Reprinted from Preprint Volume: Fifth Conference on Atmospheric Radiation, October 31-4 November 1983, Baltimore, Maryland. Published by the American Meteorological Society, Boston, Mass.

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The role of longwave radiative processes in the general circulation of the lower atmosphere

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1. Introduction

We will describe recent studies, performed at NCAR, which illustrate quantitatively the importance of the longwave radiative processes to the general circulation of the lower atmosphere (troposphere/stratosphere). The focus of this review paper will be on the following aspects of the general circulation: zonal mean circulation; surface energy budget; and climate sensitivity. The primary objective of this paper is to indicate avenues for future research which would contribute to the process of developing a quantitative theory of climate and climate change. Towards this goal, we will concentrate on the following topics: a) interaction between meridional gradients in longwave heating rates and zonal mean circulation; b) cloud-radiative effects; c) H_2O continuum effects; d) stratospheric processes.

Admittedly, the above topics are not an exhaustive set but they are sufficient to illustrate the stated objectives and furthermore these topics are currently receiving a considerable amount of deserved attention.

2. Effects of meridional gradients in longwave heating rates

It is generally believed that the zonal mean general circulation is driven by the equator to pole gradient in the absorbed solar radiation which in turn contributes to the corresponding meridional and vertical gradients in latent heat release. In this viewpoint, the longwave radiative processes contributes to the zonal mean/circulation in the following ways: a) the tropospheric cooling destabilizes the atmosphere providing the necessary instability for the onset of convection; b) as a Newtonian cooling process, provides a dissipative mechanism for planetary scale eddies.

This viewpoint, although it provides a convenient and plausible theoretical background for understanding the zonal mean circulation, is a severe oversimplification of the complex manner by which longwave radiative processes maintain the general circulation. For example, let us consider the recent General Circulation Model (GCM) studies by Ramanathan et al. (1983), hereafter referred to as R. The GCM used for this study is the NCAR Community Climate Model (CCM). The CCM is a spectral GCM and it is described in Pitcher et al. (1983). The CCM has an interactive cloud-radiative scheme.

In order to illustrate the role of longwave radiative processes, R removed several improvements in the cloud/radiation scheme that resulted in ignoring several temperature and latitudinal dependent radiative processes. R performed two experiments, one with the CONTROL model which has all of the cloud/radiation improvements, and the second with the degraded radiation model. For the same initial conditions for temperature, humidity, solar insolation, and ozone, the changes in the radiative heating rates at the initial time (i.e., the time when the model integrations were begun) between the degraded and the CONTROL models are shown in Fig. 1. It is seen that the effect of the radiation model degradation is to enhance the meridional gradient of radiative heating rates (primarily due to longwave radiation changes) in the troposphere and to enhance the pole to pole gradient of radiative heating rates (both solar and longwave) in the stratosphere. The details of the cloud/radiation degradation that produced the changes in Fig. 1 are described at considerable length in R and hence will not be repeated here. In any case, this detail is not of relevance to our discussions since the primary interest is the response of the general circulation to the changes in meridional gradients in radiative heating rates.

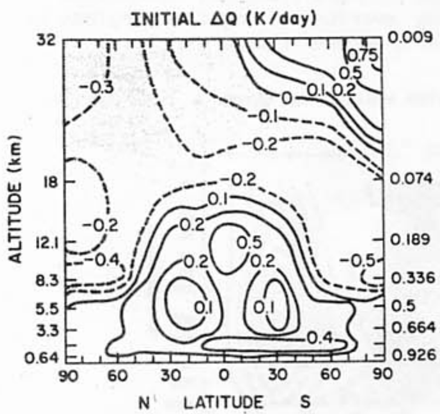

Fig. 1. Zonal mean change in net radiative heating rate (Q). ΔQ is the difference in Q between the degraded cloud/radiation model and the CONTROL model.

