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Abstract

A correlated k-distribution model for the atmospheric transmission of major molecular species has been used to calculate the tropospheric radiative forcing for the ground state, ν_3 , band of SF₆ and CH₄. A mid latitude summer, clear sky approximation, temperature-pressure distribution was used in the radiative transfer calculations. For the SF₆ calculations a value of 0.26 W/m² was obtained for the ν_3 band forcing using a new value of the measured integrated band absorption for SF₆. The abundance used was 1 ppbv of SF₆. Hot band contributions to the forcing are estimated to be on the order of three times the value of the ν_3 value giving a total radiative forcing of about 0.73 W/m². For the CH₄ calculation a value of 1.71 W/m² was obtained and this number agrees with previously published CH₄ radiative forcing values to within four percent. The radiative forcing calculation for SF₆ is used to estimate the global warming potential (GWP) of SF₆ using an approximate model developed to provide reasonably accurate GWPs. The results give GWPs for SF₆ of the order of 12000–25000 (CO₂ = 1). We estimate the likely range of the radiative forcing and GWP values based on two recent measurements of the total integrated band strength of SF₆. Comparison of the GWPs of SF₆ to those of CF₄ (3600–8500) and CFC-11 (4500–1400) indicates that SF₆ has the potential to be a major greenhouse gas if large amounts are introduced into the atmosphere.

I. Introduction

In a recent publication Grossman and Wuebbles (1992, "GW") an approximate model for the calculation of the global warming potentials (GWP) of trace gases in the atmosphere was described and used to calculate the GWP for SF₆. The GWP of a gas is defined as,

$$GWP(c_i) = \frac{\int_0^t \Delta F(c_i, t) dt}{\int_0^t \Delta F(c_{CO_2}, t) dt} \quad (1)$$

where ΔF is the change in radiative forcing with time as a function of the species concentration (c_i). The approximate model for Equation 1 given by GW is,

$$GWP(C_i) = \frac{m_{CFC-11}}{m_i} \cdot \frac{a_i}{a_{CFC-11}} \cdot \frac{\tau_i}{\tau_{CFC-11}} \cdot \frac{(1 - \exp(-t/\tau_i))}{(1 - \exp(-t/\tau_{CFC-11}))} GWP(CFC-11) \quad (2)$$

where the a 's are the radiative forcing values at the tropopause in W/m² per ppbv, the m 's are the molecular mass, and the τ 's are the atmospheric lifetimes. For SF₆ an a_{SF_6} value for the primary, ground state, ν_3 band absorption of 0.197 W/m² per ppbv (Stordal, 1993) and a τ value of 3200 years (Ravishankara, *et al.*, 1993) were used to calculate the GWP. GWP values (CO₂ = 1) of 4513, 6127, and 9938 were obtained at times of 20, 100, and 500 years indicating the significance of SF₆ as a greenhouse gas relative to CO₂. The a_{SF_6} value obtained by Stordal was based on a calculation using an integrated band strength of 5.243×10^{-17} cm⁻¹/mols-cm⁻² (HITRAN91) at 296K or 1409 cm⁻¹/atm-cm⁻² at STP for the ν_3 band of SF₆, and a McClatchey mid latitude summer atmosphere and a clear sky approximation (MLSCS). It was assumed by GW that the differences in the GWP of SF₆ resulting from the use of an a calculated using a MLSCS model and that using the IPCC (1990) standard atmosphere would be small and this would permit the use of the IPCC (1990) values for a and GWP (CFC11) in Equation 2.

