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Stratospheric temperature response to improved solar CO_2 and H_2O parameterizations

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Abstract. A fixed-dynamical heating model is used to investigate the temperature changes in the stratosphere due to improved CO_2 and H_2O shortwave heating parameterizations. Besides being governed by the magnitude of the local heating, the temperature change in any layer due to the improved parameterizations is also dependent on the distribution of the solar heating in other stratospheric layers. This is a consequence of the longwave radiative exchange process, in which the temperature change in other layers, due to the imposed heating perturbations, leads to an exchange of longwave radiative energy with the layer in question, thus affecting its response. Thus the vertical profile of the heating rate becomes a significant factor in determining the stratospheric thermal profile. This investigation also confirms the sensitivity of the temperature response in the lower stratosphere to perturbations in the shortwave CO_2 and H_2O heating.

Introduction

In a previous paper [*Freidenreich and Ramaswamy*, 1993] (hereinafter FR93) an investigation was made of changes in the solar heating rate due to an improved broadband CO_2 + H_2O parameterization. The improvements consisted of a modification of the *Lacis-Hansen* [1974] H_2O and the *Sasamori et al.* [1972] CO_2 formulations, based on line-by-line "benchmark" computations. It was found that the improved formulations constituted an additional heat input in the stratosphere, especially in the lower stratosphere. In this paper we investigate the changes in the simulated stratospheric temperatures due to this additional heating and study the characteristics of the longwave radiative process which affects the magnitude of these changes.

To determine the changes in temperature we make use of the concept of fixed-dynamical heating, or FDH [*Fels and Kaplan*, 1975; *Fels et al.*, 1980]. The fundamental assumption behind this approach is that the dynamical heating is invariant, so that the total radiative heating is also fixed. Thus any perturbations in the shortwave heating will be balanced by a change in the longwave heating, accompanied by a new equilibrium temperature profile. In our present application of this concept, changing the CO_2 and the H_2O parameterizations constitutes a perturbation of the shortwave heating. It is noted that *Kiehl et al.* [1985] used the FDH technique to analyze the stratospheric temperature response to inclusion of shortwave CO_2 absorption.

The FDH model uses the zonally averaged "climatology" (i.e., temperature, water vapor, and ozone profiles, cloud amounts and properties, and surface albedos) generated from a control run of Geophysical Fluid Dynamics Laboratory's (GFDL) SKYHI general circulation model (GCM), with a resolution of 3.6 degrees in longitude and 3 degrees in latitude. The simulated temperature profiles from the GCM are generally in good agreement with observations except in the polar stratosphere [*Hamilton et al.*, 1995]. For the present study we consider only the climatological conditions for summer (June, July, and August). The solar zenith angle and the fraction of the day are fixed at their appropriate values for July 15. The CO_2 amount used is 354 parts per million by volume (ppmv).

The dynamical heating rate in any layer of the stratosphere, which is the negative of the total radiative (shortwave + longwave) heating in that layer, is computed using the climatology cited above and the unmodified (i.e., the original Lacis-Hansen and Sasamori) shortwave parameterizations. In contrast to the broadband treatment of the shortwave radiative transfer, the longwave portion of the model is based on a 10-cm^{-1} random band model formulation that includes the Voigt effects in the upper stratosphere [*Fels*, 1979] and that has been employed in earlier studies [*Ramaswamy et al.*, 1992]. The dynamical heating rate thus obtained is held fixed throughout the study. The radiative perturbations are obtained through application of one or both of the modified shortwave parameterizations. Using the FDH concept [*Fels et al.*, 1980], a new equilibrium temperature profile is determined for the entire stratosphere. The FDH model uses a time marching procedure with a time step of 3 hours. The new equilibrium state is defined when the temperature between two successive iterations is less than 10^{-5} K in all layers. The FDH response, that is, the change due to the modifications, is the difference between the new and the climatological temperature profiles. Variables (including temperature) in the troposphere, that is, below the model's tropopause, are held fixed during the time integration. The height of the tropopause varies from 110 mbar in the equatorial regions to 290 mbar in the polar regions. At 22.5°N, a latitude that is used in subsidiary experiments described below, the height of the tropopause is 150 mbar.

