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Linear additivity of climate response for combined albedo and greenhouse perturbations

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Abstract. Using an atmospheric general circulation model with fixed cloud amounts and microphysical properties, and coupled to a mixed-layer static ocean, we perform idealized experiments to inquire into the linear characteristics of the modeled climate system's mean response to simultaneous greenhouse and Northern Hemisphere midlatitude albedo perturbations, two forcings deemed to be important during the present times. The two forcings are chosen to be equal and opposite in the global, annual-mean such that a linear behavior would be expected to lead to a complete offset of the global, annual-mean surface temperature change, which is indeed obtained. The monthly and annual zonal-mean surface temperature, and the annual zonal-mean precipitation responses to the combined forcings, also are reasonably similar to the sum of the responses to the individual forcings. The albedo forcing case casts a distinct signature on the circulation and precipitation changes in the northern and southern equatorial regions, which is absent for the greenhouse forcing case. The combined simulation yields a result similar to that for the albedo forcing case, one that is consistent with linear additive expectations.

1. Introduction

In contemporary discussions of the anthropogenic climate forcing of Earth, it is recognized that there is a substantial positive and negative forcing due to greenhouse gases and sulfate aerosols, respectively [*Schimel et al.*, 1996]. With the increased recognition of the tropospheric aerosol contribution to climate forcing, there has arisen a motivation to explore the consequences of aerosol-induced albedo perturbations [*Taylor and Penner*, 1994; *Mitchell et al.*, 1995]. An issue of central importance in this regard is whether the modeled climate response is linearly additive when the two kinds of radiative perturbations operate simultaneously [*Wigley*, 1994]. What makes this issue intriguing is that not only do the two forcings differ in sign but they also have completely different spatial patterns [*Shine et al.*, 1995]. Model studies to date suggest that the global, annual-mean surface temperature response and the seasonal response to combined forcings are, indeed, linearly additive [*Santer et al.*, 1995; *Cox et al.*, 1995; *Penner et al.*, 1996].

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Quite apart from being a scientific curiosity in climate change research, the resolution of the above issue is particularly important for policy decisions concerning the anthropogenic build-up of greenhouse gas and aerosol concentrations. As noted by *Wigley* [1994], a related factor is that, because climate model integrations are computationally expensive, the validity of a linearly additive characteristic in the response to combined forcings would be useful as a first-order indicator of climate change. Thus, with the intent of extracting insights into the character of the response to combined greenhouse and albedo perturbations, we pose the following questions: Does the zonal-mean surface temperature response for a northern hemisphere midlatitude albedo and greenhouse perturbation add up linearly to resemble the combined case, just as for the global-mean? Is such a linearity also apparent in the annual, zonal-mean precipitation change? Are there distinctive features associated with either forcing that emerge also when both operate simultaneously? We build upon the general circulation model (GCM) investigations of *Chen and Ramaswamy* [1996a, b; hereafter CR96a and b, respectively] to address these questions.

2. GCM Experiments

The GCM employed is a version of the GFDL R15 atmospheric general circulation model with fixed cloud amounts, coupled to a mixed-layer static ocean; cloud microphysical properties are prescribed and held fixed in each simulation (CR96a). The greenhouse perturbation ("GHG") studied here consists of an increase in the model's CO_2 content by a factor of 1.45 which yields a global, annual-mean forcing of 1.9 W/m^2 (estimated at the tropopause; see CR96a). While the choice of the forcing value is somewhat arbitrary, it is comparable to that due to the total anthropogenic greenhouse gas changes [*Schimel et al.*, 1996]. The midlatitude northern hemisphere albedo perturbation ("ALB") corresponds to the 'LLI' case discussed in CR96b. The perturbation is obtained by imposing an increase in the liquid water content of the low clouds occurring between 20 and 70N in the model such that the global, annual-mean albedo forcing is approximately -1.9 W/m^2. The albedo forcing thus imposed is an idealized one, resulting in a net solar irradiance change at the tropopause (or equivalently, top-of-the-atmosphere) between 20 and 70N, with a zonal distribution that is similar to the anthropogenic sulfate aerosol forcing [*Shine et al.*, 1995]. Though the "ALB" and "GHG" forcings have the same magnitude in the global, annual-mean, they have a very different spatial distribution (CR96 a, b). The forcing values chosen for the purposes of this study ensure a substantial response signal in the