Recent experimental data of Ko *et al.* (1993) gives a total integrated band absorption for SF₆ of 5898 cm⁻¹/atm-cm⁻² (STP) compared with the previous value of 4800 cm⁻¹/atm-cm⁻² (STP) (Rinsland *et al.*, 1990). Ko *et al.* (1993) used this new data to calculate a GWP of SF₆ of ~16000 at a time of 20 years which is a factor of ~4 times the result obtained by GW. According to Rinsland *et al.* (1990) the difference between 4800 (total absorption strength) and 1409 (ν_3 band strength) cm⁻¹/atm-cm⁻² (STP) is the contribution of the hot bands of SF₆ which are excited at tropospheric temperatures. The total band strength and individual line strengths for the ν_3 band lines are obtained by first scaling the measured value of the total absorption strength of 4800 cm⁻¹/atm-cm⁻² (Schatz and Hornig, 1953) to the ν_3 band dipole moment at STP using the method of Fox and Person (1976). The scaling factor between the total absorption band strength and the ν_3 band integrated strength given by Fox and Person (1976) is

$$S(\nu_3) = S(\text{total}) (1 - \exp(-948 hc/kT))/Z\nu, \quad (3)$$

where Z_v is the vibrational partition function given by Fox (1976). At a temperature of 273K, $S(\nu_3) = S(\text{total})/2.6$, and at 296K, $S(\nu_3) = S(\text{total})/3.2$. The ν_3 band dipole moment obtained by Fox and Person (1976) of 0.388 debye units is temperature independent. Rinsland *et al.* (1990) use the ν_3 band dipole moment to scale the relative intensities of the ν_3 band lines at 0C to absolute intensities and then use the procedure of Fox (1976) to scale the absolute intensity of each line to 296K. The intensities are then summed to give $5.243 \times 10^{-17} \text{ cm}^{-1}/\text{mols-cm}^{-2}$ or $1409 \text{ cm}^{-1}/\text{atm-cm}^{-2}$ STP at 296K. If the total integrated band strength has a value of $5898 \text{ cm}^{-1}/\text{atm-cm}^{-2}$ STP, the method outlined above suggests that the individual line strengths and the total line strength of the ν_3 band given in the HITRAN91 data base should be increased by the factor $5898/4800$ (1.23). Varanasi (1993) has also measured the total integrated band strength of SF_6 and finds a value of $4800 \text{ cm}^{-1}/\text{atm-cm}^{-2}$ (STP). This value is in agreement with the original Schatz and Hornig (1953) value and opposed to the Ko *et al.* (1993) value of $5898 \text{ cm}^{-1}/\text{atm-cm}^{-2}$ (STP). We believe that these two values represent the range of likely values of the total integrated band strength of SF_6 . Rinsland *et al.* (1990) gives a crude approximation to the line list for the first hot band, the $\nu_3 + \nu_6 - \nu_6$ band. The lines for this band are approximated by the ν_3 band lines shifted, in wave number, by -1.11 cm^{-1} and scaled in strength by a factor of 0.5589. The next hot band should be a factor of two weaker than the first hot band but no approximate line data was given. The sum of the hot band contributions should produce an increase in total integrated band strength of a factor of the order of 3.2 to 3.4 since Equation (3) is, according to Fox and Person (1976), an approximation to the true scaling factor. Varanasi *et al.* (1992) measured the line opacity of SF_6 in a 0.48 cm^{-1} spectral region centered at 947.84 cm^{-1} at 295K and 1013 mb. They found absorption coefficient factors on the order of 2 times those of the ν_3 band. This spectral region is too small to draw significant conclusions about the integrated band strengths other than to infer that there is a strong hot band contribution to the SF_6 absorption.

The main purpose of this paper is to do a first principles calculation of the radiative forcing of SF_6 and CH_4 using the line by line data in the HITRAN91 data base (Rothman *et al.*, 1991) for the MLSCS. For the case of SF_6 a calculation will be made using the approximate line list for the first hot band (Rinsland, 1990) as well as a calculation of the forcing using ν_3 band line strengths which have been scaled to the Ko *et al.* (1993) value of the total integrated band strength of $5898 \text{ cm}^{-1}/\text{atm-cm}^{-2}$ (STP). An estimate will be made for the total radiative forcing contribution of the hot bands of SF_6 . GWP calculations for SF_6 will be made and compared to the CFCs. Lastly, the radiative forcing result for CH_4 in the MLSCS atmosphere will be compared to the IPCC (1990) result for CH_4 to determine the systematic differences between the two atmosphere models. This comparison can provide an indication of the validity of the use of the IPCC (1990) value of the CFC-11 radiative forcing in a GWP calculation which uses a MLSCS value of the SF_6 radiative forcing.

