Influence of CO$_2$ line profiles on radiative and radiative-convective equilibrium states of the Venus lower atmosphere

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[1] Influence of CO$_2$ line profiles on vertical temperature distributions in the radiative and radiative-convective equilibria is examined in the Venus atmosphere. The CO$_2$ opacity obtained by the Voigt (Lorentz) profile without the line cutoff is shown to be excessive since this opacity gives surface temperatures of about 860–1020 K in the radiative-convective equilibrium. On the other hand, the opacity obtained by the extremely sub–Lorentzian profiles of Pollack et al. (1993) and Tonkov et al. (1996) are underestimated; the surface temperature obtained with this opacity remains 600 K even in the radiative equilibrium. In this case, convection does not take place below the cloud layer because of the cloud opacity. It is also shown that Fukabori et al.’s (1986) and Meadows and Crisp’s (1996) profiles, both of which have intermediate absorption coefficients, give temperature distributions close to the observed one in the radiative-convective equilibrium. In these cases, the convection layer extends from the surface to 30–50 km altitudes. Then, the temperature distribution below the cloud layer is determined by a dry adiabatic lapse rate and the temperature near the cloud bottom. The surface temperature in the radiative-convective equilibrium is strongly affected by the temperature near the cloud bottom in this situation. The detailed structure of the H$_2$SO$_4$ cloud must be taken into account to construct a realistic radiative transfer model.


1. Introduction

[2] It is well known that the high surface temperature (about 730 K) of the Venus atmosphere can be explained by the greenhouse effect due to a vast amount of carbon dioxide (about 92 atm at the surface). Pollack and Young [1975] calculated temperature structures of the Venus atmosphere in the radiative and radiative-convective equilibria by taking carbon dioxide, water vapor, and aerosols into account. Their result shows that the temperature profile obtained for the pure radiative equilibrium is strongly superadiabatic below about the 10 atm level (30 km altitude), and the surface temperature is about 1300 K, which is much higher than observed. On the other hand, the calculated radiative-convective temperature profile agrees well with the observed value, although the temperatures are somewhat lower than the observed value near the surface. A convective layer is formed from the surface to about 10–20 atm levels (20–30 km altitudes). It should be noted that the transmission functions were simply assumed to be an exponential function of the opacity, which follows a power law dependence on total pressure and temperature.

[3] The radiative-convective equilibrium states of the Venus atmosphere have also been calculated by Matsuda and Matsuno [1978]; they based their calculations on the data provided by Venera 8 on the solar flux at the ground. The surface temperatures are 850–900 K and 700–800 K in the pure radiative and radiative-convective equilibrium states, respectively. As in the result of Pollack and Young [1975], superadiabatic temperature profiles appear in the pure radiative calculations. It is noteworthy, however, that the convective activity splits into two layers, one extending from 0 to 20 km altitudes and the other extending from 30 to 65 km altitudes. The interruption of the convective layer seems qualitatively consistent with the observational results of Pioneer Venus and Veneras [Seiff, 1983], in which positive
static stability of about 1–2 K km\(^{-1}\) appears at 30–50 km altitudes between the neutral or slightly unstable layers. It has also been shown that the increases of the surface temperature caused by the existence of water vapor in the atmosphere are about 150 and 70–80 K in the pure radiative and radiative-convective equilibria, respectively. The surface temperature is hardly affected by the H\(_2\)SO\(_4\) cloud infrared opacity in the pure radiative equilibrium but is increased by about 80 K in the radiative-convective equilibrium. In Matsuda and Matsuno’s [1978] radiative transfer model, the transmission functions are represented by a two-parameter model for 0–2200 cm\(^{-1}\) and an exponential function with one parameter for 2200–6000 cm\(^{-1}\). As in the work of Pollack and Young [1975], the \(p\) scaling and Curtis-Godson approximations are employed to include effects of the pressure broadening.

Using data provided by Pioneer Venus and Veneras 11 and 12, Pollack et al. [1980] constructed greenhouse models including the infrared absorption due to CO\(_2\), H\(_2\)O, SO\(_2\), CO, HCl, and the H\(_2\)SO\(_4\) cloud in order to calculate the radiative-convective equilibrium states. The vertical profile of the solar heating is fixed to the globally averaged profile on the basis of the Pioneer Venus observations [Tomasko et al., 1980]. Their results show that the observed temperature profile, especially the temperature lapse rate of the lower atmosphere, can be successfully reproduced. The convection layers are formed at 0–30 km and 50–55 km altitudes, as in the result of Matsuda and Matsuno [1978]. They have also estimated the surface temperature decrease caused by the removal of various infrared absorbing gases: the decreases due to H\(_2\)O and the cloud are 218 and 113 K, respectively. In their study, the transmission functions are assumed to be an exponential function of the opacity (defined in 48 wave number intervals in 25–4800 cm\(^{-1}\)), which follows a power law dependence on the amount of the absorbing gas, total pressure, and temperature.

