EFFECT OF ATMOSPHERIC OVERLAPPING BANDS AND THEIR TREATMENT ON THE CALCULATION OF THERMAL RADIATION

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ABSTRACT

The effect of the overlapping band of atmospheric gases and its treatment on the calculation of flux and cooling rate due to the long wave radiation is investigated in detail by a new transmission model for overlapping bands, taking the 15 μm band of CO_2 as an example. It is found that the presence of band overlapping has a quite significant influence on radiative fluxes and cooling rates in the upper stratosphere and the troposphere, in particular, at the earth's surface. However, in the middle-lower stratosphere, the overlapping effect appears to be insignificant. It is also shown that the usual wide-band transmission model treating the overlapping effect overestimates the net longwave fluxes in the lower stratosphere and, in particular, in the troposphere including the surface. But, in the middle-upper stratosphere, the contrary is the case.

I. INTRODUCTION

It is well known that there are many overlapping bands in the infrared spectra of the earth's atmospheric constituents, such as the 1.43 μm$(3\nu_3)$ band of CO_2 and the 1.38 μm (ψ) band of H_2O, the 2.0 μm $(2\nu_1+\nu_3)$ band of CO_2 and the 1.87 μm (Ω) band of H_2O, the 2.7 μm$(\nu_1+\nu_3)$ band of CO_2 and the 2.7 μm (X) band of H_2O, and so on. In the 15 μm band region, there is the absorption due to the 14 μm(ν_2) band of O_3 and the wings of the rotational band of H_2O and the 17 μm (ν_2) band of N_2O (see Fig. 1). In addition, the non-resonant absorption due to liquid water whose spectral bands spread over the entire infrared region and the continuum absorption due to water dimer $(H_2O)_2$ in the 8—12 μm window region are also overlapping with the line absorption due to other gases. Therefore, to investigate the effect resulted from such overlapping and to find an accurate and fast algorithm of treatment are of importance for studying atmospheric radiation, particularly, radiative transfer in clouds and the greenhouse effect due to trace gases.

The usual approach to this problem is based on the so-called multiplication property of the transmission. If we assume that there are two absorbing components denoted by W and U in a spectral interval $\Delta\nu$, their transmissions are denoted by $T(W)$ and $T(U)$ respectively, and the resultant transmission due to the mixture of W and U is denoted by $T(W,U)$, we will have[1]

$$T(W,U)=T(W)T(U). \qquad (1)$$

Here, It should be emphasized that Eq. (1) holds strictly only for the monochromatic (or exponential) transmission. Eq. (1) also holds for the mean transmission of a finite spectral interval or a whole band if, and only if, the transmissions of both components are completely uncorrelated, i.e. the spectral distributions of absorption coefficients of both components are completely random. Unfortunately, in the real atmosphere the situation will not be so. Hence care should be taken in using Eq. (1). The author has indicated that, in general, the use of Eq. (1) will underestimate the transmission function $T(W,U)$ as the spectral interval, $\Delta\nu$, is larger[2]. In order to decrease the error induced by using Eq. (1), many