II. Correlated K-Distribution Calculations

The radiative forcing term a_i in Equation 2 is defined as the difference in the net radiative flux at the tropopause due to a change in the composition by 1 ppbv of a single molecular species while, at the same time, keeping the composition of all other species constant. In a recent publication Grant *et al.* (1992, "G1") and Grossman and Grant (1992, "G2") a correlated

k-distribution model for the transmission of the major atmospheric molecular absorption species was used to calculate the fluxes and heating rates in the 0–2500 cm^{-1} wavenumber range. This model gives accuracies in the fluxes and heating rates of better than ten percent when compared to line by line calculations in approximately three orders of magnitude less time. The altitude range covered by these calculations was 0–60 km. Heating rate accuracies of better than ten percent were achieved with respect to detailed line by line calculations. The k-distributions were calculated using the HITRAN91 database (Rothman *et al.*, 1991) to obtain the line parameters within each wavenumber sub interval, the FASCODE2 code (Clough, 1986) to calculate a grid of detailed line by line opacities, and the ABSORT code (G1) to calculate the cumulative probability distributions and the k-distributions for each atmospheric layer. Although the ν_3 band of SF_6 line parameters exist in the HITRAN91 data base, the molecular constants necessary for the opacity calculation have not been implemented in the FASCODE2 code. The vibrational frequencies for SF_6 have been given by McDowell *et al.* (1976) and Rinsland *et al.* (1990). The values adopted were 774 (1), 642 (2), 948 (3), 615 (3), 523 (3), and 348 (3) cm^{-1} , for ν_1 to ν_6 , with the numbers in the parentheses denoting the degeneracy factors. These numbers were inserted into the FASCODE2 code and the line by line calculations at each atmospheric layer were performed. The HITRAN91 data base shows that all of the lines in the ν_3 band of SF_6 are contained in the 940–955 cm^{-1} wavenumber band. Figures 1a, 1b, and 1c show the opacity distribution function, $f(k)$, the cumulative probability distribution, $g(k)$, and the k-distribution, $k(g)$, at an atmospheric pressure of 945.2 mb in the 940–955 cm^{-1} wavenumber range for a gas composed of 1 ppbv of SF_6 plus the current atmospheric abundances of H_2O , CO_2 , O_3 , CH_4 , and N_2O . Figures 2 and 3 show the same quantities at atmospheric pressures of 178.5 and 1.48 mb respectively. Figure 4 shows the k-distributions for the above mixture and pressures plotted on the same graph. Figures 5a, 5b, and 5c show the $f(k)$, $g(k)$, and $k(g)$ functions for a gas consisting of just the current atmospheric abundances of H_2O , CO_2 , O_3 , CH_4 , and N_2O (no SF_6) at a pressure of 945.2 mb for the wavenumber region 940–955 cm^{-1} . Figures 6 and 7 show the same quantities at atmospheric pressures of 178.5 and 1.48 mb respectively. Figure 8 shows the k-distributions for this mixture plotted on the same graph. The $f(k)$, $g(k)$, and $k(g)$ functions for CH_4 in the 1100–1340 cm^{-1} wavenumber range are illustrated in G1.

III. Parameters of the Calculations

The parameters of the SF_6 and CH_4 radiative forcing calculations are:

1. McClatchey mid latitude, summer, pressure-temperature distribution (McClatchey *et al.*, 1972).
2. Altitude resolution;
 - a. 1 km, 0–20 km altitude,
 - b. 2 km, 20–80 km altitude.
3. A ground temperature of 294 K.
4. Molecular mixing ratios;
 - a. A CO_2 mixing ratio of 354 ppm,
 - b. A CH_4 mixing ratio of 1.72 ppm,

- c. A N₂O mixing ratio of 350 ppb,
 - d. A SF₆ mixing ratio of 1.00 ppb,
 - e. H₂O and O₃ mixing ratios as specified in the McClatchey atmosphere, non-uniform distribution.
5. Wave number intervals;
- a. 940–955 cm⁻¹, single interval, for the SF₆ calculation.
 - b. 930–955 cm⁻¹, single interval, for the SF₆ + 1st hot band calculation.
 - c. 950–1650 cm⁻¹, 25 cm⁻¹ sub intervals, for the CH₄ calculation.
6. The tropopause was set at 179 mb (12.5 km altitude).