In order to investigate the climate evolution of Venus, Bullock [1997] and Bullock and Grinspoon [2001] constructed an infrared radiative transfer model which reproduced the observed vertical temperature profile very well. In their studies, the gaseous absorption coefficients are evaluated by the line-by-line method from the HITRAN 1996 and HITTEMP databases. In order to take the effects of the CO\(_2\) line profile being sub-Lorentzian far from the line center [Goody and Yung, 1996] into account, the line wing absorption is truncated at 120 cm\(^{-1}\) from the line centers. In addition to the CO\(_2\) absorption by the permitted transitions, the continuum absorption due to the interaction of a pair of CO\(_2\) molecules is also included in their model; this opacity is assumed to be proportional to a squared value of the CO\(_2\) density. This kind of continuum absorption is often referred to as the pressure-induced absorption. In their studies, the distribution of the continuum absorption coefficients is based on the work of Moskalenko et al. [1979]. However, it seems somewhat different in weak absorption regions from that given by Moskalenko et al. [1979].

Since it is commonly recognized that the CO\(_2\) line profiles are sub-Lorentzian in the wave number regions far from the line centers, the line shapes are usually represented by the product of the Lorentz (Voigt) profile and a factor \(\chi\), which is a function of the distance from the line center in the wave number region. The functional form of \(\chi\) is expected to be dependent on temperature and absorption bands. If we could determine an exact form of \(\chi\), the line cutoff might no longer be necessary for the calculation of the absorption coefficients because of the permitted transitions. However, the functional form of \(\chi\) has so far been measured and proposed only for limited absorption bands. Hence, the artificial cutoff is often imposed on \(\chi\) at a certain wave number, and an additional continuum absorption is used to mimic the far wing absorption of CO\(_2\). For example, Pollack et al. [1993] employed the line cutoff at 120 cm\(^{-1}\) from the line center, together with the continuum absorption. Further laboratory and theoretical works are expected to be made for the accurate evaluation of the CO\(_2\) absorption coefficients in the future. In the present stage, however, it is useful to compare the effects of various CO\(_2\) line shapes proposed on the equilibrium states in the radiative-convective model of the Venus atmosphere. In this study we calculate the equilibrium temperature distributions by using various CO\(_2\) line shapes of infrared absorption. By comparing these results with observations, it is empirically possible to deduce the most reasonable representation of \(\chi\) which can produce the most realistic temperature profile of the Venus atmosphere.

In addition to the high surface temperature, the atmospheric superrotation is one of the most remarkable features of the Venus atmosphere [Schubert, 1983]. It is thought that the Venus atmosphere below the cloud bottom (about 45 km altitude) also plays a quite important role in the generation of the superrotation. However, for lack of observations the dynamical structure in this atmospheric layer remains scarcely known. Recent numerical experiments based on general circulation models have suggested that several different mechanisms may be possible as an explanation of the Venus atmospheric superrotation [Takagi and Matsuda, 1999; Yamamoto and Takahashi, 2004; Takagi and Matsuda, 2006, 2007; Lee et al., 2007; Hollingsworth et al., 2007; Kido and Wakata, 2008]. However, in these studies, the radiative process is extremely simplified by the Newtonian cooling, while the Venus atmosphere is optically quite thick in the infrared region because of a vast amount of CO\(_2\). Hence, this simplification cannot be justified, especially in the Venus lower atmosphere. As a result, the lower atmospheric motions cannot be correctly treated in these studies. An accurate radiative transfer model is also required for further investigations of the dynamics of the Venus atmosphere.

2. Model

In order to examine how the radiative and radiative-convective equilibrium temperature profiles in the lower Venus atmosphere depend on the CO\(_2\) line profiles, we have developed a one-dimensional, two-stream model of the infrared radiative transfer based on the correlated \(k\) distribution method [Liou, 2002]. The equations and methods used in the present study are briefly described in sections 2.1, 2.2, 2.3, and 2.4.