Results

Figure 1a displays the difference in the solar heating rate between the modified and unmodified CO_2 + H_2O parameterization over all latitudes. Note that this figure differs slightly from figure 7 in FR93 in the polar northern hemisphere lower stratosphere; this is due to the use of a coarser latitudinal resolution in the present FDH calculations. As noted in FR93, the increase in heating in the upper stratosphere is due mainly

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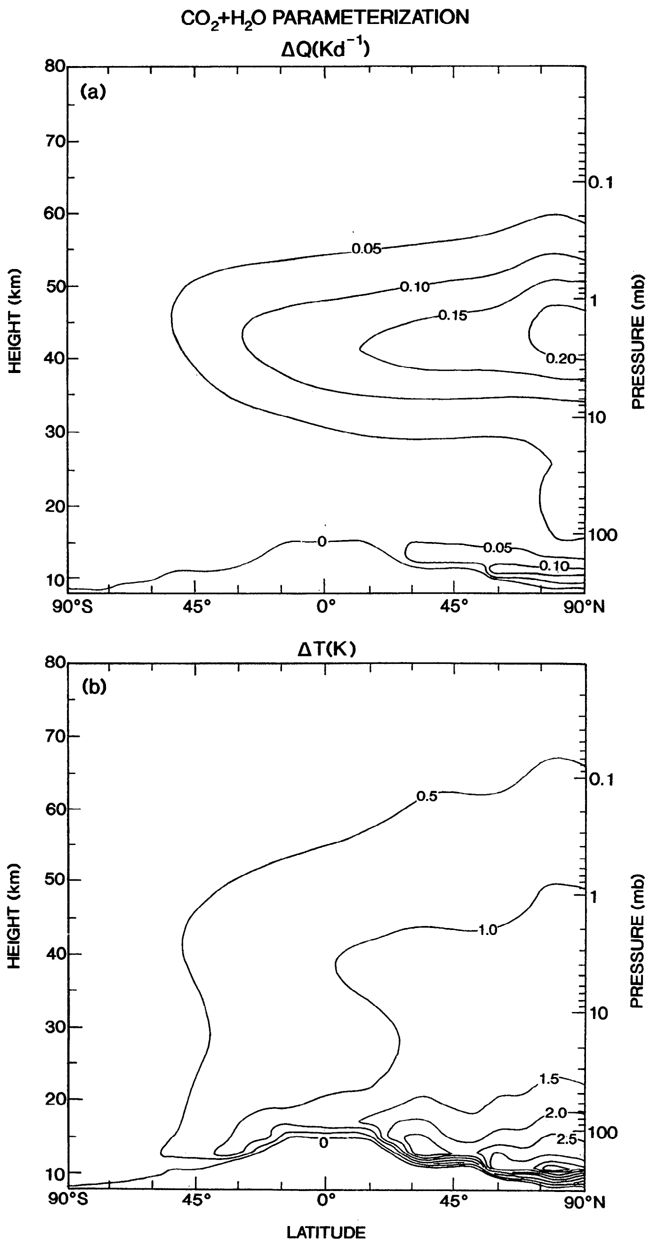

Figure 1. Vertical profile of the difference in (a) solar heating rate (kelvin per day) and (b) associated equilibrium temperature (kelvin), between the modified and the unmodified broadband parameterizations for CO_2 + H_2O. The basic, zonally averaged climatology is obtained from the GFDL SKYHI general circulation model for summer conditions with a CO_2 mixing ratio of 354 ppmv. The solar zenith angle and the fraction of the day are fixed at the appropriate values for July 15. The temperature change profile is derived using a FDH model and is limited to regions above the tropopause.

to increased CO_2 absorption, while in the lower stratosphere, it is due to increased absorption by both CO_2 and H_2O. Figure 1b presents the corresponding temperature changes using the FDH model. The largest temperature increases (>2 K) occur in the summer hemisphere lower stratosphere in conjunction with the relatively large heating rate perturbations there. A smaller maximum in the temperature increase (>1 K) occurs in the upper stratosphere in association with the maximum heating rate perturbation there. Thus the additional heating due to the improved CO_2 + H_2O broadband parameterization can have a significant effect on the simulated temperatures, especially in the lower stratosphere. The relatively large temperature response to a small heating perturbation in the lower stratosphere further illustrates the sensitivity of the thermal profile in that region. This is due to the generally long radiative damping time there associated with the longwave radiative flux exchange mechanisms [*Fels et al.*, 1980; *Kiehl et al.*, 1985; *Kiehl and Solomon*, 1986].