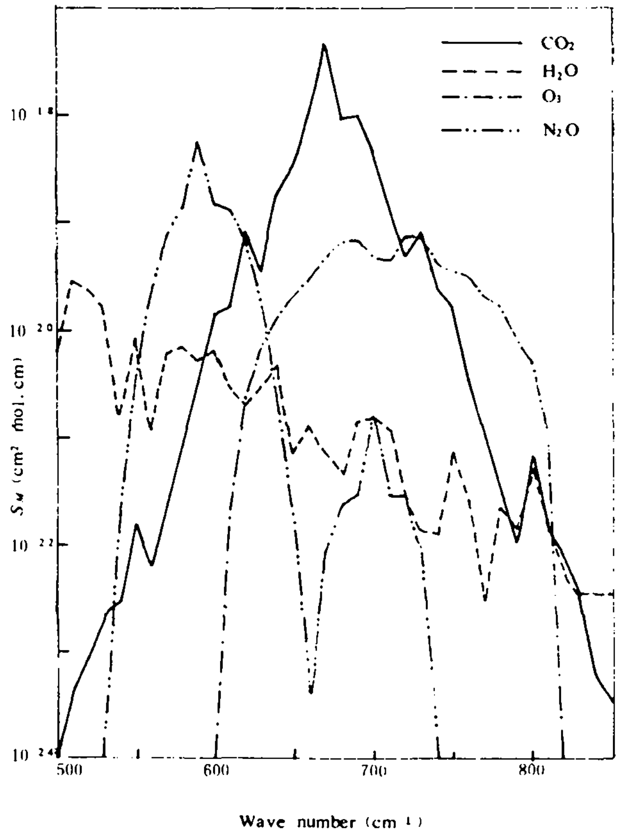

Fig. 1. The overlapping of absorption bands due to the atmospheric gases in the 15 μm region. The ordinate is the sum of intensity of lines per 10 cm^{-1}.

authors[3,4] have taken the spectral interval $\Delta\nu$ as small as possible, and used the so-called narrow band representation of the transmission function.

Wang and Ryan[3] have investigated the overlapping effect of atmospheric H_2O, CO_2 and O_3 on the CO_2 radiation. However, no comparison has been made between the narrow and wide band representations of the transmission functions. Recently, Kichl and Ramanathan[4] have compared the overlapping treatments for the wide band representation with the narrow band model in a paper about CO_2 radiative parameterization used in climate models. Because of, however, the neglect of Doppler broadening effect, they had to limit their flux calculations up to 25 km in altitude.

The effect of the simultaneous absorption due to H_2O, O_3 and N_2O on calculating the flux and the cooling rate due to the 15 μm band of CO_2 is examined in this work by a new transmission model for the overlapping bands, which was developed by the author in Ref. [2]. Because of taking account of Voigt profile for combined Doppler and Lorentz broadening, the calculation may be effective up to 60 km in altitude.

II. TRANSMISSION MODEL FOR OVERLAPPING BANDS

A new method for calculating and representing the infrared transmission function of the atmospheric constituents has been developed by the author in [2]. Basic idea of the method is that the process of radiation is independent from each other in the radiative transfer problems under consideration. Thus, we can rearrange the absorption coefficients according to their numerical values in the spectral interval $\Delta\nu$. The exponential sum fitting of transmission function has been solved satisfactorily in this way. This method has been applied successfully to calculating the radiative cooling rate due to the 9.6 μm band of ozone which is notoriously difficult in the radiative transfer calculation. Especially, by using the method it is possible to avoid the application of the Curtis-Godson approximation and the diffuse factor of 1.66 used in the usual band model techniques for dealing with an inhomogeneous path of the atmosphere and with integration over zenith angle, respectively. The accuracy of this method is comparable to the line-by-line integration. Now let us examine how this method will be applied to treating the overlapping bands of atmospheric constituents.

For the convenience of description, we still assume that there are two atmospheric constituents W and U, and that their absorption bands which have complex band structures are overlapping in the spectral interval $\Delta\nu$. For W-component, firstly, we can rearrange the absorption coefficients $k_{\nu w}$ in the $\Delta\nu$, according to their numerical values. Then the mean transmission function $T(W)$ can be easily represented by a sum of M exponential functions as[2]

$$T(W)=\frac{1}{\Delta\nu}\int_{\Delta\nu}\exp(-k_{\nu w}w)d\nu \\ \cong\sum_{i=1}^{M}P_i\exp(-k_w^iw), \tag{2}$$

where w is the absorber amount of W-component and P_i a set of weights associated with k_w^i, which may be thought as a set of equivalent absorption coefficients. Now , let us see what happens while the absorption coefficients $k_{\nu w}$ of W-component are rearranged according to their numerical values, the absorption coefficients $k_{\nu u}$ of U-component are also rearranged according to the order of rearrangement for W-component, but not according to the numerical values of $k_{\nu u}$ themselves. After that, it is clear that the absorption coefficients $k_{\nu w}$ of W-component will become a monotonous and smooth curve in the new wavenumber space ν^* (see Fig. 2). Thus, we can divide the whole interval $\Delta\nu$ into M subintervals whose widths are $\Delta\nu_i^*$, respectively, using vertically dotted lines in Fig. 2 as the divided lines and representing the mean transmission function $T(W)$ over $\Delta\nu$ by summing up M

