General Circulation Model Feedback Sensitivity Assessment

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Feedback Effects in Climate GCMs

Estimating the magnitude of the climate system response to a radiative forcing perturbation is made difficult by feedback contributions that can magnify or diminish the initial effect of the forcing. A comparative study of radiative forcing parameterizations in 12 different general circulation models (GCMs) by Cess et al. (1993) showed that GCM forcing for doubled CO_2 ranged from 3.38 to 4.74 Wm^{-2}, but that the spread in the global mean surface temperature response to the radiative forcing ranged from 1.7° to 5.3°C. This larger spread in the GCMs' responses is a clear indication of their greater diversity in feedback sensitivity than in their radiative forcing. As climate changes in response to the initial forcing, feedback contributions arise from the additional radiative effects that are generated by

1. changes in water vapor amount and distribution
2. changes in cloud cover, height and optical depth
3. changes in snow/ice cover, i.e., surface albedo
4. changes in advected energy transports.

Since the feedbacks that contribute to the total change in global temperature are produced by complex interactions between different physical processes, it is very difficult to isolate and evaluate the strength of individual feedbacks directly from the GCM output, even in carefully constrained climate experiments.

Radiative-Convective-Advective Equilibrium

Whenever the local atmospheric temperature gradients become unstable because of solar heating of the ground, "convective adjustment" takes place. Energy is transported upward within the troposphere and, in the process, the "critical lapse rate" of tropospheric temperature is established. Similarly, in response to the seasonally driven change in solar forcing, there is a latitudinal redistribution of energy by dynamical transports resulting in the meridional advection of energy. In view of the continuous change in diurnal and seasonal radiative forcing, the atmosphere is never actually allowed to reach equilibrium. However, on an annually averaged basis, there is reason to expect that the net Top-of-the-Atmosphere solar and thermal fluxes and the meridionally advected sensible, latent, and geopotential energy must be in balance at each latitude when the global climate is in an equilibrium state. On this basis, it is appropriate to consider a detailed 1-Dimensional Radiative-Convective Model (1-D RCM) type energy balance analysis for each individual latitude zone.

Feedback Analysis

The relative strengths of the different climate feedbacks can be determined by computing the magnitude of the change in equilibrium surface temperature attributable to specific changes in atmospheric structure and/or to changes in the concentration and distribution of the radiatively active constituents. This information can be obtained by using a 2-Dimensional Radiative-Convective-Advective equilibrium model (2-D RCAM) to analyze the changes in the latitudinal energy balance that take place between the GCM experiment and the GCM control run. The input information required for this analysis consists of the zonally averaged annual average temperature and water vapor profiles, advected energy transports, cloud cover, and surface albedo from the GCM experiment and control runs.

As the first step, we need to express the radiative forcing perturbation in terms of the equivalent equilibrium temperature change, ΔT_0, that would restore the radiative energy balance in the absence of feedback contributions. The latitudinal dependence of this radiative forcing term, ΔT_0, is shown in the upper panels of Figure 1 by the heavy red lines for the 2% solar constant and doubled CO_2 experiments, respectively. The net feedback factor, f, can then be identified as the multiplication factor that relates the radiative forcing term to the total change in equilibrium temperature. Thus,

$$\Delta T_t = f \Delta T_o$$

where ΔT_t is the total change in equilibrium surface temperature with all feedback contributions included, and ΔT_0 is the no-feedbacks forcing. Since ΔT_t consists of both forcing and feedback components, we can write

$$\Delta T_t = \Delta T_o + \Delta T_{feedbacks}$$

If we assume that the feedback contributions can be separated into portions that are identifiable with specific feedback processes, then

$$\Delta T_{feedbacks} = \Delta T_w + \Delta T_c + \Delta T_s + \Delta T_a +$$

where the subscripts w,c,s,a designate the broad categories of water vapor, cloud, snow/ice, and advective feedbacks, respectively. (The water vapor feedback, for example, may be subdivided further into specific ΔT components associated with changes in column amount, changes in vertical distribution, and lapse rate changes in the temperature profile.) By implication, the climate feedbacks are assumed ultimately to be temperature driven, and their response is assumed to be the total change in temperature that is encountered. Hence the relative strength of the feedback contribution of the i^{th} feedback process is given by the ratio