GCM simulations. The choice of an equal magnitude for the two forcings is deliberate and is designed to investigate whether the combined simulation, with a net zero global, annual-mean forcing, yields a null climate response. In the combined simulation ("ALB+GHG"), both forcings operate simultaneously. The equilibrium model climate response for each simulation is examined by taking the averages of the last 10 years of 35-year runs, and subtracting the corresponding values obtained in the 'control' run (CR96a, b). We denote the sum of the individual responses by "ALB"+"GHG", which differs from the notation used to denote the response to the combined forcings.

3. Results

The global, annual-mean surface temperature change for the "GHG", "ALB" and "ALB+GHG" simulations is 1.31, -1.39 and -0.09, respectively, thus confirming expectations from an arithmetic summation [see also *Santer et al.*, 1995 and *Cox et al.*, 1995]. However, these global, annual-mean results cannot be taken to imply *a priori* that linearity is present in other aspects of climate change. The null global-mean response indicates that the total climate feedback, which is similar for the individual forcings (CR96a,b), adds up linearly to yield a near-zero, global-mean response for the combined case, in spite of the fact that the negative forcing occurs in only one hemisphere. This inference does not necessarily imply a linear additivity in the strengths of the individual feedback mechanisms, which in fact are dissimilar for the individual greenhouse and albedo perturbations (CR96 a, b).

Figure 1 illustrates the zonal, annual-mean surface temperature change for the three simulations, and for the arithmetic sum, "ALB"+ "GHG". In accordance with the forcing distribution, "ALB" yields a negative response that is concentrated in the northern hemisphere, while "GHG" induces a positive response in both hemispheres. Relative to "GHG", the albedo changes initiate a larger difference between the northern and southern hemisphere polar (60-90^{o}) responses, a factor of considerable interest in the detection and attribution of climate change [*Santer et al.*, 1996]. The linear sum of the individual responses ("ALB"+"GHG") is approximately similar to the combined case ("ALB+GHG") at most latitudes. The departure of the mean values from a strict linearity in the ~60-90N region is not statistically significant owing to the large variability exhibited by the model at these high latitudes [see, for example, *Manabe and Stouffer*, 1996].

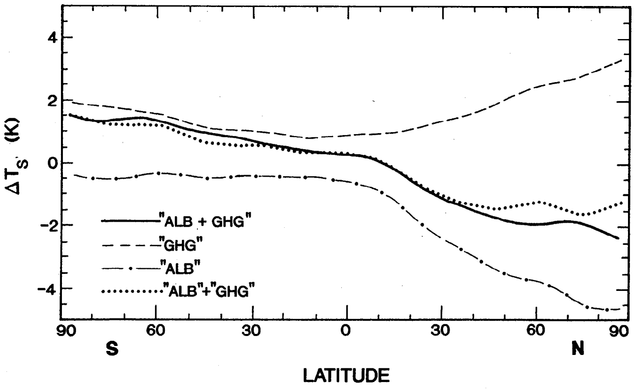

Figure 1. Change (with respect to 'control') in the annual, zonal-mean surface temperature (K) for the "ALB", "GHG", and "ALB+GHG" simulations, and as obtained by summing "ALB" and "GHG".