Both versions (CONTROL and degraded) of the CCM were integrated for 400 (model) days, with prescribed January sea surface temperature and perpetual January solar incidence at the top-of-the-atmosphere. The zonal mean winds and temperature for the CONTROL and the degraded model are shown in Figs. 2 and 3. The difference between the two versions are dramatic. The enhancement in the meridional gradient in radiative heating rates has resulted in a significantly stronger (and unrealistic) zonal mean circulation and in a stronger meridional temperature gradient. In order to illustrate the last point, Fig. 4 shows the difference in temperature between the degraded and the CONTROL. We show results for two different

[1]On sabbatical leave at NASA Langley Research Center, Virginia, from August 1983 to July 1984.
[2]The National Center for Atmospheric Research is sponsored by the National Science Foundation.

versions of the degraded model, one with computed variable cirrus and another with prescribed zonally symmetric cirrus clouds.

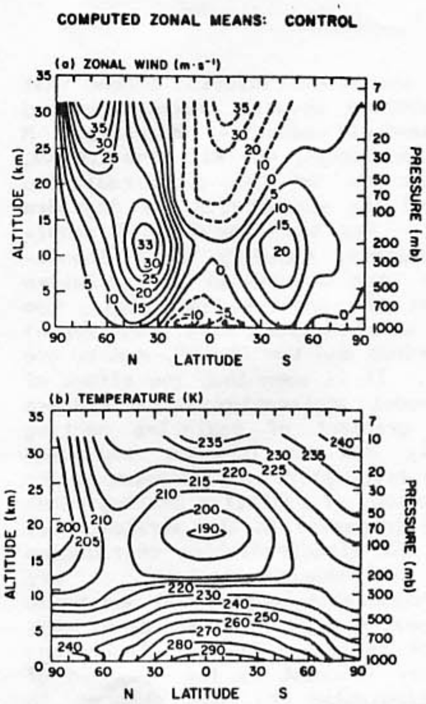

Fig. 2. Computed (a) zonal mean zonal wind and (b) temperature for perpetual January conditions by CONTROL, 120-day averages. Negative regions in (a) are denoted by dashed lines.

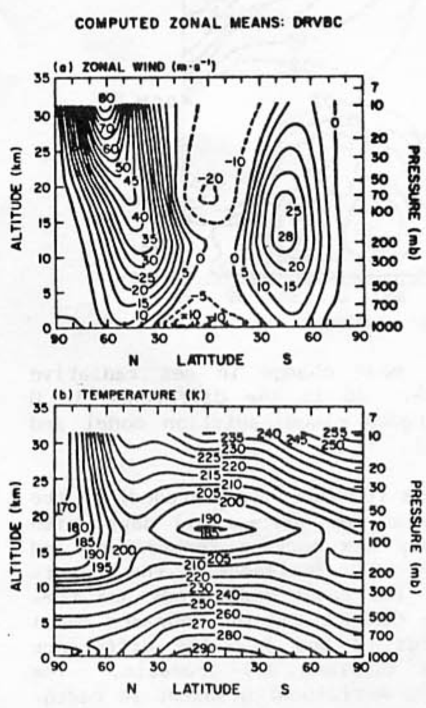

Fig. 3. As in Fig. 2 but for the degraded radiation model DRVBC is degraded radiation model with variable black cirrus. Negative regions in (a) are denoted by dashed lines.

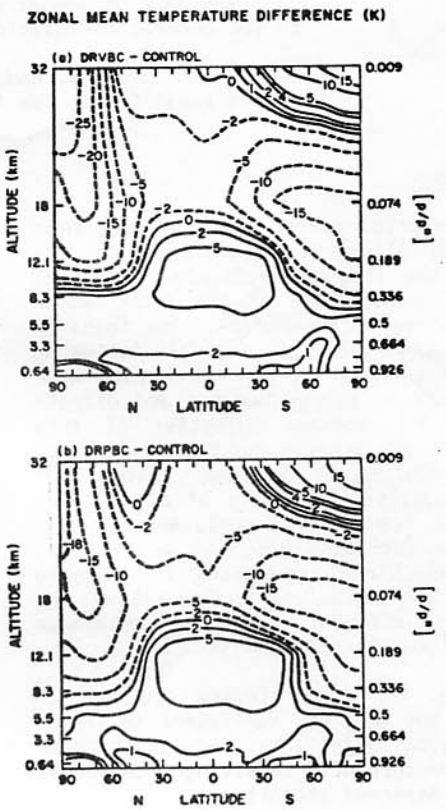

Fig. 4. The zonal mean temperature difference between the experiment and CONTROL. (a) DRVBC-CONTROL; (b) DRPBC-CONTROL. Degraded radiation with variable black cirrus is DRPBC. Negative regions are denoted by dashed lines.