The assumption of constant mixing ratios of CH₄ and N₂O in the stratosphere is not valid, however the contribution of the stratospheric CH₄ and N₂O to the tropospheric radiative forcing will be negligible.

IV. Results and Discussion

Radiative forcing calculations, for the ν_3 band of SF₆, the ν_3 band plus the first hot band of SF₆, the new scaled ν_3 band plus the first hot band of SF₆, and CH₄, have been performed using the correlated k-distribution transmission model and the radiative transfer model outlined in G1 to calculate the tropospheric fluxes and heating rates. Figure 9 shows the downward flux (a), the heating rate (b), the upward flux (c), and the net upward flux (d), as a function of altitude for the wave number interval 940–955 cm⁻¹ for the ν_3 band SF₆ calculation. The solid lines represent a mixture containing 1 ppbv of SF₆, at all altitudes, plus the standard abundances of H₂O, CO₂, O₃, and N₂O, treated as a single combined gas. The dotted lines represent the results for the same mixture without SF₆. The net upward flux is defined as the upward flux at each atmospheric level minus the upward flux due to the ground at the bottom of the atmosphere. The radiative forcing is given by the expression,

$$f = F_{NU1} - F_{NU2} - F_{D2} + F_{D1} , \quad (4)$$

where the F_D s are the downward fluxes and the F_{NU} s are the net upward fluxes. The subscripts 1 and 2 denote the mixture with 1 ppbv SF₆ and the mixture without SF₆, respectively. The flux values at the tropopause for the SF₆ calculation are,

$$\begin{aligned} F_{NU1} &= 0.3795 & F_{D1} &= 0.0463 \\ F_{NU2} &= 0.1585 & F_{D2} &= 0.00405 \end{aligned} \quad \left(\text{W/m}^2 \right)$$

Substitution of these values into Equation 3 gives a radiative forcing value of 0.2633 W/m². This represents a difference of about 33 percent with respect to the value of 0.197 W/m² given by Stordal (1993). Tests performed using larger wave number intervals, 935–960 cm⁻¹ and 925–950

plus 950–975 cm^{-1} , yielded forcing values which differed by less than one percent. Table 1 summarizes the SF_6 calculations. The addition of the first hot band ($\nu_3 + \nu_6 - \nu_6$) adds ~40 percent to the ν_3 band result. This is a reasonable result in view of the strength factors of 0.558 at 296K and 0.312 at 220K given by Rinsland *et al.* (1990). According to Rinsland the next hot band ($\nu_3 + \nu_5 - \nu_5$) should contribute approximately a 20 percent increase to the ν_3 band forcing. The third entry in Table 1 is our estimate of the total SF_6 radiative forcing based on an approximation of the ν_3 band value which has been scaled using equation (3) and an integrated band strength of 4800 $\text{cm}^{-1}/\text{atm}\cdot\text{cm}^{-2}$ (STP). Under the assumption that the total ν_3 band moment of 0.388 debyes (Fox and Person, 1976) is used in a multiplicative scaling of the individual ν_3 band relative line strengths, Rinsland *et al.* (1990), we multiply all the ν_3 band line strengths by the ratio of the Ko *et al.* (1993) total integrated band strength value, 5898 $\text{cm}^{-1}/\text{atm}\cdot\text{cm}^{-2}$ (STP), to the Varanasi (1993) value of 4800 $\text{cm}^{-1}/\text{atm}\cdot\text{cm}^{-2}$ (STP). The scaling factor is 1.2278. The fourth entry in Table 1 is the radiative forcing obtained by scaling the ν_3 band line strengths by 1.2278 and adding the approximation for the first hot band (the 1.2278 scaling also applies to the first hot band). The calculated forcing using the scaled band strengths is about 1.19 times the value obtained for the unscaled band strengths. The approximately 4 percent difference between the scaling factor and the actual radiative forcing is probably due to saturation effects at the high cumulative probability end of the correlated k-distributions. The final entry in Table 1 is the value obtained by Stordal (1993) using the total integrated band strength of 5898 $\text{cm}^{-1}/\text{atm}\cdot\text{cm}^{-2}$ (STP) in a weak line approximation, band model calculation.