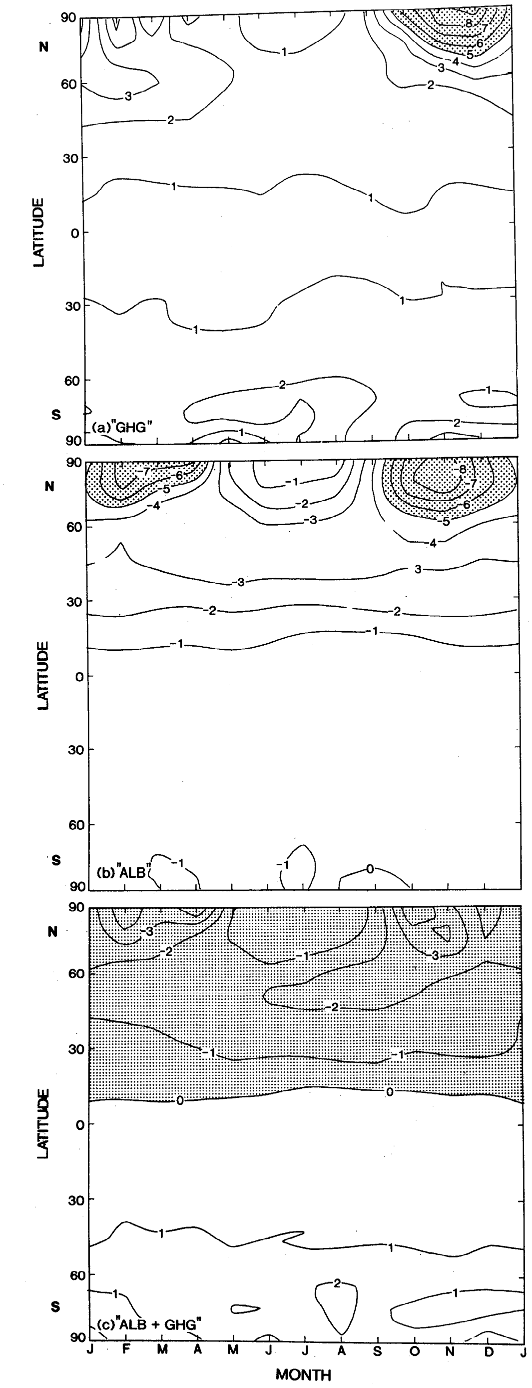

Figure 2. Monthly, zonal-mean change (with respect to 'control') in the surface temperature (K) for the (a) "GHG", (b) "ALB", and (c) "ALB+GHG" simulations.

Figure 2 illustrates the monthly, zonal-mean surface temperature changes. For "GHG", there is a polar amplification, particularly strong from fall through winter, owing to changes in sea-ice distribution and thickness [*Manabe and Stouffer*, 1980; CR96a]. The "ALB" simulation, owing to its relatively larger hemispheric forcing than "GHG", exhibits stronger amplification effects in the northern polar region throughout the year. However, in the southern polar region, the "ALB" response is relatively weak due to the weak interhemispheric exchange of the albedo-induced energy changes in the model (CR96b).

The "ALB+GHG" result suggests an approximate linear additivity of the individual effects in the seasonal cycle of the mean surface temperature changes, with a considerable weakening of the northern polar response relative to both "ALB" and "GHG". The negative albedo response dominates over the greenhouse one in almost the entire northern hemisphere while the converse is true in the south, consistent with the asymmetrical hemispheric distribution of the two forcings.

In the northern polar region, the seasonal "GHG" effect is generally less than "ALB", and the combined result is a negative change. For example, at 75N, the "GHG", "ALB" and "ALB+GHG" cases yield, respectively: for January, 4, -5 and -2.5 K; for April, 2, -4, and -2.5 K; for July, 1, -1.5 and -0.5 K; for October, 3.5, -6.5 and -3.5 K. Just as for the annual-means, the zonal, monthly-mean changes must be juxtaposed with the model's seasonal variability, which is notably large in the high latitudes (not shown) and thus renders the apparent departures from linearity statistically insignificant. There is a substantial difference in the magnitude of the winter-to-summer northern polar temperature changes. This holds for both "ALB" (cooling) and "GHG" (warming) cases, more so for the former. The linear characteristic of the climate system's response yields, for the combined case, a weakening of this gradient. The equator-to-pole gradient, too, is less for the combined case relative to "ALB" and "GHG" almost throughout the year.