$$g_i = \Delta T_i / \Delta T_t$$

where ΔT_i denotes the equilibrium temperature change contribution (as obtained with the 2-D RCAM) for the specified change in the amount and/or distribution of the radiative constituent associated with the i^{th} feedback process. It follows, then, that the individual feedback strengths, g_i, are additive quantities, but feedback factors combine non-linearly as

$$f = (1 - \Sigma g_i)^{-1}$$

Thus, with the help of a 2-D RCAM, this approach yields the latitudinal dependence of the radiative forcing and of the climate feedback sensitivity shown in Figure 1. Hansen et al. (1984) carried out a similar analysis using globally averaged annual average GCM output and running the GCM radiation code as a 1-D RCM to determine the global average feedback sensitivity of the GISS GCM for the 2% solar constant and the doubled CO_2 experiments. While this approach yields only information on the GCM global feedback sensitivity, the analysis is greatly simplified in that globally averaged, the advected energy fluxes are zero, and knowledge of the annually averaged latitudinal solar zenith angle dependence is not required.

Model Results

The upper panels in Figure 1 show the latitudinal dependence of radiative forcing, ΔT_0, and of the principal feedback components for the 2% solar constant and doubled CO_2 experiments, respectively. Even though the radiative forcing (heavy red lines) is concentrated in the tropics for the solar constant change and is latitudinally uniform for CO_2 forcing, the latitudinal temperature response of the GCM (heavy black lines) and the overall feedback contributions (multi-colored lines) of water vapor, snow/ice, cloud, and advective feedbacks are remarkably similar for the two forcings. The green and yellow lines demonstrate the general ability of the 2-D RCAM to reproduce the actual GCM temperature changes in terms of annually averaged GCM climatological information. The green line represents the sum of individual ΔT_i responses computed separately, and the yellow line is the combined response, ΔT_t, to all constituent changes computed together in the 2-D RCAM; the relatively small differences indicate that non-linearities in feedback interactions are comfortably small.

The bottom panels in Figure 1 show the magnitude and latitudinal variability of the individual components of the advective and water vapor feedbacks. These can be