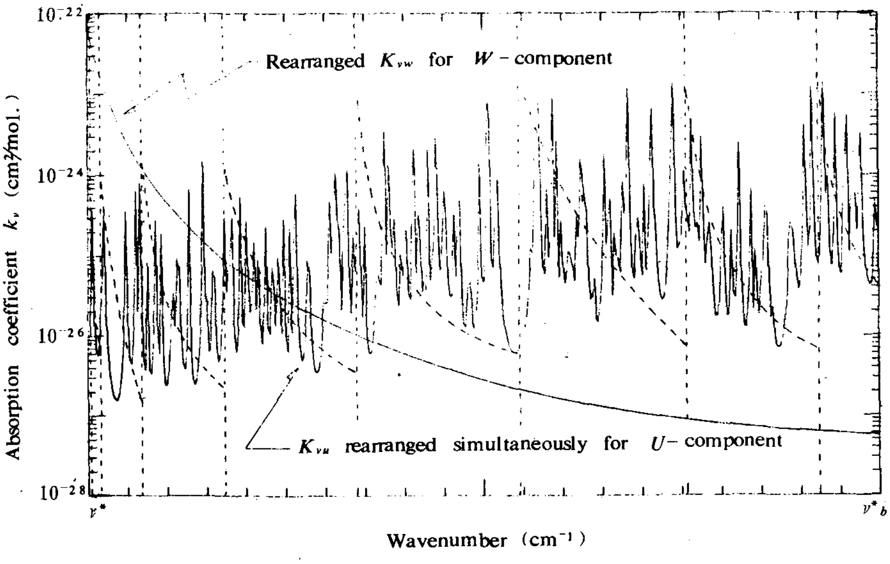

Fig. 2. Schematic illustration of the approach used for overlapping bands in the present study (see the text).

exponential transmissions in Eq. (2). If there is no correlation between the absorption coefficients of both W- and U-components in the original wavenumber space ν, the arrangement of the absorption coefficients of U-component would be completely random in the new wavenumber space ν^* after above mentioned simultaneous rearrangement of the absorption coefficients of both components W and U. As before, however, because the absorption coefficients of W and U components correlate, more or less, with each other in the original wavenumber space ν, the arrangement of the absorption coefficients of U-component is not completely random. As a result, we should not replace the mean transmission of U-component over $\Delta\nu$ by its transmission over the ith subinterval $\Delta\nu^*_i$ in a simple manner. We can, however, rearrange again the absorption coefficients of U-component in every subinterval $\Delta\nu^*_i$ and obtain M monotonous smooth curves denoted by slant dotted lines in Fig. 2. Then, the transmission over $\Delta\nu^*_i$ may be represented by use of the exponential sum fitting method. Because all the transmissions obtained in this way are of exponential, we can write

$$\begin{aligned} T_i(W, U) &= \exp(-k_w^i w) \cdot \left[\frac{1}{\Delta\nu^*_i} \int_{\Delta\nu^*_i} \exp(-k_{\nu^* u} u) d\nu^* \right] \\ &\cong \exp(-k_w^i w) \cdot \sum_{j=1,N} Q_{ij} \exp(-k_u^{ij} u), \end{aligned}$$

where u is the absorber amount of U-component and Q_{ij} a set of weights associated with k_u^{ij}, which may be thought as a set of equivalent absorption coefficients of U-component in the ith subinterval.

Finally, we have

$$\begin{aligned} T(W, U) &= \sum_{i=1,M} P_i \exp(-k_w^i w) \left(\sum_{j=1,N} Q_{ij} \exp(-k_u^{ij} u) \right) \\ &= \sum_{\substack{i=1,M \\ j=1,N}} P_i Q_{ij} \exp(-k_w^i w + k_u^{ij} u) \end{aligned} \tag{3}$$

for the resultant transmission of components W and U over the whole interval $\Delta\nu$. For striking a balance between the accuracy and the time-consuming of calculation, M and N are respectively taken to be 9 and 5 in Eq. (3).

The author has pointed out in Ref. [2] that the resultant transmission given by this approach is always satisfactory. Clearly, this approach can be easily generalized to the case in which there are more than two atmospheric constituents. To save space, this will not be discussed here.