Figure 3 illustrates the changes in the zonal-mean precipitation rates (land+ocean areas). The changes due to CO_2 result in a fairly uniform increase of precipitation everywhere, with the exception of a slight decrease in the southern subtropics. In contrast, the "ALB" simulation yields distinct changes just to the north and south of the equator. This feature due to the albedo perturbation becomes superposed on the "ALB+GHG" simulation, in approximate accordance with expectations from a linear addition ("ALB"+"GHG"). It is cautioned that this agreement could be fortuitous and is likely model-dependent. Further, the decadal-mean patterns could be subject to considerable interdecadal variability.

The changes in the precipitation pattern can be further understood by considering the changes in the mass meridional streamfunction (Figure 4). The "control" simulation (see Figure 5b of CR96b) indicates separate cells just north and south of the equator, with a rising motion at the equator and descent in the subtropical regions. In "ALB" (Figure 4b), there is a weakening of the ascending branch to the north of the equator, and a strengthening of the rising motion just south of the equator. As pointed out in CR96b, the difference in the hemispheric responses (see Figure 1) yields an enhanced temperature gradient, induces a change in the tropical meridional circulation, and intensifies somewhat the heat and moisture exchange between the two hemispheres across the equator. Thus, the tendency for a relatively larger surface cooling in the northern tropical regions (Figures 1, 2) due to the albedo change reduces convective activity, diabatic heating, low-level moisture flux convergence and precipitation (Figure 3). In contrast, the ascending motion and all the above-mentioned variables are enhanced in the southern equatorial region, thus effectively moving the tropical precipitation belt towards the warmer hemisphere. No such features are observed for "GHG" (Figure 4a), and differential changes across the equator are less distinguishable (also Figure 3). There is a tendency to strengthen the ascending motion in both the northern and southern equatorial regions, but the magnitudes are less than for "ALB".

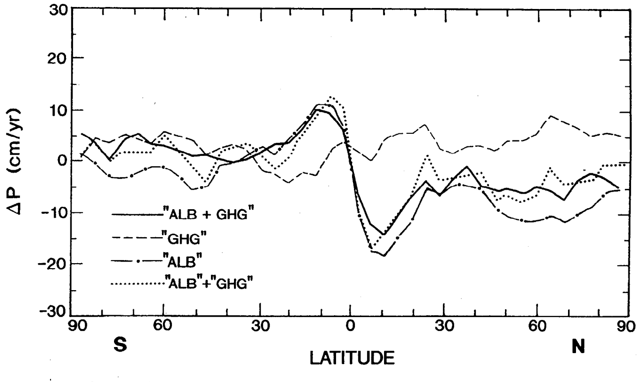

Figure 3. As is Figure 1, except for the change in the precipitation rate (cm/yr).

