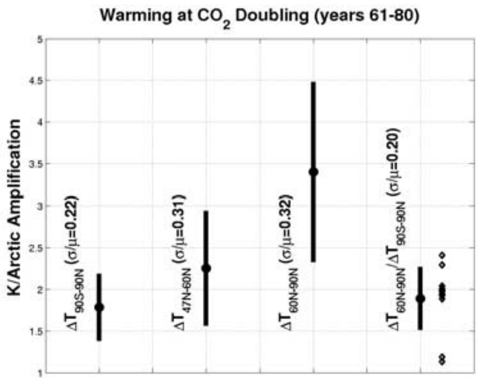

Figure 1. Model mean global, sub-Arctic, and Arctic warmings and their standard deviations. Model mean Arctic amplification and its standard deviation are also plotted. The diamonds at right represent the polar amplification values for the individual models.

[6] The CO_2 forcing, F_{CO2}, is produced by a separate radiation calculation and provided as a diagnostic in the AR4 archive. The other ''forcing'', from the atmosphere's perspective, is the net top-of-atmosphere flux, F_N:

$$F_N = \Delta S - \Delta OLR \tag{2}$$

where ΔS is the perturbation top-of-atmosphere shortwave absorption and ΔOLR is the perturbation outgoing longwave radiation. Since the atmospheric heat content change is negligible compared to this flux, F_N is approximately equal to the perturbation of the net heat flux through the surface plus the convergence of atmospheric heat transport. For the globe there is no perturbation atmospheric heat transport convergence so F_N represents the global surface flux – dominated by ocean heat uptake.

[7] The surface albedo feedback is estimated as:

$$f_{SAF} = \frac{\Delta S_{\alpha \to \alpha'}}{\Delta T} \tag{3}$$

where $\Delta S_{\alpha \to \alpha'}$ represents the change in the top-of atmosphere shortwave due to replacing the control run surface albedo, α, with the perturbation run surface albedo, α'. The method used for this replacement actually estimates the surface change but this has been shown for the GFDL model to be close to the top-of-atmosphere value [*Winton*, 2005a, 2005b]. Unfortunately, the other radiative feedbacks – temperature, water vapor, and cloud – cannot be evaluated with standard diagnostics. The standard diagnostics for evaluating the role of clouds, the clear sky radiative fluxes, are not directly useful for calculating the cloud feedback [*Soden et al.*, 2004] (see also B. J. Soden and I. M. Held, An assessment of climate feedbacks in coupled ocean-atmosphere models, submitted to *Journal of Climate*, 2005) (hereinafter referred to as Soden and Held, submitted manuscript, 2005). The methods for accurately calculating these feedbacks involve specially instrumented runs of the models and/or the model radiation codes [*Colman*, 2003a; Soden and Held, submitted manuscript, 2005]. To sidestep this difficulty, we group the feedbacks besides SAF into two composite feedbacks: non-SAF shortwave feedback, and longwave feedback. The non-SAF shortwave feedback contains contributions from clouds and water vapor. The longwave feedback contains contributions from clouds, water vapor and temperature. The non-SAF shortwave feedback and the longwave feedback are defined by:

$$f_{NON-SAF-SW} = \frac{\Delta S}{\Delta T} - f_{SAF} \tag{4}$$

and

$$f_{LW} = -\frac{F_{CO2} + \Delta OLR}{\Delta T} \tag{5}$$

respectively.

[8] The Arctic amplification is defined as the ratio of the Arctic and global warming. Using (1) for the global and Arctic regions, the Arctic amplification is related to the forcings and feedbacks in the two regions by:

$$\frac{\Delta T_A}{\Delta T_G} = \frac{(F_{CO2} + F_N)_A}{(F_{CO2} + F_N)_G} \frac{(f_{SAF} + f_{NON-SAF-SW} + f_{LW})_G}{(f_{SAF} + f_{NON-SAF-SW} + f_{LW})_A} \tag{6}$$

where the subscripts A and G refer to the Arctic and global regions respectively.

3. Results

[9] We begin by looking at the Arctic amplification of climate change in the 1%/year CO_2 increase experiments of the models. Figure 1 shows the model mean warming at CO_2 doubling (years 61–80) and the intermodel standard deviation for the globe, the Arctic (60N–90N), and a sub-Arctic region (47N–60N) constructed to have the same area as the Arctic region. The Arctic has a warming that is, on average, 1.9 times that of the globe and is much more variable among the models than that of the globe. The ratio of the standard deviation to the mean warming (coefficient of variation), a kind of noise to signal ratio, is 0.32 for the Arctic and 0.22 for the globe. This might reflect the particular difficulty of modeling Arctic climate processes specifically or it might simply reflect the greater variation in model simulations of regional climate change. The sub-Arctic region warming is only slightly amplified over global and has a variability that is intermediate between that of the globe and Arctic. The standard deviation to mean warming ratio is nearly the same for the sub-Arctic and Arctic suggesting that the models encounter roughly the same challenge in simulating climate change in the two regions. The diamonds at the right in Figure 1 show the Arctic amplifications for the individual models. Eight of the models have very similar amplifications just below 2, two are somewhat higher, and two have very little amplification.