III. RESULTS AND DISCUSSIONS

The fluxes and cooling rates due to long wave radiations in the 15μm (530—810 cm^{-1}) band region have been calculated by use of the transmission model for the overlapping bands described in Section II for the simultaneous absorption due to H_2O, O_3 and N_2O. For the convenience of treating the overlapping bands and the variation of the Planck function with wavenumber, we divide the 15μm band regime of CO_2 into three subintervals, i.e. 530—610, 610—730 and 730—810 cm^{-1}. We take account of the overlapping of bands of CO_2, H_2O and N_2O in the subinterval of 530—610 cm^{-1}, and CO_2, H_2O and O_3 in 610—730 cm^{-1} and 730—810 cm^{-1}, respectively. The spectral data are taken from Ref. [2]. Approaches to the flux and cooling rate due to long wave radiation, including the treatment of inhomogeneous path and diffuse radiation, will not be discussed here since they are all the same as those in Ref. [5]. The model atmosphere used in the computations is taken from the U.S. standard atmosphere (1962)[6], except for the concentration of CO_2 which is taken to be 335 ppm.

In order to examine the influence of different treatments for overlapping bands on the flux and cooling rate due to long wave radiation, the calculations are also carried out by the traditional multiplicative rule for wide band transmissions of the overlapping bands, where according to the usual practice, the Curtis-Godson approximation and the diffuse factor of 1.66 are used for treating the vertically inhomogeneous path of the atmosphere and the integration of diffuse radiations over angle, respectively.

For the convenience of the statement, the doubling of CO_2 is denoted as $2 \times CO_2$ and taking the overlapping effect of absorption bands of gases into accout as $CO_2+H_2O+O_3$ (or/and $+N_2O$). In addition, we will name the traditional multiplication treatment of wide bands for the overlapping effect as the traditional method for short.

The upward fluxes ($F^{\uparrow}$), downward fluxes ($F^{\downarrow}$) and net fluxes (F_N) (W/m^2) at the surface, tropopause and top of the clear atmosphere obtained for the 530—610 cm^{-1}, 610—730 cm^{-1}, 730—810 cm^{-1} and 530—810 cm^{-1} regimes, are shown in Tables 1(a)—(d) respectively. In general, the stronger the absorption band or/and the more the absorber amount, the more the downward fluxes at all altitudes except the top of the atmosphere and the smaller the upward fluxes at all levels except the surface and vice versa. These results are clearly shown in the table.

Firstly, the influence of the overlapping of absorption bands on the fluxes due to long wave radiation is examined. As can be seen from Table 1 (d), when the overlapping of bands is not taken into account, i.e. for a non-overlapping model calculation, the downward thermal flux to the surface amounts to 127.50 W/m^2 which is mainly contributed from CO_2 and H_2O, being 72.52 and 51.77 W/m^2 respectively, while the contributions from N_2O and O_3 are relatively small, being 1.97 and 1.24 W/m^2 respectively. When the overlapping of bands is taken into account in our method, the downward thermal flux to the surface is 90.46 W/m^2 for a $CO_2+H_2O+N_2O+O_3$ atmosphere which is substantially smaller than the amount of 127.50 W/m^2 for the non-overlapping model calculation. We have found, however, that the overlapping of absorption bands has less influence on the downward flux from the stratosphere to the tropopause. In our overlapping model calculation the value of 14.38 W/m^2 for the $CO_2+H_2O+O_3+N_2O$ atmosphere is comparable to that of 15.17 W/m^2 for the non-overlapping calculation. What is shown in Fig. 3 (a) is the differences between the downward fluxes obtained by our overlapping model calculation and those by the non-overlapping model calculation. Fig. 3 (b) is the same as Fig. 3 (a) but for the cooling rate. As shown in the figure, because of the overlapping of bands, the downward fluxes and the cooling rates for the troposphere, especially for the surface, decrease significantly, while an opposite trend appears in the upper stratosphere. However, the overlapping of bands has no significant influence on the middle-lower stratosphere.