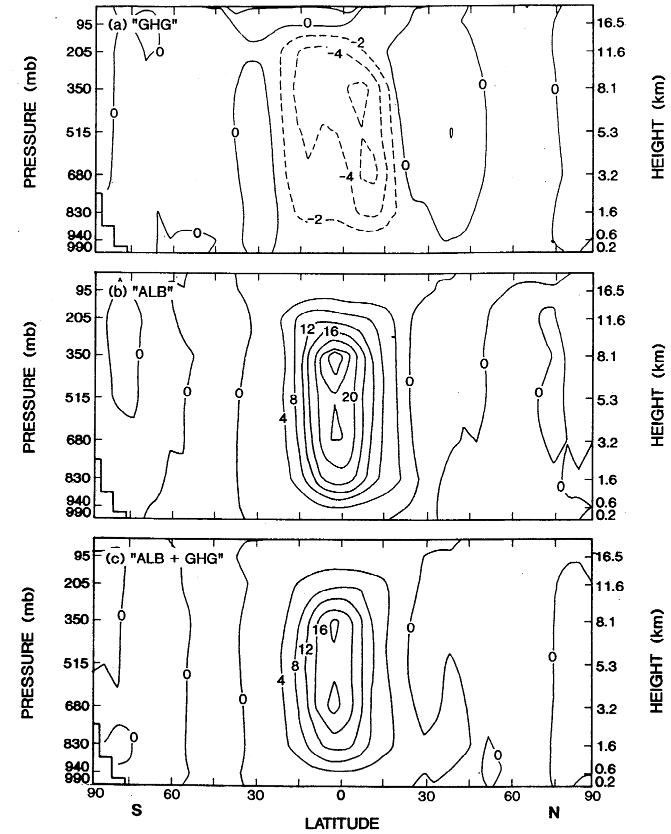

Figure 4. Change (with respect to 'control'; see CR96b) in the annual, zonal-mean mass meridional streamfunction for (a) "GHG", (b) "ALB", and (c) "ALB+GHG" simulations. Solid (positive values) and dashed (negative values) contours indicate changes in the clockwise and anticlockwise sense, respectively, in units of 10^9 kg s^{-1}.

The "ALB+GHG" simulation (Figure 4c) clearly indicates that, in the mean, the sum zonal effect is one of an approximate superposition of the individual "ALB" and "GHG" response patterns. The effect due to the northern hemisphere albedo perturbation is manifest in a dominant manner, consistent with the precipitation changes (Figure 3). These results suggest that an increased albedo in the midlatitude northern hemisphere due to anthropogenic sulfate aerosols could affect the equatorial climate through a latitudinal shift of the intertropical convergence zone. This occurs despite the greenhouse gases' effects, and in spite of a near-complete offset in the global annual-mean forcing and surface temperature response.

4. Discussion

Our study indicates that aspects of the climate responses to a combined greenhouse and a northern hemisphere midlatitude albedo forcing behave as a linear sum of the responses to the individual forcings. On time scales less than annual, and spatial scales less than global, while there is still a good qualitative capture of the net effect based on linear additivity expectations, such a linearity need not be quantitatively exact for the mean value of the response, e.g., at high latitudes. However, the concept of linear additivity may still be applicable because, in these regions, the model's variability is large [*Manabe and Stouffer*, 1996] and, thus, apparent departures of the mean value from linearity expectations need not be statistically significant [see also *Penner et al.*, 1996]. With respect to the questions posed at the outset, we find that, in addition to the global, annual-mean change, the surface temperature changes in the monthly-and annually-averaged zonal sense also add up in an approximately linear manner; likewise, for the annual, zonal-mean precipitation. In addition, this study finds that the northern hemisphere midlatitude albedo perturbation exerts a characteristic precipitation change just north and south of the equator; this is manifest in the combined simulation, too, in accordance with linear expectations.

The results here strongly suggest that there are limitations in interpreting climate change based solely on the global, annual-mean surface temperature response, reiterating and extending earlier findings [*Santer et al.*, 1995; *Cox et al.*, 1995]. Thus, even if a linear and/or complete offset in the global annual-mean surface temperature change were to occur due to greenhouse gases and albedo forcings from aerosols, this could be accompanied by distinct shifts in the equatorial precipitation. While policy debates concerning anthropogenic emissions could still regard the linear sum of the global annual-mean surface temperature changes as a rough indicator of climate change for combined forcings, the danger of over-reliance on this single parameter and its limitation in describing significant changes in other climate variables must be recognized.