The differences in the shapes of the profiles illustrated in Figures 1a and 1b are a manifestation of how the radiative exchange mechanism in the longwave affects the temperature change in any given layer. In order to examine this process more closely, additional sets of FDH computations are performed. In these, the shortwave heating perturbations are confined to particular stratospheric layers and the associated temperature changes are determined. The values of the heating perturbations chosen for these experiments are those due to CO_2 only or H_2O only at 22.5°N. Figure 2 shows the profiles of the heating perturbations throughout the stratosphere at 22.5°N due to CO_2 only and H_2O only; also shown is the corresponding profile for CO_2 + H_2O. For any layer or layers, the values of the perturbations imposed in these subsidiary computations are identical to those actually arising due to the improved CO_2 or H_2O parameterizations. The temperature changes occurring in these series of calculations are contrasted with those obtained when the heating perturbations due to CO_2 only or H_2O only, as the case may be, occur in all layers. The latter, shown in Figure 2, will be defined as reference cases for convenience.

There are separate reference cases for CO_2 only and H_2O only. Three sets of such subsidiary experiments are performed; the first two are for CO_2 only, and the third one is for H_2O only. In the analyses below, one specific pressure is selected to study the temperature responses. The selected pressure for each set of experiments corresponds to the center of a layer in

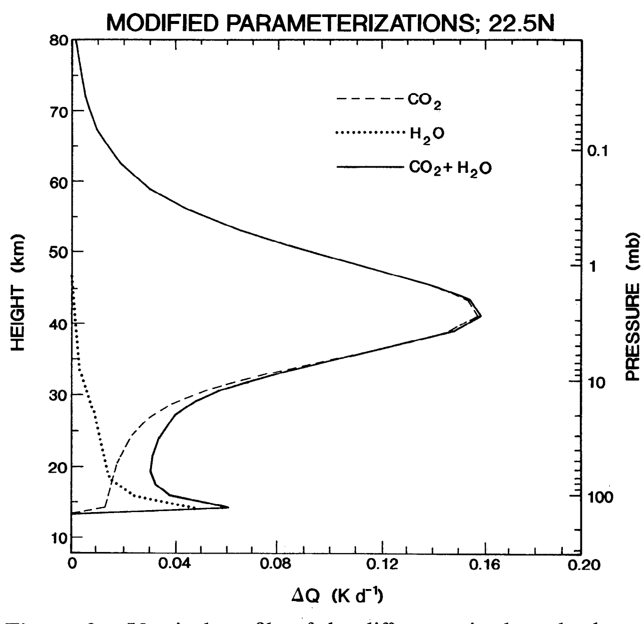

Figure 2. Vertical profile of the difference in the solar heating rate (kelvin per day) at 22.5°N, between the modified and the unmodified broadband parameterizations for CO_2 only, H_2O only, and CO_2 + H_2O.

which a maximum in the temperature response occurs for the respective reference cases (3.8 and 103 mbar for CO_2; 132 mbar for H_2O). For each of the three sets, the first experiment consists of placing a heating perturbation only in the layer selected for the study; subsequent experiments involve the imposition of the appropriate heating perturbations in additional surrounding layers. In the following discussion, we use the term "local" to refer to the selected layer, and "distant" to refer to the other stratospheric layers.