[10] As noted, a special calculation is needed from each model to evaluate F_{CO2}, the impact of doubled CO_2 on the longwave flux at the tropopause allowing for the rapid adjustment of the stratosphere. Six of the twelve models have provided the doubled CO_2 forcing. These are listed in Table 1 for the global and Arctic regions. The direct CO_2 forcing is less for the Arctic than for the globe in all of these models. If this were the only difference between the two regions there would be less warming in the Arctic than for

Table 1. Global and Arctic Doubled CO_2 Tropopause Level Forcing for the Six Models Providing Data

Model	F_{CO2} (W/m^2) Global	F_{CO2} (W/m^2) Arctic	Arctic/Global
GISS MODEL E	4.21	3.20	0.76
MIROC 3.2 HIRES	3.59	2.69	0.75
MIROC 3.2 MEDRES	3.66	3.21	0.88
MPI ECHAM 5	3.98	3.25	0.82
UKMO HADCM3	4.03	3.12	0.78
UKMO HADGEM1	4.02	3.41	0.85

the globe. The reason for this has been discussed by *Colman* [2001] and *Pierrehumbert et al.* [2005]. The impact of any infrared absorber on OLR is dependent upon the vertical temperature gradient. In the limit of no gradient, greenhouse absorbers have no impact on OLR. Since the Arctic has a lower vertical temperature gradient than the globe as a whole, a given change in a greenhouse absorber will be less effective there. This effect can also be seen for water vapor in the work by *Colman* [2001, 2003b], Soden and Held (submitted manuscript, 2005) and *Pierrehumbert et al.* [2005], and for cloud fraction from *Colman* [2003b]. In winter, when the Arctic vertical temperature gradient is even smaller than the annual mean, the water vapor feedback is especially small and can even become negative [*Colman*, 2001, 2003b].

[11] The model mean forcings and feedbacks for global, sub-Arctic and Arctic regions are shown in Table 2. For models that did not report their CO_2 forcing, the mean of the six reporting models has been used to distinguish the longwave feedback in the perturbation OLR (equation (5)). All of the forcings and feedbacks show significant differences between the global and Arctic regions with intermediate values in the sub-Arctic region. As expected the SAF is larger for the Arctic than for the globe. It is perhaps surprising that the SAF for the sub-Arctic region is nearly as large as that of the Arctic. Although the surface albedo change and consequent shortwave change are smaller there than for the Arctic, the temperature change is also smaller (Figure 1) leading to a similar value for the equation (3) ratio. Differences in net TOA forcing and longwave feedback also contribute to amplification of Arctic climate change. The net TOA forcing is negative for the globe as expected for the transient uptake of heat by the global ocean. Furthermore there is a significant (at the 1% level) intermodel correlation between the global warmings and downward net fluxes. This might suggest treating this term as a (negative) feedback. However, F_N behaves quite differently in the Arctic. Although the model average Arctic F_N is near zero, there is a wide variation between the models, from -1.0 to 1.6 W/m^2. Between the models, the Arctic F_N is nearly uncorrelated with ΔT_A, ΔT_G, and $\Delta T_G -$ ΔT_A, discouraging treatment as a feedback. For uniformity, F_N is treated as a forcing in both regions.

Table 2. Model Mean Forcings and Feedbacks: Global, Sub-Arctic, and Arctic

Region	Forcings, W/m^2 F_{CO2}	Forcings, W/m^2 F_N	Feedbacks, $W/m^2/K$ f_{SAF}	Feedbacks, $W/m^2/K$ $f_{NON\text{-}SAF\text{-}SW}$	Feedbacks, $W/m^2/K$ f_{LW}
Global	3.92	−1.22	0.29	0.56	−2.45
Sub-Arctic	3.43	−0.77	0.72	0.03	−2.11
Arctic	3.15	0.07	0.75	−0.20	−1.61

Table 3. Arctic Amplification With Model Mean Parameters and Global to Arctic Forcing/Feedback Replacement (First Row) and Sub-Arctic to Arctic Forcing/Feedback Replacement (Second Row)

	Neutralized: None	F_{CO2}	F_N	f_{SAF}	$f_{NON\text{-}SAF\text{-}SW}$	f_{LW}
$\Delta T_A/\Delta T_G$	1.81	2.24	1.08	1.26	6.48	1.01
$\Delta T_A/\Delta T_{SA}$	1.56	1.70	1.15	1.52	2.00	1.06