The principal conclusion is that meridional gradients in longwave radiative heating rates play a significant and active role in determining the atmospheric zonal mean circulation. Furthermore, the meridional gradient in longwave heating rates are strongly determined by subtleties in radition such as: the dependence of cloud emissivity on water content and temperature; the temperature dependence of spectroscopic parameters for CO_2, H_2O, O_3; the meridional gradients in the H_2O and O_3. This is particularly important for the lower stratosphere and the upper troposphere. Current state-of-the-art climate models (including GCMs) have not adequately treated the contribution to the meridional heating gradients from the above processes (with the possible exception of CO_2).

3. Cloud radiative effects

Numerous radiative transfer calculations have demonstrated the significant importance of longwave radiative effects of clouds to the surface energy budget, to the divergence of the longwave radiation within the lower atmosphere, and to the energy budget of the surface-atmosphere system. However, the interaction between the above cloud radiative effects and the thermal/dynamical structure of the atmosphere are poorly understood.

In order to demonstrate the potential importance of clouds, we will consider the cirrus clouds which seem to exert a significant influence on the meridional radiative heating gradient within the upper troposphere. Our discussion of this topic is also based on the GCM study of Ramanathan et al. (1983) performed with the CCM. In Fig. 5 we show the effect of cirrus on the computed outgoing longwave flux at the top of the atmosphere. For the purposes of the present discussion, the term "cirrus" refers to clouds at altitudes above about 10 km from equator to midlatitudes (45°) and polewards of 45° it refers to clouds at altitudes above about 7 km. The CONTROL model shown in Fig. 5 does not form cirrus while the other two model curves (dashed and dash-dot) include the radiative effects of cirrus, one of which (dash curve) employs a variable cirrus emissivity which depends on cloud liquid water content (LWC) and the other (dash-dot) assumes a black (emissivity = 1) cirrus. This curve indicates the significant effect of cirrus on the tropical energy budget and gives an indication of the cirrus effects on the meridional heating gradient. However, the effects of cirrus on the outgoing longwave flux as shown in Fig. 5 is only an incomplete picture of the cirrus effects. For a more complete understanding of the problem, we should consider the cirrus effects on longwave radiative heating rates, which are illustrated in Fig. 6 for various latitudes.

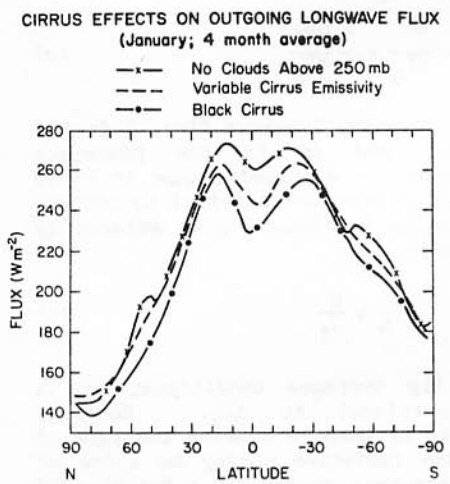

Fig. 5. Effects of cirrus on the outgoing longwave flux. For each of the three cases, the CCM was run for 200 days and the average of the last 1220 days are shown in the figure.

For the purposes of the calculations shown in Fig. 6, we adopt the zonally symmetric high cloud distribution of London (1957). We note that the black cirrus enhances significantly the tropical upper tropospheric radiative heating rate and causes a significant cooling in the polar latitudes. Thus, the black cirrus causes a significant enhancement of the upper tropospheric meridional radiative heating gradient.