2.1. Radiative Transfer

The radiative and radiative-convective equilibria are calculated as asymptotic steady states of an initial value
problem in the present study. The equation representing the
time evolution of temperature distribution is written as
\[
\frac{\partial T}{\partial t} = \frac{g}{C_p} \frac{\partial}{\partial p} \left[ \int \left( F_1^p(p) + F_2^p(p) \right) dp \right] + Q(p),
\]
where \( p \) is the pressure, \( t \) is the time, \( g \) is the gravity, \( T \) is the
temperature, \( C_p \) is the specific heat at constant pressure, and \( Q(p) \) is the heating rate due to the absorption of the solar flux. \( F_1^p(p) \) and \( F_2^p(p) \) are upward and downward radiative fluxes at wave number \( n \) in the infrared region, respectively; \( g \) is set to 8.9 m s\(^{-2}\). \( C_p \) varies with altitude from 1200 J kg\(^{-1}\) K\(^{-1}\) at the surface to 740 J kg\(^{-1}\) K\(^{-1}\) at the
100 km altitude in the Venus atmosphere [Seiff et al., 1985]. This variation may not be neglected if the static stability of radiative equilibrium temperatures is examined. If the gas-eous \( CO_2 \) is assumed to be an ideal gas, \( C_p \) of \( CO_2 \) may be represented approximately as follows [Staley, 1970]:
\[
C_p(T) = \frac{7}{2} R + \sum_{n=0}^\infty \left( \frac{T^2}{2T_n} \right)^2 \sinh \left( \frac{T}{2T_n} \right) \frac{R}{C_n},
\]
where \( T_n \) is the vibrational temperature, which takes values of 960, 960, 2000, and 3380 K for \( CO_2 \). Since the O–O bending modes are degenerate, 960 K is duplicated in equation (2). In this study, the solar heating profile, \( Q_o \), is fixed to the distribution of the absorbed solar energy averaged over the sphere after Tomasko et al. [1980].

[10] The spectral range of thermal radiation is assumed to be from 0 to 6000 cm\(^{-1}\) in the present study. The absorption coefficients in this region are calculated by the line-by-line method at each pressure level [Urban et al., 2004]. The temperature required in this calculation is prescribed by the Venus International Reference Atmosphere (VIRA) data [Seiff et al., 1985]. It is assumed that the Venus atmosphere consists of only two molecular species, \( CO_2 \) and \( H_2O \). Bullock [1997] has shown that change in the surface temperature due to minor components, such as \( SO_2 \) and \( CO_2 \), is only a few degrees kelvin in the radiative-convective equilibrium. This result implies that these minor species other than \( CO_2 \) and \( H_2O \) may be negligible in the present study. The mixing ratio of \( H_2O \) is based on the works of Pollack et al. [1993] and Meadows and Crisp [1996]. The spectroscopic data of \( CO_2 \) and \( H_2O \) are taken from the HITRAN 2004 and HITEMP databases. In the line-by-line calculations, five different line profiles (described in section 2.2) are used for \( CO_2 \), since the line profile of \( CO_2 \) is far from uniquely determined, as mentioned in section 1. The continuum absorption due to the \( CO_2-CO_2 \) interaction is also taken into account [Moskalenko et al., 1979]. The details of the continuum absorption are discussed in section 2.3. In contrast to \( CO_2 \), it is known that \( H_2O \) shows a super-Lorentzian behavior in far wings [Goody and Yung, 1996]. It is assumed, however, that \( H_2O \) has the Voigt profile in order to focus on the difference arising from various \( CO_2 \) line profiles in the present study. The \( H_2O \) continuum absorption, whose origin is not well understood even in the terrestrial atmosphere [Bullock, 1997], is also neglected for the same reason.