The study here should be regarded as another step in understanding the climate response due to a combination of different radiative forcing types. It is evident that all global-mean changes are not accompanied by the same pattern of zonal-mean changes and that, even with no global-mean change in response to forcings, there could be notable changes in the pattern of climate. Further GCM studies need to be done to examine the sensitivity of the linear additivity concept to uncertainties in physical parameterizations, cloud feedbacks (including amounts and properties), oceanic heat transports, and variability on various spatial and temporal scales. It is noted that other simulations [*Cox et al.*, 1995; *Penner et al.*, 1996], which have employed interactive clouds (unlike the study here), also suggest a linear additivity of the surface temperature response. It is important to determine whether more spatially heterogenous or larger values of forcings could alter the linear behavior. Finally, while this study has examined equilibrium solutions, a similar examination should be carried out for transient simulations, too.

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References

Chen, C-T., and V. Ramaswamy, Sensitivity of simulated global climate to perturbations in low cloud microphysical properties. I. Globally uniform perturbations, *J. Climate*, *9*, 1385-1402, 1996.

Chen, C-T., and V. Ramaswamy, Sensitivity of simulated global climate to perturbations in low cloud microphysical properties. II. Spatially localized perturbations, *J. Climate*, in press.

Cox, S. J., W-C. Wang and S. E. Schwartz, Climate response to forcings by sulfate aerosols and greenhouse gases, *Geophys. Res. Lett.*, *18*, 2509-2512, 1995.

Manabe, S., and R. J. Stouffer, Sensitivity of a global climate model to an increase of CO_2 concentration in the atmosphere, *J. Geophys. Res.*, *85*, 5529-5554, 1980.

Manabe, S., and R. J. Stouffer, Low-frequency variability of surface air temperature in a 1000-year integration of a coupled atmosphere-ocean-land surface model, *J. Climate*, *9*, 376-393, 1996.

Mitchell, J. F. B., T. J. Johns, J. M. Gregory and S. F. B. Tett, Climate response to increasing levels of greenhouse gases and sulfate aerosols, *Nature*, *376*, 501-504, 1995.

Penner, J. E., T. M. L. Wigley, P. Jaumann, B. D. Santer, and K. E. Taylor, Anthropogenic aerosols and climate change: A method for calibrating forcing. Submitted to *Assessing Climate Change-The Story of the Model Evaluation Consortium for Climate Assessment*, in press, 1996.

Santer, B. D., K. E. Taylor, T. M. L. Wigley, J. E. Penner, P. D. Jones and U. Cubasch, Towards the detection and attribution of an anthropogenic effect on climate. *Clim. Dyn.*, *12*, 79-100, 1995.

Santer, B. D., T. M. L. Wigley, T. P. Barnett, and E. Anyamba, Detection of climate change and attribution of causes. In *Climate Change 1995: The Science of Climate Change, Contribution of Working Group I to the Second Assessment of the Intergovernmental Panel on Climate Change* (J. T. Houghton et al., eds.), Cambridge University Press, New York, pp. 407-443, 1996.

Schimel, D. et al., Radiative forcing of climate change. In *Climate Change 1995: The Science of Climate Change, Contribution of Working Group I to the Second Assessment of the Intergovernmental Panel on Climate Change* (J. T. Houghton et al., eds.), Cambridge University Press, New York, pp. 65-131, 1996.

Shine, K. P., Y. Fouquart, V. Ramaswamy, S. Solomon and J. Srinivasan, Radiative Forcing. In *Climate Change 1994: Radiative Forcing of Climate Change and An Evaluation of the IPCC IS92 Emission Scenarios* (J. T. Houghton et al., eds.), Cambridge University Press, Cambridge, New York, pp. 163-203, 1995.

Taylor, K. E., and J. E. Penner, Response of the climate system to atmospheric aerosols and greenhouse gases. *Nature*, *369*, 734-737, 1994.

Wigley, T. M. L., Outlook becoming hazier. *Nature*, *369*, 709-710, 1994.

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