Mean zonal winds as computed by the model with black cirrus is shown in Fig. 7. This figure should be compared with Fig. 2a which shows the zonal winds computed by the CONTROL model (without cirrus). In response to the enhanced meridional radiative heating gradient, the zonal circulation is significantly stronger in the model with black cirrus. Both the summer and the winter jets have strengthened by as much as 10 m s^{-1}. The corresponding temperature change due to the black cirrus is shown in Fig. 8. In this figure, we also show the case which employs variable non-black cirrus. The black cirrus warms the tropical upper troposphere by as much as 6 K while cooling the polar upper troposphere by about 10 K. These temperature changes are quite significant, particulary in view of the fact that the sea-surface temperatures are held fixed in the model. Consequently, the temperature changes induced by the cirrus radiative heating (Fig. 6) implies that longwave radiative processes are as important as other dynamical processes (e.g., moist convection and dynamical transport of sensible heat) in maintaining the vertical and meridional gradients in temperature and winds in the upper troposphere.

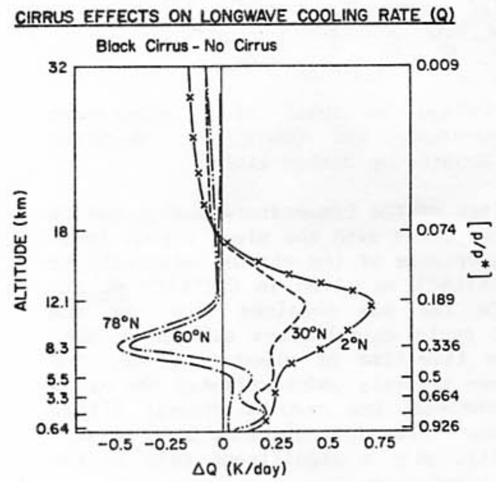

Fig. 6. Initial change in net radiative heating rate due to the introduction of black cirrus.

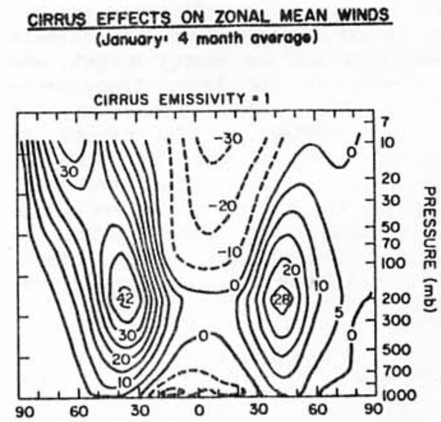

Fig. 7. Zonal mean zonal winds for mean January conditions as computed by the CCM, with black cirrus.

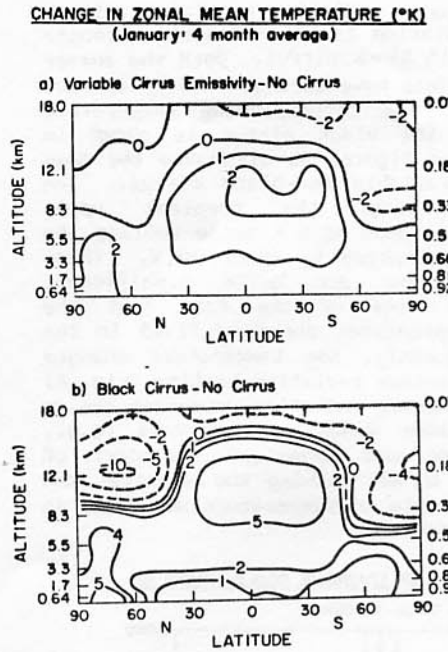

Fig. 8. Change in zonal mean temperature between experiment and CONTROL. Negative changes are denoted by dashed lines.

Comparison of the temperature change due to the non-black cirrus with the black cirrus indicates the importance of the cirrus emissivity to water content(LWC) as given in Griffith et al. (1980). The LWC was obtained from the GCM hydrological cycle calculations without accounting for the life-time of clouds. Hence, the model may have severely underestimated the cloud LWC. Nevertheless, the results clearly illustrate that subtleties in radiation, such as cirrus emissivity, play a significant role in the zonal mean circulation.