Table 1. SF_6 Radiative Forcing (W/m^2)

ν_3 band (HITRAN91)	0.2633
ν_3 band + $\nu_3 + \nu_6 - \nu_6$ band (Rinsland <i>et al.</i> , 1990)	0.3790
Total $\text{SF}_6 - 4800 \text{ cm}^{-1}/\text{atm}\cdot\text{cm}^{-2}$ (STP)	0.731
ν_3 band + $\nu_3 + \nu_6 - \nu_6$ band (HITRAN91 scaled)	0.4499
Total $\text{SF}_6 - 5898 \text{ cm}^{-1}/\text{atm}\cdot\text{cm}^{-2}$ (STP) (Stordal, 1993)	0.897

In order to assess the systematic differences between our MLSCS calculation and the IPCC (1990) formulae for radiative forcing, we calculate the tropospheric radiative forcing for CH_4 in the MLSCS approximation. Figure 10 shows the downward flux (a), the heating rate (b), the upward flux (c), and the net upward flux (d), as a function of altitude for the wave number interval 950–1650 cm^{-1} for the pure CH_4 calculation. The solid lines represent a mixture containing 3.44 ppmv of CH_4 , at all altitudes. The dotted lines represent the results for the standard mixing ratio of CH_4 of 1.72 ppmv (this is the 2X forcing). The flux values at the tropopause for the CH_4 calculation are,

$$\begin{aligned}
 F_{NU1} &= 5.8571 & F_{D1} &= 0.29359 \\
 & & & \left(\text{W}/\text{m}^2 \right) \\
 F_{NU2} &= 4.386 & F_{D2} &= 0.20680
 \end{aligned}$$

Substitution of these values into Equation 3 gives a radiative forcing value of 1.71 W/m^2 . Ramanathan *et al.* (1987) published the results of a pure CH_4 radiative forcing calculation for a

MLSCS atmosphere. A tropospheric forcing value of 1.78 W/m^2 was obtained by Ramanathan *et al.* (1987) for the same wave number interval and mixing ratios as given above. The result obtained in this paper differs with that of Ramanathan *et al.* (1987) by about four percent. In order to assess the effect of overlapping absorption features of other gases in the $950\text{--}1650 \text{ cm}^{-1}$ wavenumber range, a radiative forcing calculation was performed for the $2 \times \text{CH}_4$ mixing ratio plus the normal abundances of H_2O , CO_2 , O_3 , and N_2O . Figure 11 shows the downward flux (a), the heating rate (b), the upward flux (c), and the net upward flux (d), as a function of altitude for the wave number interval $950\text{--}1650 \text{ cm}^{-1}$ for the CH_4 calculation. The solid lines represent a mixture containing 3.44 ppmv of CH_4 , at all altitudes, plus the standard abundances of H_2O , CO_2 , O_3 , and N_2O , treated as a single combined gas. The dotted lines represent the results for the same mixture except that the mixing ratio of CH_4 is 1.72 ppmv . The flux values at the tropopause for the this calculation are,

$$\begin{array}{ll} F_{NU1} = 37.297 & F_{D1} = 2.5270 \\ & (W/m^2) \\ F_{NU2} = 35.892 & F_{D2} = 2.3780 \end{array}$$

Substitution of these values into Equation 3 gives a tropospheric radiative forcing value of 1.56 W/m^2 . The effect of overlapping absorption features of other gases reduces the radiative forcing by about nine percent. According to IPCC (1990), the effect of overlapping absorption features of other gases should reduce the pure CH_4 radiative forcing by about 15 percent. The above results are consistent with this number. If the formula given in IPCC (1990) for CH_4 is used to calculate the tropospheric forcing for pure CH_4 , a value of 0.6184 is obtained. Apparently the use of the MLSCS approximation, results in a factor of 2.7 increase in the radiative forcing over the IPCC value. This factor is probably due to a different temperature-pressure distribution and the incorporation of a cloud model in the IPCC forcing estimates.