Secondly, the error introduced by the traditional method for overlapping bands in calculating the radiation fluxes due to the thermal radiations is investigated. A wide band model for transmission is used for calculating the transmission due to some gases. The transmission obtained by this approach is the mean transmission over the interval $\Delta\nu$, which overestimates the transmission in the neighborhood of the centers of stronger lines and underestimates the transmission due to the wings of stronger lines and the weak lines, as compared with that from our method. In addition, as before, the resultant transmission will be underestimated when it is obtained from the multiplication of transmissions due to the component gases. It should be especially emphasized , however, that due to the variation of line shape with altitude the degree of overestimation or underestimation may be different either in the different spectral intervals or at the different levels of the atmosphere. Moreover, it also depends on the selection of the atmospheric model, in particular, on the profiles of the temperature and absorber amounts. As the differential of the Planck function with respect to altitude will vary in its sign along an atmospheric path, the influence of such overestimation or underestimation on the thermal fluxes appears to be extremely complicated. It is found that though the traditional method may come to a conclusion which is agree qualitatively with our method in examining the influence of the overlapping

Table 1. The Longwave Fluxes in W/m^2 for 15 μm Band Region (The number in parentheses denotes the result for $2\times CO_2$)

(a) 530—610 cm^{-1} (Upward flux at the surface is a constant of 34.15 in all cases)

Fluxes		Surface	Tropopause (12 km)			Top
Event		$F^{\downarrow}$	$F^{\uparrow}$	$F^{\downarrow}$	F_N	$F^{\uparrow}$
	CO_2	12.83(16.68)	29.35(27.50)	0.95(1.53)	28.40(25.97)	28.90(27.00)
	H_2O	26.50	27.80	0.07	27.73	27.80
	N_2O	1.97	33.35	0.25	33.11	33.15
$CO_2+H_2O+N_2O$	Traditional Treatment	27.70(28.22)	25.56(24.76)	1.35(1.89)	24.21(22.86)	24.39(23.22)
	This work	29.53(30.26)	24.86(23.78)	1.11(1.63)	23.75(22.15)	24.54(23.38)

(b) 610—730 cm^{-1} (Upward flux at the surface is a constant of 49.30 in all cases)

Fluxes		Surface	Tropopause (12 km)			Top
Event		$F^{\downarrow}$	$F^{\uparrow}$	$F^{\downarrow}$	F_N	$F^{\uparrow}$
	CO_2	48.16(48.88)	18.94(17.68)	12.18(13.44)	6.76(4.23)	19.96(19.52)
	H_2O	21.24	44.29	0.03	44.26	44.29
	O_3	0.96	49.13	0.77	48.36	47.83
$CO_2+H_2O+O_3$	Traditional Treatment	43.01(45.73)	24.77(22.98)	13.04(14.15)	11.72(8.82)	19.54(19.17)
	This work	48.44(48.96)	18.85(17.64)	12.35(13.57)	6.51(4.07)	19.97(19.54)

(c) 730—810 cm^{-1} (Upward flux at the surface is a constant of 29.85 in all cases)

Fluxes		Surface	Tropopause (12 km)			Top
Event		$F^{\downarrow}$	$F^{\uparrow}$	$F^{\downarrow}$	F_N	$F^{\uparrow}$
	CO_2	11.53(14.74)	24.44(22.53)	0.68(1.06)	23.76(21.48)	24.03(22.10)
	H_2O	4.04	28.87	0.01	28.86	28.86
	O_3	0.28	29.80	0.23	29.57	29.32
$CO_2+H_2O+O_3$	Traditional Treatment	11.30(13.11)	24.93(23.60)	0.98(1.35)	23.95(22.26)	23.26(21.48)
	This work	12.49(15.42)	24.15(22.35)	0.92(1.26)	23.22(21.08)	23.57(21.77)

(d) 530—810 cm^{-1} (Upward flux at the surface is a constant of 113.3 in all cases)

Fluxes		Surface	Tropopause (12 km)			Top
Event		$F^{\downarrow}$	$F^{\uparrow}$	$F^{\downarrow}$	F_N	$F^{\uparrow}$
	CO_2	72.52(80.30)	72.74(67.72)	13.81(16.03)	58.93(51.69)	72.90(68.63)
	H_2O	51.77	100.90	0.11	100.80	100.90
	N_2O	1.97	112.50	0.25	112.25	112.30
	O_3	1.24	113.08	1.00	112.08	111.30
$CO_2+H_2O+N_2O+O_3$	Traditional Treatment	82.01(87.06)	75.26(71.34)	15.37(17.39)	59.89(53.95)	67.19(63.87)
	This work	90.46(94.64)	67.86(63.77)	14.38(16.45)	53.48(47.31)	68.08(64.69)