4. H_2O continuum

The H_2O continuum in the wavelength interval of 8-30 µm has attracted a lot of attention recently primarily because it influences several aspects of the global climate including climate sensitivity, tropical surface energy budget, and meridional gradients in the lower troposphere radiative heating rates. The source for this absorption, i.e., whether it is caused by dimers, water clusters, or the far wings of rotational lines, is still not satisfactorily resolved. However, the nature of the continuum absorption is reasonably well characterized by both atmospheric and laboratory observations. The spectral transmission, T_ω, can be written as (Roberts et al., 1976)

$$T_\omega = e^{-[k_\omega Ue]} \tag{1}$$

where U is the H_2O amount, e is the partial pressure of H_2O (atm), and ω is the wavenumber. The k_ω, continuum absorption coefficient, has the following spectral dependence (Roberts et al., 1976):

$$k_\omega = \alpha_0 + \alpha_1 e^{-\beta\omega} \tag{2}$$

where α_0, α_1, and β are constants, and ω is the wavenumber in cm^{-1}. From (1), with the appropriate values for the constants, k_ω increases from about 4 gm^{-1} cm^2 atm^{-1} at wavelengths less than 8 µm (or $\omega > 1250$ cm^{-1}) to about 1300 around 30 µm. Furthermore, the opacity scales as e^2 (note that in (1), $U \propto e$). Hence, the continuum significantly enhances the atmospheric opacity in the tropics and that too in the lowest few kilometers above the ground while its opacity is negligible polewards of midlatitudes (also see the discussions in Cox, 1973). The consequences of this opacity variation to the meridional gradients in lower tropospheric cooling rates and in surface energy budget as well as the resulting effects on the lower tropospheric circulation needs to be explored in detail.

The continuum absorption also has a significant impact on the sensitivity of climate to, for example, increases in CO_2 and solar constant (among several others). We show in Fig. 9a the effect of the continuum on the climate feedback parameter, λ_T, as a function of surface temperature, T_S. The results shown in Fig. 9a are estimated from a 1-D radiative-convective model (Lal and Ramanathan, 1981). The feedback parameter, λ_T, is defined as

$$\lambda_T = \frac{dF}{dT_S} + \frac{S}{4}\frac{d\alpha_p}{dT_S} \tag{3}$$

where F is the outgoing longwave flux, S is the solar constant, and α_p is the planetary albedo. The globally averaged change in T_S (a major measure of climate sensitivity) to perturbation in radiative heating, Q', is related by (Dickinson, 1982):

$$\Delta T_S = \frac{Q'}{\lambda_T} \tag{4}$$

For globally averaged conditions, λ_T is inversely proportional to ΔT_S. However, Fig. 9a can also be used to examine the rate of loss of longwave radiative energy to space of the surface/atmosphere system as a function of T_S (and hence latitude), particularly because, as shown in Fig. 9b, most of the contribution to λ_T comes from the longwave sensitivity. It is seen that the continuum has a negligible effect on λ_T for $T_S < 280$ K while it cuts down the rate of loss of energy to space by as much as a factor of two (with increase in T_S) for T_S representative of the tropics. The basic conclusion is that a proper treatment of continuum is essential for climate sensitivity experiments involving the tropical regions.

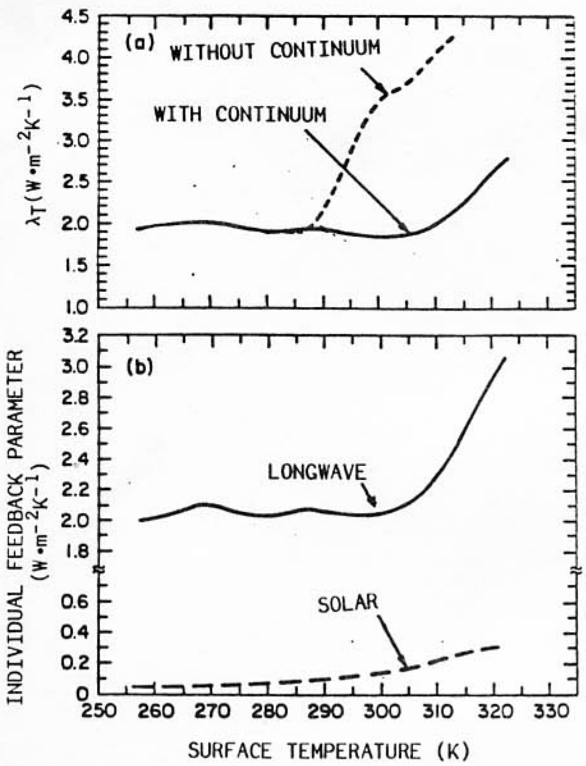

Fig. 9. (a) The effect of continuum on the climate feedback parameter λ_T (see Eq. 3); (b) the relative contribution of longwave and solar processes to the climate feedback parameter.