[12] To quantify the impact of individual forcings and feedbacks on Arctic amplification we replace each Arctic term with its global counterpart in (6) and note the Arctic amplification that remains when the term is thus neutralized (Table 3, first line). The second line of Table 3 shows the result of performing this neutralization exercise upon the amplification of the Arctic temperature change over that of the sub-Arctic. For these calculations the model mean forcings and feedbacks are used. Due to the nonlinearity of (6), the model mean terms give an Arctic-global amplification that is slightly less than the model mean Arctic amplification: 1.81 vs. 1.9. The largest impact comes from neutralizing the non-SAF-SW term which increases the Arctic amplification to over 6. This result implies that the Arctic-global difference in this feedback strongly opposes Arctic amplification. Even reducing the global feedback by the Arctic-to-global insolation ratio (0.6) before substituting for the Arctic feedback would only bring this number down to 3.6, leaving it as the difference with the largest impact on Arctic amplification. A small increase in amplification comes from neutralizing the CO_2 forcing. Neutralizing either the longwave feedback or net TOA forcing nearly eliminates the Arctic amplification, implying that the Arctic-global differences in these terms strongly favor Arctic amplification. Neutralizing SAF reduces the Arctic amplification but does not eliminate it. The neutralization of factors contributing to Arctic-sub-Arctic amplification show similar effects except that the SAF neutralization has virtually no impact. These results support the interpretation of SAF as a contributor to Arctic amplification but not a dominating influence upon it.

[13] Now we turn to the causes of the differences in the model simulations of Arctic amplification (Figure 1). Our method for evaluating the impact of an individual forcing or feedback upon a specific model's relative Arctic amplification is similar to that used to evaluate the role of the individual factors in Arctic amplification. We neutralize each forcing or feedback as a source of intermodel variation by replacing both the global and Arctic values by their model mean counterparts in equation (6). Performing all such replacements would result in a value of 1.81 (Table 3). We can quantify the impact of the individual effect on the outlying behavior as the degree to which its neutralization moves the model's outlying amplification toward this value. The results of performing this intermodel neutralization procedure for the four outlying models is shown in Table 4. The first low-lying model has the non-SAF shortwave feedback as the dominant contributor to its low amplification with a significant contribution from the net TOA forcing and an opposing (amplification decreasing)

Table 4. Arctic Amplification of Four Outlying Models (Two Low and Two High) When Individual Effects are Neutralized By Replacing the Given Model Forcing or Feedback With the Model Mean Value[a]

	Neutralized					
	None	F_{CO2}	F_N	f_{SAF}	$f_{NON\text{-}SAF\text{-}SW}$	f_{LW}
Model 1	1.13	1.13	1.34	1.18	1.65	0.78
Model 2	1.18	1.29	1.23	1.34	1.35	1.18
Model 3	2.29	2.29	2.98	2.39	1.64	1.82
Model 4	2.41	2.28	2.75	1.97	1.91	2.31

[a]Using all model mean values gives an Arctic amplification of 1.81 (Table 3).

effect from the longwave feedback. The second low amplification model has small contributions toward its low amplification from all factors except the longwave feedback. The non-SAF shortwave forcing is the dominant contributor to the high amplification of the third model joined by a significant contribution from the longwave feedback. The two shortwave feedbacks dominate the high amplification of the fourth model. Summarizing, multiple factors contribute to the outlying behavior of the four models but, in each case, the non-SAF shortwave feedback has the largest influence. For both global and Arctic regions this is the feedback with the largest intermodel variation.

[14] The intermodel neutralization procedure was also applied to the eight similarly amplified models. The standard deviation of amplifications was larger for each neutralized effect than for the unmodified amplifications, indicating compensations between the various forcings and feedbacks are contributing to the agreement within this group.

4. Conclusions

[15] The analysis of forcings and feedbacks performed in this paper shows that the Arctic amplification arises from a balance of significant differences in all forcings and feedbacks between the Arctic and the globe. The direct CO_2 forcing and non-SAF shortwave feedback inhibit Arctic amplification while the net TOA flux forcing, SAF, and longwave feedback favor it. The SAF, while important, is a lesser factor than the net TOA flux forcing and the longwave feedback in promoting Arctic amplification. Comparing the Arctic and sub-Arctic regions (Table 2), SAF is a negligible influence on the substantially greater temperature change in the Arctic. Multiple factors also contribute to the model differences in Arctic amplification with the non-SAF shortwave feedback seemingly the most important.

[16] Since multiple processes contribute to the two composite feedbacks and the net TOA flux forcing, it is difficult to associate the Arctic-global differences with specific features of the atmosphere's CO_2 response. For example, there are reasons to expect significant contributions to the Arctic-global longwave feedback difference from cloud, water vapor and temperature feedbacks [*Colman*, 2001, 2003a; *Vavrus*, 2004; Soden and Held, submitted manuscript, 2005]. Combining these feedbacks might lead to either an under- or overestimation of the relative role of SAF. A clearer picture of the mechanisms of Arctic amplification in the models will require application of more refined feedback analysis techniques.

[17] A caveat must also be attached to the factor replacement technique employed in this study. The determination of a factor as forcing or feedback and the association of a feedback with a particular temperature change are somewhat arbitrary. This determination affects the role a factor plays in the adjustment that occurs when another factor is perturbed. The increased CO_2 experiment alone is inadequate to distinguish dependencies from co-variation and thus insufficient for accurately formulating these terms. Idealized "ghost forcing" experiments would be helpful for this purpose.

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