According to Stordal (1993) the trpopspheric radiative forcing value for CFC-11 in the MLSCS approximation is 0.329 W/m^2 as opposed to the IPCC (1992) value of 0.22 W/m^2 . This suggests a reduction of the SF_6 radiative forcing by a factor of 1.5. We believe that the IPCC (1990) value for the CH_4 forcing may be systematically low and should not be used to correct the SF_6 forcing to the IPCC standard. We will use the CFC-11 correction factor of 1.5 in the GWP calculations to follow. Thus the ν_3 band SF_6 radiative forcing of 0.2633 W/m^2 , obtained in this paper, should be reduced by a factor of 1.5 to 0.1666 W/m^2 before calculating the GWP with Equation 2 which uses IPCC results for CFC-11. A calculation of the GWP for SF_6 using the parameters given in Table 2 was made.

Table 2. Approximate Model Calculation Parameters

mass SF ₆	=	146 amu
mass CFC-11	=	137.5 amu
a (SF ₆)	=	0.1755 W/m ²
		0.1755 (ν ₃ Band-HITRAN91) W/m ²
		0.2527 (ν ₃ , ν ₃ + ν ₆ - ν ₆)
		0.2999 (ν ₃ , ν ₃ + ν ₆ - ν ₆ , scaled)
a (CFC-11)	=	0.22 W/m ² (IPCC, 1990)
τ SF ₆	=	3200 years (Ravishankara, <i>et al.</i> , 1993)
τ CFC-11	=	55 years (IPCC, 1992)
GWP (CFC-11)	=	4500 @ t = 20 years (IPCC, 1992)
	=	3400 @ t = 100 years
	=	1400 @ t = 500 years

Table 3 shows the results of the approximate model calculation of GWP (SF₆) at times of 20, 100, and 500 years.

Table 3. Global Warming Potential for SF₆ (CO₂ = 1)

SF ₆	Time (Years)		
	20	100	500
ν ₃ band (HITRAN91)	4020	5459	8854
ν ₃ band + ν ₃ + ν ₆ - ν ₆ band (Rinseland <i>et al.</i> , 1990)	5788	7861	12749
Total SF ₆ - 4800 cm ⁻¹ /atm-cm ⁻² (STP)	11147	15139	24553
ν ₃ band + ν ₃ + ν ₆ - ν ₆ band (HITRAN91 scaled)	6869	9329	15130
Total SF ₆ - 5898 cm ⁻¹ /atm-cm ⁻² (STP) (Stordal, 1993)	13697	18602	30170

The GWPs for the total integrated band strength given in Table 3 were obtained using a value of 0.897 W/m² given by Stordal (1993) and then decreased by a factor of 1.5 to correct for the MLSCS approximation. Our value of 13697 at 20 years compares reasonably to the 16000 value given by Ko *et al.* (1993). The likely range of SF₆ GWP values lies between 11147 and 13697 at 20 years to between 24553 and 30170 at 500 years depending on the total integrated band strength value, 4800 or 5898 cm⁻¹/atm-cm⁻² (STP). Previous calculations of the GWP of CF₄ (Wuebbles and Grossman, 1992) give GWPs on the order of 4000 at 20 years and the IPCC (1990) value for the GWP of CFC-11 at 20 years is also on the order of 4000. The GWP results show that SF₆ is, on a per gram basis, one of the strongest greenhouse gases known. Extreme care should be taken to insure that large quantities of SF₆ are not released into the atmosphere.