[11] The calculation of the infrared fluxes, \( F_1(p) \) and \( F_2(p) \), is based on the correlated \( k \) distribution method. The correlated \( k \) absorption coefficients are evaluated for 30 channels which have an equal interval in the wave number region. In the calculation of transmission functions from the cumulative absorption probabilities, the Curtis matrix method [Curtis, 1956] is employed to include the large optical thickness properly. The integral over the wave number region in equation (1) should be replaced by summation over the channels. By using the transmission function between the levels of pressures \( p_n \) and \( p' \), \( T_n(p_n, p') \), where \( n \) indicates the \( n \)th channel of the spectral region, \( \Delta \nu_n \), the upward and downward fluxes are expressed as follows:
\[
F_i^p(p) = B_i(p) + \int_{p_n}^{p_i} T_n(p_n, p) \frac{B_n(p_n)}{dp} dp
\]
\[
= B_i(p_n) - B_i(T_n) + \int_{p_n}^{p_i} T_n(p_n, p) \frac{B_n(p_n)}{dp} dp + \int_{p_n}^{p_i} \frac{B_n(p_n)}{dp} dp\],
\]
where \( p_n \) and \( p_i \) are the pressures at the bottom and top boundaries, respectively, and \( B_i(p_n) \) is the Planck function at the temperature \( T(p_n) \) integrated over \( \Delta \nu_n \). \( B_i(T_n) \) and \( B_i(p_n) \) are the integrated Planck functions at the temperature of the bottom atmosphere \( (T_n) \) and that of the ground \( (T_g) \), respectively. In the present study, the atmospheric layer from 9.2 \times 10^4 hPa (the surface) to 4.3 hPa (about 80 km [Seiff et al., 1985]) is divided into 50 layers, which have approximately equal intervals in the \( p \) and \( log p \) coordinates in the lower and upper layers, respectively.

[12] For obtaining the radiative-convective equilibrium temperatures, it is assumed that the heat transport by free convection appearing in unstably stratified layers is represented by the vertical eddy diffusion. After Matsuda and Matsuno [1978], the temperature variation due to the eddy diffusion can be written as follows:
\[
\frac{dT}{dt}_{\text{conv}} = -\frac{g}{C_p} \frac{\partial}{\partial p} \left[ \rho K(p) \Gamma(p) \right],
\]
where \( \rho \) is the atmospheric density and \( \Gamma(p) \) is the static stability defined by
\[
\Gamma(p) = \frac{dT}{dp} + \frac{g}{C_p} = -\rho \frac{\partial T}{\partial p} + \frac{g}{C_p}.
\]
\( K(p) \) is the eddy diffusion coefficient, which is calculated on the basis of the mixing length theory as follows:
\[
K(p) = \begin{cases} \frac{l^2}{T} \sqrt{\frac{\rho}{\Gamma(p)}} \quad & (\Gamma(p) < 0) \\ 0 \quad & (\Gamma(p) > 0) \end{cases}
\]
where \( l \) is the mixing length, which is assumed to be 2 km [after Matsuda and Matsuno, 1978].

[13] In order to ensure stable numerical computations, the time increment \( \Delta t \) in the time integration of equation (1) should be less than the shortest radiative relaxation time in
the whole atmospheric layer, which is about 1 (Earth) day in this case. \( \Delta t \) is set to 43,200 s (half of a day) in the following calculations. On the other hand, for obtaining the radiative equilibrium, it is necessary to carry out integration for a time span comparable with the longest relaxation time of this system. In the present study, this time is controlled by the atmospheric opacity that depends on the type of the CO\(_2\) line profile and varies from a few hundred years to about 1500 years.

2.2. Line Profiles

[14] In the present study, the effects of the CO\(_2\) line profiles proposed so far are examined in light of the radiative and radiative-convective equilibrium temperatures, which are strongly influenced by the CO\(_2\) line profiles through CO\(_2\) absorption coefficients. The types of line profiles used in the following calculations are shown in Figure 1.

[15] Profile A, which gives the largest absorption coefficients, is the Voigt profile without any line cutoff. It is noted that the Voigt profile is identical to the Lorentz profile in the Venus atmosphere below the cloud layer. It may be predicted, therefore, that the optical thickness is overestimated in this case. Profile B is based on the sub-Lorentzian profile of Pollack et al. [1993], where the function \( \chi \) is set to 0 beyond 120 cm\(^{-1}\) from the line center. A wave number-independent continuum coefficient, which was introduced by Kamp et al. [1988] and Kamp and Taylor [1990], adopted by Pollack et al. [1993] to compensate the far wing contributions omitted in this profile is not employed in the present study. Therefore, the optical thickness may be underestimated for this type. Profile C is proposed by Tonkov et al. [1996]; it is based on measurements of CO\(_2\) absorption in the 2.3 \( \mu \)m band (3800–4700 cm\(^{-1}\)). Tonkov et al. suggested in their study that the derived functional form of \( \chi \) may be valid only within approximately 600 cm\(^{-1}\) from line centers. It is assumed, however, that \( \chi \) is also valid in the spectral regions outward of 600 cm\(^{-1}\) from line centers in the present study. Profile D is proposed by Fukabori et al. [1986]; it is based on the measurements of 2.7 and 2.0 \( \mu \)m CO\(_2\) bands. As \( \chi \) depends on the absorption bands, a few sets of the two parameters are proposed for the 2.7 and 2.0 \( \mu \)m bands. In the following calculations, parameter values of \( \mu = 3 \) and \( \nu_m = 6 \) [see Fukabori et al., 1986, equations (10) and (11)] which give a fairly good fit for the 2.0 \( \mu \)m band, are employed. Profile E, which is empirically derived for the 1.18 \( \mu \)m window, is taken from the work by Meadows and Crisp [1996]. It is noted that the \( \chi \) factor is multiplied by the van Vleck–Weisskopf profile at distances between the Voigt cutoff (40 Doppler half widths from the line center) and an empirically determined distance, 150 cm\(^{-1}\), in their formulation.