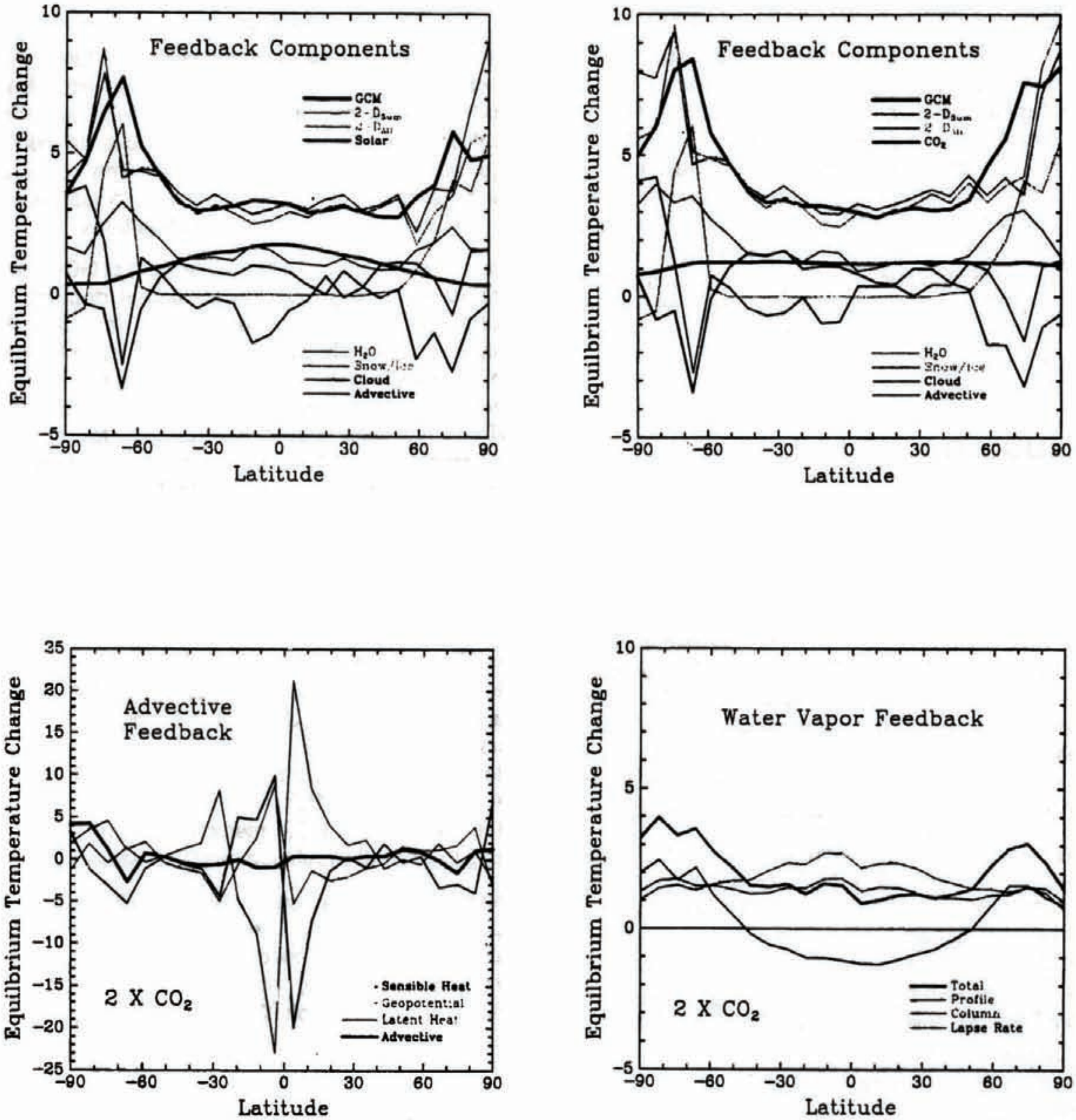

Figure 1. The upper panels show GCM surface temperature response (heavy black) and radiative forcing (heavy red), for 2% solar constant and doubled CO_2 experiments, respectively. The blue, grey, purple, and magenta lines represent feedback contributions to the equilibrium temperature change from water vapor, snow/ice, cloud, and advective feedbacks, respectively. The green line is the sum of individual ΔT_i responses computed separately, while the yellow line is the combined response, ΔT_t, to all constituent changes taken together. The bottom panels show the individual components of the advective and water vapor feedbacks.

separately analyzed and used as a diagnostic tool to investigate changes in dynamical energy transport and in the hydrological cycle in response to climate forcing perturbations. As expected, there is large-scale cancellation between the advective transports of geopotential energy and of sensible and latent heat. Within the water vapor feedback components, feedback enhancement is increased by changes in the vertical distribution of water vapor, which, in low to mid-latitudes, is largely canceled by the negative lapse rate feedback due to moist convection. However, at polar latitudes the change in lapse rate provides positive feedback.

Conclusions

By using the zonally averaged, annual average climatologies of the GCM experiments as input data to the 2-D RCAM (which uses the same radiation code as the GCM), we can closely reproduce the latitudinal dependence of the annual average atmospheric thermal structure and surface temperature changes that were obtained in GCM climate change simulations. Since the radiative input parameters of the 2-D RCAM can be changed at will, the equilibrium surface temperature change can be evaluated separately for each specified change in amount or vertical distribution of individual radiative constituents, thus defining the magnitude of individual relative feedback strengths.

Water vapor feedback is strongly positive and roughly uniform with latitude. Positive feedback at low to middle latitudes is enhanced by the vertical shift in water vapor, which is largely canceled by the negative lapse rate feedback due to moist convection. Snow/ice albedo feedback is associated primarily with changes in sea ice and is confined to polar latitudes. Cloud feedback is strongly positive at low to middle latitudes, due primarily to a decrease in low clouds and an increase in cirrus. Negative cloud feedback occurs in the polar regions. Sensible, latent, and geopotential energy feedbacks are individually large, but tend to cancel each other. The net advected energy feedback is highly variable with latitude and is strongly anti-correlated with cloud feedback.

As demonstrated, a quantitative measure of GCM response to radiative forcing and the latitudinal dependence of feedback sensitivity can be obtained from 2-D RCAM analysis of annually averaged GCM climatologies from climate change experiments. This type of analysis can provide important diagnostic information regarding GCM performance and would be suitable for conducting intercomparisons of GCM feedback sensitivity. Such intercomparisons would help to clarify the reasons for the 1.7° to 5.3 °C range of GCM response to doubled CO_2.

References

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