For the first set of experiments, four different segments of the CO_2 only heating perturbation profile in Figure 2 are considered: the layer between 3.3 and 4.5 mbar, the layers between 0.3 and 4.5 mbar, the layers between 0.3 and 25 mbar, and, finally, the complete (i.e., reference case) profile. Figure 3 illustrates the temperature response corresponding to each segment considered. First, we note that the response extends to beyond the layer(s) where the heating perturbation is imposed. A heating rate perturbation confined to the layer between 3.3 and 4.5 mbar results in a temperature response at 3.8 mbar that is about 60% of the reference value. Including the heating perturbations in additional layers above it, up to 0.3 mbar, increases the temperature response at 3.8 mbar to about 70% of the reference value. When the lower stratospheric heating perturbations down to 25 mbar are also included, the resultant temperature response at 3.8 mbar becomes nearly the same as that obtained in the reference case. Thus the maximum temperature perturbation occurring in the upper stratosphere at 3.8 mbar in the reference case is influenced significantly (~40%) by heating perturbations in distant layers, both from above and from below through the longwave radiative exchange mechanism. More specifically, the increase in the temperature of the other stratospheric layers, as a result of the heating perturbations imposed there, causes an increase in the exchange of longwave radiative energy with the selected layer, thus enhancing the temperature response of the latter.

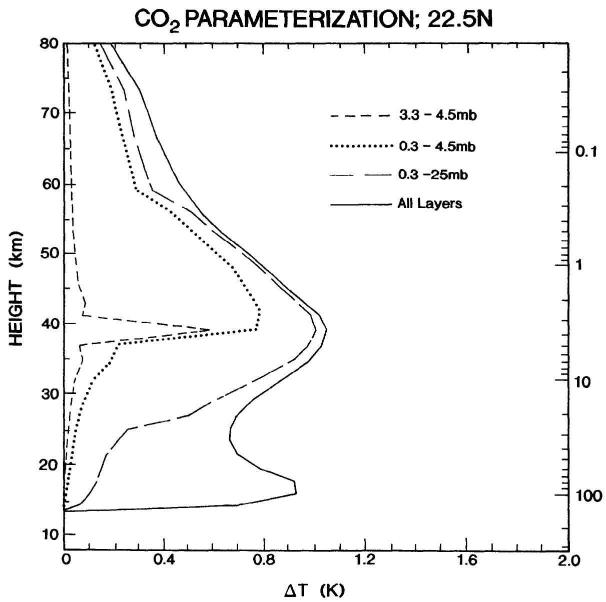

Figure 3. Vertical profile of the difference in the equilibrium temperature (kelvin) at 22.5°N, between the modified and the unmodified broadband parameterization for CO_2 only, due to heating perturbations confined to the particular layers indicated (see Figure 2). Also shown is the corresponding profile due to heating perturbations throughout the stratosphere. The change at 3.8 mbar is focussed on in the text.

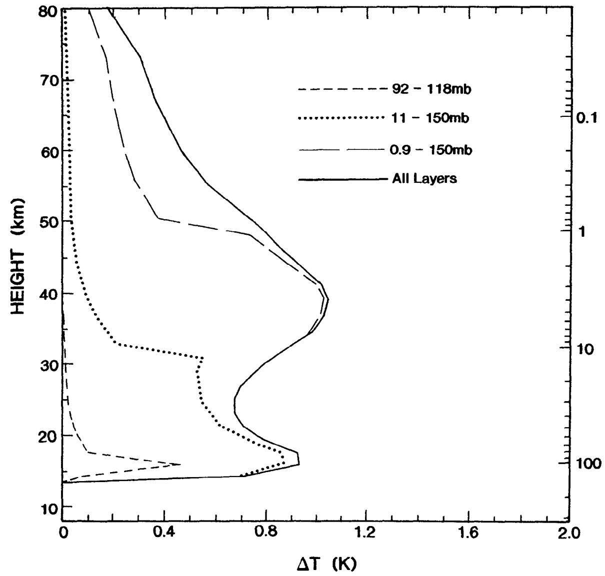

Figure 4. Same as Figure 3, except that the layers considered for the heating perturbations are different. The focus is on the temperature change occurring at 103 mbar.