[16] Figure 2 shows the CO\(_2\) absorption coefficients calculated by using line profiles A, B, C, D, and E. The temperature and pressure for which the line profiles are determined are assumed to be those at the surface and at 50 km altitude in the Venus atmosphere. It can immediately be seen that the absorption coefficients obtained for the five profiles are quite different in the spectral regions of low absorption: the window regions. For profile A, the window regions are completely masked by the far wing absorption because of the strong bands not only at the surface but also at 50 km altitude. In contrast, the absorption coefficients obtained for profile B are considerably small in the window regions. It is also found that the absorption coefficients at the surface and at 50 km altitude is smaller than that for profile A. The absorption coefficients obtained for profile C are similar to those for profile B. Though the line cutoff is not employed in profile C, it seems that the far wing contributions are negligible in this case. The absorption coefficients obtained for profiles D and E show intermediate features: those for profiles D and E are

![Figure 1. CO\(_2\) line profiles used in the present study for calculating absorption coefficients. Profile A is the Voigt profile, and profiles B, C, D, and E are taken from the works of Pollack et al. [1993], Tonkov et al. [1996], Fukabori et al. [1986], and Meadows and Crisp [1996], respectively. All the profiles are calculated for 92 atm and 730 K.](image-url)
smaller by about one and two orders than those for profile A in the window regions, respectively. It is inferred from these distributions that the $p$ dependence of the absorption coefficients in the window regions is highly sensitive to the assumed line profile, so that it cannot be simply substituted by the grey continuum whose opacity is commonly assumed to be proportional to the pressure squared.

2.3. Pressure-Induced Absorption of $\text{CO}_2$

[17] In addition to the absorption caused by the permitted transition lines of the vibrational-rotational and rotational bands, it has been shown by Moskalenko et al. [1979] that the pressure-induced absorption (PIA) caused by the interaction of molecule pairs, such as $\text{CO}_2$-$\text{CO}_2$ and $\text{CO}_2$-$\text{N}_2$, may appear in the Venus atmosphere. As the individual
rotational lines of the molecule pairs are greatly broadened because of the brief time span of intermolecular interaction, the PIA is often referred to as the continuum absorption. Since the opacity due to the PIA is approximately proportional to the pressure squared, $\rho^2$, the PIA of CO$_2$ cannot be neglected in the lower Venus atmosphere.

[18] Pollack et al. [1993] proposed that the PIA and the far wing contribution of the lines caused by the permitted transitions are approximated by a wave number–independent continuum coefficient. However, as inferred from the absorption coefficients shown in Figure 2, the absorption coefficients due to the far wing contribution are not uniformly proportional to pressure since the sub-Lorentz factors $\chi$ vary with wavelength, and their $p$ dependence is different from that due to the PIA. Hence, it is desirable that the PIA and the far wing contribution be treated separately.

[19] In the present study, we employ the CO$_2$ continuum absorption based on the work of Moskalenko et al. [1979], whose total opacity is shown in Figure 3. Strong absorption occurs at wave numbers less than 500 cm$^{-1}$ and at about 1200–1400 cm$^{-1}$. It is quite interesting that the strong absorption due to the PIA appears in the window regions of the absorption because of the permitted transitions, as shown in Figure 2. It is also shown that PIA is weak in the regions of wave numbers of 500–1000 cm$^{-1}$, 2000–2500 cm$^{-1}$, and 3100–4000 cm$^{-1}$. Bullock [1997] has also employed the CO$_2$ continuum based on the work of Moskalenko et al. [1979]. It should be noted, however, that the opacity used by Bullock [1997] is considerably larger than that used in the present study in the weak absorption regions.