The continuum region in the 12-20 µm overlaps with the 15 µm CO_2 bands and Kiehl and Ramanathan (1983) have examined the impact of this overlap on the radiative heating rates due to doubled CO_2. In Fig. 10 we show the vertical distribution of the change in longwave heating rate due to a doubling of CO_2 with and without the H_2O continuum. From Fig. 10 it is clear that the tropospheric changes in radiative heating rates is significantly altered by the continuum bands. As concluded in Kiehl and Ramanathan (1983) the effect of the continuum on the CO_2 induced radiative heating of the joint surface troposphere system is negligible. The main effect of the continuum is to alter the vertical distribution of the heating profile, i.e., the continuum absorbs the enhanced downward emission by CO_2 causing an increase in the CO_2 heating of the lower troposphere but, at the same time, results in a compensatory decrease in the CO_2 emitted downward flux to the surface.

5. Stratospheric processes

The tropopause and the lower stratosphere at most latitude belts and for all the seasons, is one of the most sensitive regions to radiative processes. The radiative response time for this altitude region seems to be about 100 days (see Fig. 11 of R) and the response time including the effect of dynamics is also about 100 days (see Fig. 17 of R). This implies that perturbation in radiative heating as small as 0.1 K/day would result in a temperature change of about 10 K. Similar conclusions can also be inferred from the GCM studies of Fels et al. (1980).

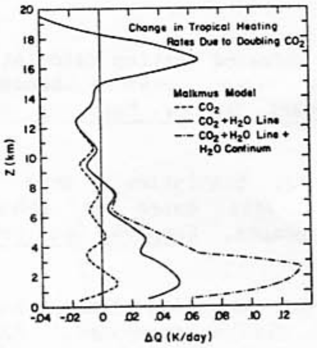

Fig. 10. The effect of H_2O-CO_2 15 µm overlap on heating rates due to doubling of CO_2. Shown are changes in heating rates for pure CO_2, CO_2 with the pure rotation band of H_2O and CO_2, pure rotation band of H_2O and the H_2O continuum for the tropical profile of McClatchey et al. (1971). Adopted from Kiehl and Ramanathan (1983).

Water vapor is one of the major constituents determining the cooling rate of the lower stratosphere, and its vertical and latitudinal distribution are largely unknown, except for few station measurements. As summarized in Elsaesser et al. (1980), the available station measurements reveal significant vertical and latitudinal variations in stratospheric H_2O. Recent satellite observations may help alleviate the problem of data insufficiency, but in the meantime GCMs resort to arbitrary and ad-hoc prescriptions of specifying a constant mixing ratio of 3 ppm (by mass) within the entire stratosphere.

Furthermore, penetrating cumulonimbus clouds and their huge anvils (Danielsen, 1982; Kley et al., 1982) can introduce significant longitudinal asymmetries in longwave cooling due to H_2O and clouds within the lower stratosphere. These asymmetries are ignored in models because of the constant mixing ratio prescription. Furthermore, the longwave and solar heating by O_3 plays an important role in determining the height of the tropical tropopause. For example, a 50% decrease in O_3 cools the tropical tropopause by more than 10 K (Fels et al., 1980). The quality of the climatological O_3 data used in models is largely unknown.

A proper simulation of the lower stratospheric thermal structure is crucial for simulating the capping of the tropospheric jet within the upper troposphere and the separation of the stratospheric polar night jet from the tropospheric wintertime jet. In view of the slow response time of the lower stratosphere, radiative processes play a significant role in determining this thermal structure. Our current understanding of the lower stratospheric general circulation may be revised significantly as we make advances and improvements in our knowledge of the vertical, meridional, longitudinal, and seasonal gradients of the longwave radiative heating rates caused by corresponding variations in H_2O, O_3, and clouds.

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