In the second set of subsidiary experiments, the four different segments of the CO_2 only heating perturbation profile in Figure 2 considered are the layer between 92 and 118 mbar, the layers between 11 and 150 mbar, the layers between 0.9 and 150 mbar, and the reference case corresponding to perturbations throughout the stratosphere. Figure 4 illustrates the corresponding temperature response for these four segments. The temperature response at 103 mbar, due to heating of the layer between 92 and 118 mbar, is about 50% of the reference value. Including the heating perturbations from the layers between 11 and 150 mbar increases the temperature response at 103 mbar to greater than 90% of the reference value. The addition of heating perturbations in the upper stratosphere, up to 0.9 mbar, increases the temperature response at 103 mbar to virtually 100% of the reference value. Thus the contribution to the reference temperature response at 103 mbar due to heating perturbations in distant layers is very important (~50%), with most of it coming from the vicinity of the lower stratosphere ($P > 10$ mbar). As in the case of the upper stratospheric layer, the longwave radiative exchange process, as a result of temperature increases in other layers, plays an important role in the CO_2-induced temperature increases in the lower stratosphere.

In the third set of subsidiary experiments, three different segments of the H_2O only heating perturbation profile illustrated in Figure 2 are considered: the layer between 118 and 150 mbar, the layers between 11 and 150 mbar (same as the previous set of experiments) and the reference case corresponding to perturbations throughout the stratosphere. Figure 5 shows the associated temperature responses for these specified segments. The contribution by the heating in the layer between 118 and 150 mbar to the temperature response at 132 mbar is seen to be > 80% of the value occurring in the reference case. For heating perturbations confined to the layers between 11 and 150 mbar, the resultant temperature response

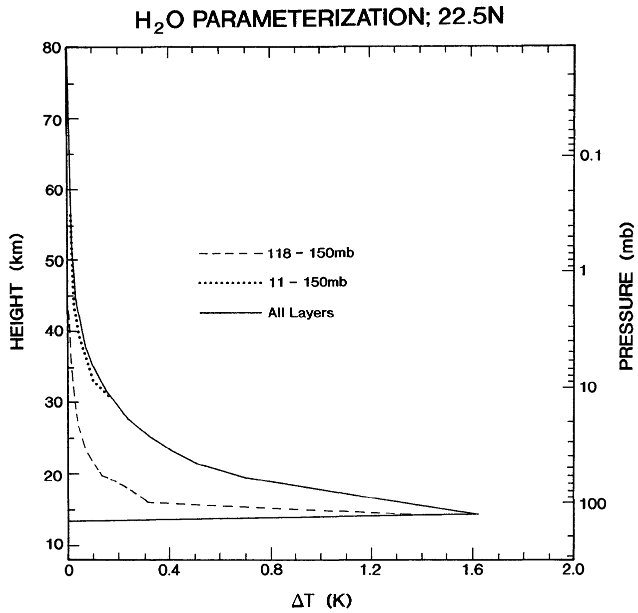

Figure 5. Same as Figure 3, except that the layers considered for the heating perturbations are different, and the perturbations are due to H_2O only (see Figure 2). The focus is on the temperature change occurring at 132 mbar.

at 132 mbar is virtually 100% of the reference value. Comparing with the results shown in Figure 4, the local heating perturbations serve to explain more of the temperature response in the lower stratosphere for the H_2O-only case than for the CO_2-only case. This is because, for H_2O only, the reference case (Figure 2) consists of a sharp maximum in the heating perturbation in the lower stratosphere, accompanied by a rapid decrease with height. It necessarily follows that the influence of the longwave radiative exchange mechanism on the lower stratosphere due to flux originating from the layers above it would be considerably weaker in the H_2O-only case, since temperature increases in the distant layers are relatively less. This feature differs considerably from the nature of the perturbation occurring in the CO_2-only reference case (Figure 2) where the maximum is actually well above the lower stratosphere.

In general, these three sets of subsidiary experiments suggest that for a given layer in the stratosphere, the heating perturbations in distant layers can affect the resultant temperature responses significantly. Thus the relative contributions of local and distant heating perturbations to the temperature response in a specific layer depend on the vertical profile of the heating perturbations, in particular the magnitudes at the different heights. However, the contributions from very distant layers that are far removed from the given layer, that is, from a layer in the upper (above 10 mbar) to a layer in the lower (100 mbar) stratosphere and vice versa, are generally small. We also note from the results for CO_2 only, H_2O only, and $CO_2 + H_2O$, that the temperature response for $CO_2 + H_2O$ is close to the value obtained by summing the responses to each gas separately.