2.4. Cloud Absorption

[20] It has been inferred from the Pioneer Venus observations that the Venus cloud consists of a main cloud deck at 45–70 km altitude and thinner hazes above and below, but its particle properties and number densities are still somewhat uncertain [Knollenberg and Hunten, 1980; Esposito et al., 1983]. It has been pointed out by Matsuda and Matsumoto [1978] and Bullock [1997] that the temperatures in the Venus lower atmosphere may be strongly influenced by the cloud through the infrared radiative transfer process. Since the cloud layer absorbs most of the solar energy deposited in the Venus atmosphere [Tomasko et al., 1980], it is also expected that the horizontal and vertical structure of the cloud strongly affects the thermal tides excited in the cloud layer and the atmospheric global circulation [Takagi and Matsuda, 2005, 2006, 2007].

[21] The cloud properties, however, are quite simplified in the present study in order to focus on the effects of the CO$_2$ absorption on the equilibrium temperature. It is assumed that the cloud layer extends from 40 to 70 km altitudes and that the infrared absorption coefficient due to the cloud is independent of the wave number. Two vertical distributions of the cloud absorption coefficients $k$ are used in the following calculations: one is a distribution with constant $k\rho$, where $\rho$ is the atmospheric density, and the other is a distribution with constant $k$. The total opacity due to the cloud is estimated to be 20–30 in 0–4000 cm$^{-1}$ by conducting calculations based on the Mie scattering theory with the cloud properties provided by Knollenberg and Hunten [1980]. Therefore, it is assumed to be 30 in the present study.

3. Results

[22] The conditions under which the radiative and radiative-convective equilibrium temperatures are calculated in the present study are summarized in Table 1. Case 1 is a nominal one where the absorption coefficients are evaluated only for the lines due to the CO$_2$ permitted transition. In case 2, the absorption due to the PIA caused by the CO$_2$ molecule pair is also taken into account, in addition to that in case 1. In case 3, the absorption due to H$_2$O is also added to those in case 2. In addition to the absorption due to CO$_2$ and H$_2$O in case 3, the cloud absorption corresponding to the constant $k$ and the constant $k\rho$ distributions is taken into account in cases 4 and 5, respectively. As mentioned in section 2.4, the total opacity due to the cloud is set to 30 in both cases.

3.1. Radiative Equilibrium

[23] Figure 4 shows vertical temperature distributions obtained in the radiative equilibrium for cases 1, 2, 3, 4, and 5 by using CO$_2$ line profiles of A, B, C, D, and E. In Figure 4, the label A1, for example, indicates an equilibrium temperature distribution calculated for case 1 by using the CO$_2$ line profile of A.

[24] As shown in Figure 4a, the surface temperatures obtained by using CO$_2$ line profile A are extraordinarily high, namely, about 1800 K for all the cases. Comparison with the VIRA temperature profile (shown by the solid line) implies that the temperature distributions are clearly superadiabatic at 0–80 km altitudes. It is predicted that the temperatures cannot become close to the observed profile even

<table>
<thead>
<tr>
<th>Case</th>
<th>CO$_2$ (Continuum)</th>
<th>H$_2$O</th>
<th>Cloud (k$\rho$ Constant)</th>
<th>Cloud (k Constant)</th>
</tr>
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<td>no</td>
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<td>no</td>
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<tr>
<td>4</td>
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<td>yes</td>
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<tr>
<td>5</td>
<td>yes</td>
<td>yes</td>
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</tr>
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</table>
if vertical convection is taken into account. (This prediction will be confirmed in section 3.2.) This result indicates that the absorption coefficients derived from the simple Lorentz or Voigt line profile, as in line profile A, are highly overestimated.