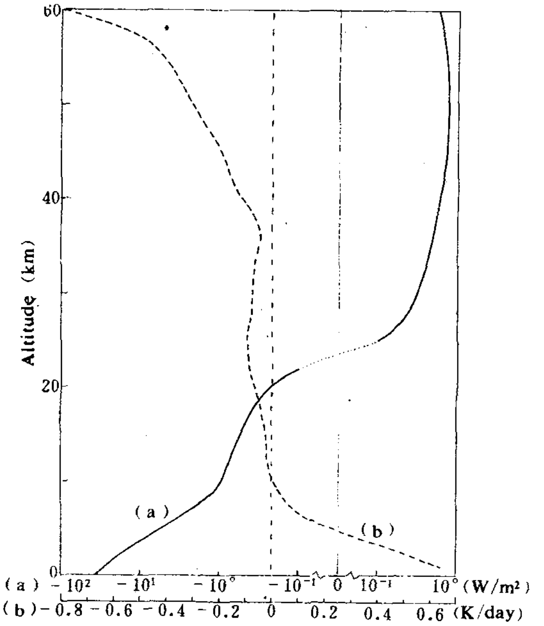

Fig. 3. The influence of the overlapping of bands on longwave flux and cooling rate.

of bands on the thermal fluxes, all the downward flux to the surface obtained by the traditional method is less than that by our method, with the error of 10% over the whole 15 μm band regime. It should be especially noted that in regions of 630—710 cm^{-1} and 730—810 cm^{-1} the downward fluxes at the surface calculated by the traditional method even are less than those by our exact method for CO_2 only, which is physically unreasonable. This kind of unreasonability is resulted from the use of the wide band transmission model. The error of net flux resulted from the traditional method is shown in Fig. 4. Below 20 km the net flux by the traditional approach is larger than that by our approach, with the maximum error of 16.52 W/m^2 at 3 km. Above 20 km, however, the former is less than the latter, but the difference of the results obtained by these two approaches is small and within 1 W/m^2 at most altitudes.

In general, the effect of band overlapping depends on two factors. One of them is the correlation between the arrangements of absorption coefficients of the overlapping bands. The greater the correlation, the more important the effect of band overlapping. The uncertainty and error inherent in the traditional approach mainly come from the fact that this approach does not consider the correlation. In other words, the multiplication law holds only if zero correlation exists in spectral features of overlapping gases. The other factor is the effective band strength of gases in the atmosphere, i. e. the resultant effect of the absolute band intensity and the amount of atmospheric gases. It is needless to say, the absorption due to one component can be neglected so long as the others are strong enough. We have indicated this point by examining the downward fluxes at the surface shown in Table 1(a)—(c) for the subintervals. Tables (a) and (c) correspond to the left wing region and the right wing region, respectively, and Table 1(b) the center region of the 15 μm band regime of CO_2. In the center region (610—730cm^{-1}), the absorption due to CO_2 is so strong that the downward flux at the surface, $F_s^{\downarrow}$, increases only by 0.72 W/m^2 as doubling the amount of CO_2. It indicates the possibility that the center region of CO_2 band is almost saturated even for the present amount of 335 ppm and the contribution of the overlapping absorption due to the other gases is negligible. For example, $F_s^{\downarrow}$ is 48.44 W/m^2 for a $CO_2+H_2O+O_3$ atmosphere and 48.16 W/m^2 for CO_2 only. The error induced by neglecting the absorption due to the gases other than CO_2 is less than 0.6%. In the wings of 15 μm band regime, however, it is necessary to take the absorption due to other gases (mainly H_2O) into account since the absorption due to CO_2 is unsaturated. The ratio between $F_s^{\downarrow}(CO_2)$ due to CO_2 and $F_s^{\downarrow}(H_2O)$ due to H_2O is shown in Table 2. The ratio reflects a relative band strength of the two gases and is found from the entries shown in Table 1 (a) and (c). As can be seen from the table, the bigger the difference between the effective band strengths of the two gases, the smaller the error induced by neglecting the weaker, and the less the effect due to the overlapping of bands. On the other hand, when the effective band strengths of the two gases are comparable and close to each other, and the error due to neglecting the weaker will become serious. It should be pointed out that because the effective band strength of atmospheric gases depends on their amounts which vary with altitude, it is possible that at some altitudes the effect of band overlapping is significant, but at other altitudes the effect is negligible. To understand the points in some detail, the reader may notice the downward fluxes to the tropopause and to the surface shown in Table 1(a), (b) and (c) for the three subintervals. In general, it should be very careful to treat the band overlapping problem.