We analyze further the temperature response at 132 and 3.8 mbar, in terms of the damping time (τ) [*Kiehl and Solomon*, 1986], defined as the ratio of the local temperature change to the layer heating perturbation. This is derived from the FDH model's heating rate perturbation and the associated temperature change. We consider the reference heating perturbation profiles corresponding to CO_2 only and H_2O only at 22.5°N (Figures 4 and 5) for the situation where the heating perturbations occur over the entire stratosphere. The magnitude of τ can be considered as a measure of the sensitivity of the layer temperature to local heating perturbations. Thus for CO_2 only, which has relatively large temperature responses in both the upper and lower stratosphere (Figure 4), the greater sensitivity of the temperature response to heating perturbations in the lower stratosphere is marked by the much larger value of τ at 132 mbar (53 days) versus 3.8 mbar (7 days). Differences in τ at 132 mbar, between the CO_2-only and H_2O-only reference cases is also of interest, since both gases contribute significantly to the combined temperature response there. The smaller value for H_2O only (35 days) compared to CO_2 only is once again a reflection of the fact that the local contribution is relatively more prominent in determining the temperature response for the H_2O-only case. Thus the value of the damping time depends in an important manner on the vertical profile of the heating perturbations.

Conclusions

From the numerical experiments, it is evident that solar heating perturbations in the lower stratosphere influence significantly the resultant temperature response throughout the stratosphere. This is most evident in the lower stratosphere due to the large radiative damping times there, confirming the conclusion of *Kiehl et al.* [1985]. It is therefore especially important to reiterate when deriving new solar parameterizations, or modifying existing ones, that they accurately reproduce the heating rates in the lower stratosphere. As evident in Figure 6 of FR93, the modified $CO_2 + H_2O$ parameterization discussed in that paper produces heating rates that are within 10% of the reference values in the lower stratosphere. The error in the total solar heating in the lower stratosphere will further depend on the accuracy in treating the O_3 and O_2 absorption. In the upper stratosphere, O_3 is the primary solar absorber so that the accuracy of the temperature profile there will depend principally on the accuracy of the O_3 parameterization.

Through an analysis of the components (CO_2 only, H_2O only, and heating perturbations confined to particular stratospheric layers) that make up the total vertical profile of heating perturbations (Figure 1a), it has also been shown that, because of the longwave exchange process, the temperature response for a given layer in the stratosphere depends significantly on the vertical distribution of the heating rate perturbations. Specifically, the temperature response in any layer depends in a general sense on the contributions arising due to the heating perturbation in that layer as well as in the additional layers surrounding it. This is because the temperature change in other layers, due to the imposed heating perturbations, leads to an exchange of longwave radiative energy with the layer in question, thus affecting the response of the latter. This holds whether the layer being considered for the temperature response is in the upper or lower stratosphere. However, if the heating is sharply peaked around a given layer and decreases rapidly away from this layer (e.g., H_2O only in the lower stratosphere), then it is the local perturbation that matters most for the temperature response of that layer.

In light of these findings, there may not be a unique relationship between a change in the layer heating and the change in temperature for that layer, as is implied by a fixed value for the damping time. This is especially so if the heating perturbation is distributed throughout the stratosphere. The result here reaffirms the findings of *Fels* [1982, 1984], namely, the vertical scale of the perturbations influences the damping time, except that the source of the perturbations in that study was temperature deviations. In general, this study reiterates the need to be careful when making estimates of the temperature response based solely on a prescribed value of the damping time. This is especially true when the damping time is derived using some arbitrary perturbation profile that differs significantly from the profile under examination. Specifically, in the case of temperature perturbations arising due to changes in the shortwave heating, if they are to be reasonably estimated from the use of a "damping time," then it would appear that a priori knowledge of the sensitivity of the temperature response to different vertical heating perturbation profiles is required.

The dependence of the damping time on the vertical shape of the perturbation makes it worthwhile to inquire into the sensitivity of the final temperature response to differences in the initial temperature profile. Further, we have investigated the problem from the perspective of fixed dynamical heating. It would be interesting to investigate the relationship between the stratospheric heating perturbations and the resulting temperature responses when the troposphere is allowed to interact, for instance, in a radiative-convective model.

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