Figure 4b shows the temperature profiles obtained by using CO₂ line profile B. The surface temperature of B1 is about 270 K, which is much lower than that of the VIRA profile (about 730 K). The profiles of B2 and B3 indicate the increase of the surface temperature due to the CO₂ continuum and H₂O are about 130 and 180 K, respectively. The surface temperatures of the profiles of B4 and B5 are about 600 K. The observed surface temperature cannot be reproduced in this case. It is confirmed from this result that the opacity derived from CO₂ line profile B is underestimated. The effects of the cloud on the surface temperature are considerably small: it is only about 20 K. However, it is clearly shown by the vertical profiles of B4 and B5 that the static stability greatly increases below the cloud layer. The temperature profiles shown in Figure 4c, which are obtained by using CO₂ line profile C, are similar to those in Figure 4b. This result is consistent with the fact that the
absorption coefficients obtained by using CO₂ line profiles B and C are quite similar, as understood in Figure 2. It may be inferred that the opacity in the weak window regions is underestimated, as in the previous case with line profile B.

[26] The temperature profiles obtained by using CO₂ line profile D based on the work of Fukabori et al. [1986] are shown in Figure 4d. In this case, the surface temperatures slightly exceed 730 K. It is also obvious that the temperature profiles are superadiabatic in 0–40 km altitudes. In the profiles of D1, D2, and D3, the temperature lapse rate, i.e., \(-dT/dz\), increases with altitude. This behavior, which is not seen in the cases of the CO₂ line profiles of A, B, and C, implies that the far wing contribution of the lines due to the CO₂-permitted transitions may have a complicated dependence on pressure and temperature. In contrast to the results obtained by using the CO₂ line profiles of B and C, as shown in Figures 4b and 4c, the increase of the surface temperature due to the H₂O opacity is substantially reduced to about 40 K, and the temperature change due to cloud opacity is almost negligible in 0–20 km altitudes.

[27] Figure 4e shows the temperature distributions obtained by using CO₂ line profile E. The surface temperatures are about 1300 K in all the cases, which is much higher than the observed one. The effects of the CO₂ continuum, the H₂O, and the cloud opacity are negligible below 40 km. The temperature profiles are strongly superadiabatic in 0–70 km altitudes. It is also shown that the temperature lapse rate increases with altitude. However, this feature is not as remarkable as that found in Figure 4d.

[28] It is clearly indicated by the results shown in Figure 4 that the pure radiative equilibrium temperatures in the Venus lower atmosphere are strongly affected by the absorption in the window regions. The effect of H₂O, which cannot be neglected in Figures 4b and 4c, is less important when the atmosphere is opaque because of the far wing absorption in the window regions of the CO₂ absorption. It should be noted that the effect of the cloud on the surface temperature is very small in the pure radiative equilibrium. In the cases of line profiles B, C, and D, the effect of the cloud on the atmospheric stability is remarkable in the cloud layer but negligible in the layer of 0–20 km altitudes.

3.2. Radiative-Convective Equilibrium

[29] In this section, the temperature profiles in the radiative-convective equilibrium are examined for the same set of the conditions as in the radiative equilibrium. As mentioned in section 2.1, the heat transfer by convection is represented by the vertical eddy diffusion in our model. The vertical temperature profiles so obtained are shown in Figure 5.

[30] Figure 5a illustrates the temperature profiles calculated with CO₂ Voigt line profile A. A comparison with the pure radiative equilibrium in Figure 4a indicates that the temperature decreased significantly in the entire atmospheric layer; it became about 860–1020 K at the surface. The decrease of the temperatures near the surface should be ascribed to the upward heat transport because of the convective activity extending from the surface to about 70 km altitude. However, as the surface temperature remains much higher than 730 K, it is confirmed that the Voigt profile overestimates the opacity of CO₂, which produces unrealistically high surface temperatures. The temperature profiles of A2 and A3 are very close to that of A1, as in the result obtained for the radiative equilibrium shown in Figure 4a. However, the temperature profiles of A4 and A5 for which the cloud opacity is taken into account are about 60 and 160 K higher than that of A1 at each altitude, respectively. In contrast to the result obtained for the radiative equilibrium, the effect of the cloud on the surface temperature cannot be neglected in the radiative-convective equilibrium.

[31] As shown in Figures 5b and 5c, the temperature profiles in the radiative-convective equilibrium obtained with the CO₂ line profiles of B and C do not decrease significantly from those for radiative equilibrium. Nevertheless, the surface temperatures remain about 600–620 K and are considerably lower than the observed surface temperature. This result strongly suggests that the CO₂ opacity obtained by using the line profiles of B and C is considerably underestimated. It should be noted that in these cases the convective activity is restricted to 0–10 km altitudes except in the cases of B3 and C3, in which the convection layer extends from the surface to about 30 km altitude.