To further examine how the approach to the overlapping band affects the variation of the longwave flux and the cooling rate, the changes in longwave fluxes and cooling rates due to doubled CO_2 (335 ppm to 670 ppm) are calculated by using the traditional treatment and our approach for a $CO_2 + H_2O + N_2O + O_3$ atmosphere (see Table 3 and Fig. 5). For the convenience of comparison, the results for CO_2 only are also shown in the table.

From the results in Tables 3 and 1 it can be seen that as increasing CO_2 abundance by a factor of two, the surface would be warmed by 7.78 W/m^2. The increased downward thermal flux to the surface is mainly contributed by the 15 μm CO_2 band wings (530—610 cm^{-1} and 730—810 cm^{-1}), being 3.85 and 3.21 W/m^2 respectively, while the contribution from the band center regime (610—730 cm^{-1}) is relatively small, only 0.72 W/m^2. As before, this is because the absorption due to the band center is close to saturation for current abundance of CO_2. For a $CO_2 + H_2O + O_3 + N_2O$ atmosphere, the presence of H_2O, O_3 and N_2O is to increase the atmospheric opacity and thus to reduce the

Table 2. The Influence of Relative Band Strength on Overlapping Effect (The number in parentheses denotes the result for $2 \times CO_2$)

Wave Number Interval (cm^{-1})	$F_s^{\downarrow}(CO_2)$ (Wm^{-2})	$F_s^{\downarrow}(H_2O)$ (Wm^{-2})	$F_s^{\downarrow}(CO_2)$: $F_s(H_2O)$	$ER1$* %	$ER2$* %
530—610	12.83(16.68)	26.50	1:2.1(1:16)	−10.26(−12.43)	39.86(49.21)
730 810	11.53(14.74)	4.04	2.9:1(3.6:1)	−7.69(−4.41)	25.70(22.63)

* The symbol $ER1$ denotes the error due to neglecting the weaker of CO_2 and H_2O and $ER2$ the error taking no account of overlapping effect but summing up the fluxes for individual components.

Table 3. The Changes in Longwave Fluxes in Wm^{-2} due to Doubling CO_2 Abundance (335 ppm→670 ppm)

Changes in Fluxes / Event		Surface			Troposphere (12 km)			Stratosphere (60 km)		
		$\Delta F^{\uparrow}$	$\Delta F^{\downarrow}$	ΔF_N	$\Delta F^{\uparrow}$	$\Delta F^{\downarrow}$	ΔF_N	$\Delta F^{\uparrow}$	$\Delta F^{\downarrow}$	ΔF_N
CO_2 only		0	7.78	−7.78	−5.02	2.22	−7.24	−4.27	0.46	−4.73
$CO_2+H_2O+N_2O+O_3$	Traditional Treatment	0	5.05	−5.05	−3.92	2.02	−5.94	−3.32	0.08	−3.40
	This work	0	4.18	−4.18	−4.09	2.08	−6.17	−3.39	0.12	−3.51

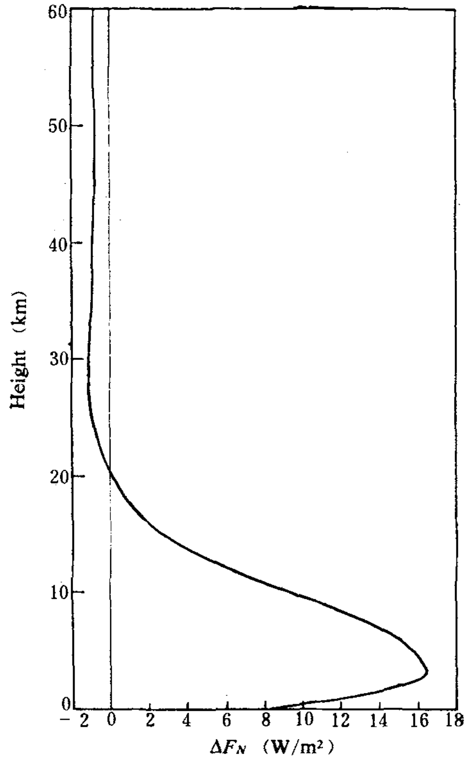

Fig. 4. The error in net flux due to the traditional treatment for the overlapping band.