[32] The temperature distributions obtained with CO₂ line profile D are illustrated in Figure 5d. While the surface temperatures obtained for the radiative equilibrium shown in Figure 4d exceed the observed one (i.e., 730 K), those obtained for the radiative-convective equilibrium are much lower than 730 K in the cases of D1, D2, and D3. The convection layer extends from the surface to 30–40 km altitudes in these cases. In such situations, the surface temperatures can be predicted from the temperatures at the bottom of the stable layer and the adiabatic lapse rate, \(g/C_p\). On the other hand, the surface temperatures of D4 and D5 are about 720 K, and their temperature profiles are very close to that of the VIRA data. It is inferred from these results that the cloud opacity affects the surface temperature more strongly in the radiative-convective equilibrium case than for the radiative equilibrium alone.

[33] Figure 5e shows the temperature distributions obtained by using CO₂ line profile E. The surface temperatures for the cases of E3, E4, and E5 are smaller than those for the radiative equilibrium by 450–650 K and become relatively close to those for the cases of D3, D4, and D5. The convection layer extends from the surface to about 45–55 km altitude in these cases. It appears that the temperature below the cloud layer is not so sensitive to the CO₂ line profiles. The reason for this is as follows: the lower atmosphere is so opaque that convection takes place; as a result, the dry adiabatic lapse rate is realized there. In this case, the temperature below the cloud layer is not affected by the opacity of the atmospheric layer below the cloud. Instead, it is controlled by the temperature at the bottom of the stable layer. It is noted that the realized temperature lapse rate remains the dry adiabatic even if the infrared opacity of the atmospheric layer is further increased. However, the vertical heat transfer due to the infrared radiative flux and the convective activity is influenced by the CO₂ line profiles. Figure 6 shows vertical profiles of the eddy diffusion coefficient, \(K(z)\), in the radiative-convective equilibrium obtained for the cases of D4, D5, E4, and E5. The eddy diffusion coefficients are about 300–600 m² s⁻¹ and 400–2000 m² s⁻¹ in the cases of D4 and D5 and in those of E4 and E5, respectively. The values in D4 and D5 are slightly smaller than those in E4 and E5 below 30 km. This result indicates that the vertical heat transfer by the infrared radiative...
ation is reduced in the cases of E4 and E5 and seems consistent with the fact that the far wing absorption given by CO$_2$ line profile E is larger than that given by line profile D. In contrast to the cases of D4 and D5, the temperatures obtained for E4 are 80 K higher than those for E5 in 0–70 km altitudes. This result suggests that the detailed cloud structure must be taken into account in order to examine correctly the radiative-convective equilibrium in the Venus atmosphere.

4. Concluding Remarks

[34] The temperature distributions in the radiative and radiative-convective equilibrium states of the Venus lower atmosphere are calculated in order to examine the influence of the CO$_2$ line profiles which have been proposed in the works of Pollack et al. [1993], Tonkov et al. [1996], Fukabori et al. [1986], and Meadows and Crisp [1996]. It is clearly shown that the CO$_2$ opacity obtained by using the Voigt (Lorentz) profile is highly overestimated to produce the surface temperature of 860–1020 K in the radiative-convective equilibrium. It is also shown that the CO$_2$ opacities obtained by using the line profiles of Pollack et al. [1993] and Tonkov et al. [1996] are underestimated since these opacities give a surface temperature of about 600–620 K even in the radiative equilibrium. The radiative-convective equilibrium temperatures closest to the observed

Figure 5. As in Figure 4 but for the radiative-convective equilibrium temperature distributions.
ones are found using the CO$_2$ line profiles of Fukabori et al. [1986] and Meadows and Crisp [1996], though the latter gives extremely high temperatures (1300 K) below the cloud layer in the radiative equilibrium. It is inferred from this result that the realistic radiative transfer model may be constructed using a CO$_2$ line profile intermediate between those of Fukabori et al. [1986] and Meadows and Crisp [1996]. It is also noted that the temperatures below the cloud layer are strongly affected by the temperature near the cloud bottom. The detailed structure and properties of the H$_2$SO$_4$ cloud should be considered in order to construct a reliable radiative transfer model which can be safely incorporated into the dynamical model of the Venus atmosphere.

### Figure 6. Vertical distributions of eddy diffusion coefficient in the radiative-convective equilibrium obtained for the cases of D4 (solid line), D5 (dashed line), E4 (dotted line), and E5 (dash-dotted line).

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### References


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