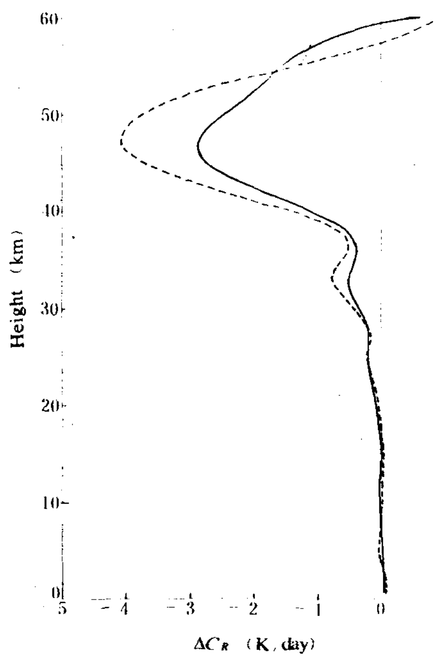

Fig. 5. The changes in cooling rates due to the doubled CO_2 abundance by use of the traditional treatment (dotted line) and the present more exact treatment (solid line) for the overlapping band for a $CO_2+H_2O+N_2O+O_3$ atmosphere.

effectiveness of CO_2 as a radiative material. Consequently, the surface warming would be reduced to 4.18 W/m², i. e. approximately reduced by a half. We also see the result obtained by the traditional treatment is 5.05 W/m² which is about 21% larger than that by our approach. It is interesting to note that the variation of longwave fluxes from the stratosphere to the tropopause appears to be small and is only about 10%, and there is slight difference between the results obtained from the two approaches for the overlapping effect, with agreement within 3%.

Fig. 5 illustrates the change of cooling rates due to the doubled CO_2 abundance for the $CO_2+H_2O+O_3+N_2O$ atmosphere. We can see from the figure that below 30 km there is fair agreement between the results of the traditional treatment and ours. From 30 km up to 54 km, the traditional approach overestimates the changes of cooling rates, with a maximum error of -1.2 K/day at 48 km. Above 54 km, however, the results for the traditional treatment is less than ours. The error in the higher altitudes is probably due to the use of the diffuse factor approximation of 1.66 in the conventional traditional treatment.

IV. CONCLUDING REMARKS

The effect of the overlapping bands and the approach to them on the fluxes and cooling rates due to longwave radiation is investigated in some detail by taking the 15 μm band regime of CO_2 as an example. The reason why we choose this spectral region is that this band region is the most important for studying the flux changes due to increased CO_2. The results indicate that the overlapping effect of bands depends not only on the correlation between spectral features (arrangement of absorption coefficients) of overlapping components but also on their effective band strength. In the 15 μm band regime of CO_2, the effect of the presence of H_2O, O_3 and N_2O is to reduce the longwave flux to the surface and, as a result, the greenhouse effect due to CO_2. We have also found that the overlapping of bands has a remarkable influence on the fluxes and cooling rates for the troposphere below 10 km and the upper stratosphere above 40 km. It is necessary to take the overlapping effect into account for studying the greenhouse effect due to the atmospheric trace gases. It seems unreasonable to ignore or to deal too roughly with the above mentioned effect in most of previous works about the CO_2 greenhouse effect. However, It is found that the overlapping of bands has slight influence on the fluxes and cooling rates at the middle-lower stratosphere. On the other hand, the traditional treatment for the overlapping bands may substantially influence the vertical flux profile, that is to say, result in the overestimation of the net longwave fluxes for the lower stratosphere and, especially, the troposphere and the surface, but in the middle-upper stratosphere the contrary is the case. When the traditional method is used for investigating the change in cooling rate due to the doubled CO_2, the results for the middle-upper stratosphere may be unsatisfactory.

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