In summary, we have used all published line data to estimate the radiative forcing of SF₆ and CH₄ and the GWP of SF₆ using the correlated k-distribution radiative transfer model. We have been able to calculate the effects of the ν_3 band and the $\nu_3 + \nu_6 - \nu_6$ hot band but the other excited bands of SF₆ contribute an approximate factor of 2 more to the radiative forcing and the GWP. We give the likely ranges in tropospheric radiative forcing and GWP values which take into account the recent measurements of the total SF₆ integrated band strength. Our calculations of the radiative forcing of CH₄ in the MLSCS approximation gives a very large difference with respect to the IPCC (1990) value and we suggest that the IPCC calculation for CH₄ be reviewed for possible improvements.

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Figure Captions

- Figure 1. The opacity distribution function, $f(k)$ (Figure 1a), the cumulative probability distribution, $g(k)$ (Figure 1b), and the k -distribution, $k(g)$ (Figure 1c), at an atmospheric pressure of 945.2 mb in the 940–955 cm^{-1} wavenumber range for a gas composed of 1 ppbv of SF_6 (ν_3 band) plus the current atmospheric abundances of H_2O , CO_2 , O_3 , CH_4 , and N_2O .
- Figure 2. The opacity distribution function, $f(k)$ (Figure 2a), the cumulative probability distribution, $g(k)$ (Figure 2b), and the k -distribution, $k(g)$ (Figure 2c), at an atmospheric pressure of 178.5 mb in the 940–955 cm^{-1} wavenumber range for a gas composed of 1 ppbv of SF_6 (ν_3 band) plus the current atmospheric abundances of H_2O , CO_2 , O_3 , CH_4 , and N_2O .
- Figure 3. The opacity distribution function, $f(k)$ (Figure 3a), the cumulative probability distribution, $g(k)$ (Figure 3b), and the k -distribution, $k(g)$ (Figure 3c), at an atmospheric pressure of 1.480 mb in the 940–955 cm^{-1} wavenumber range for a gas composed of 1 ppbv of SF_6 (ν_3 band) plus the current atmospheric abundances of H_2O , CO_2 , O_3 , CH_4 , and N_2O .
- Figure 4. The SF_6 (ν_3 band) plus other molecules k -distributions for the wave number band 940–955 cm^{-1} , at three atmospheric pressure levels, $P = 945.2, 178.5$, and 1.480 mb.
- Figure 5. The opacity distribution function, $f(k)$ (Figure 5a), the cumulative probability distribution, $g(k)$ (Figure 5b), and the k -distribution, $k(g)$ (Figure 5c), at an atmospheric pressure of 945.2 mb in the 940–955 cm^{-1} wavenumber range for a gas composed of a mixture of the current atmospheric abundances of H_2O , CO_2 , O_3 , CH_4 , and N_2O (no SF_6).
- Figure 6. The opacity distribution function, $f(k)$ (Figure 6a), the cumulative probability distribution, $g(k)$ (Figure 6b), and the k -distribution, $k(g)$ (Figure 6c), at an atmospheric pressure of 178.5 mb in the 940–955 cm^{-1} wavenumber range for a gas composed of a mixture of the current atmospheric abundances of H_2O , CO_2 , O_3 , CH_4 , and N_2O (no SF_6).
- Figure 7. The opacity distribution function, $f(k)$ (Figure 7a), the cumulative probability distribution, $g(k)$ (Figure 7b), and the k -distribution, $k(g)$ (Figure 7c), at an atmospheric pressure of 1.480 mb in the 940–955 cm^{-1} wavenumber range for a gas composed of a mixture of the current atmospheric abundances of H_2O , CO_2 , O_3 , CH_4 , and N_2O (no SF_6).
- Figure 8. The molecular combined gas (no SF_6) k -distributions for the wave number band 940–955 cm^{-1} , at three atmospheric pressure levels, $P = 945.2, 178.5$, and 1.480 mb.

- Figure 9. The downward flux (a), the heating rate (b), the upward flux (c), and the net upward flux (d), as a function of altitude for the wave number interval $940\text{--}955\text{ cm}^{-1}$ for the SF_6 (ν_3 band) calculation. The solid lines represent a mixture containing 1 ppbv of SF_6 , at all altitudes, plus the current atmospheric abundances of H_2O , CO_2 , O_3 , and N_2O , treated as a single combined gas. The dotted lines represent the results for the same mixture without SF_6 . The net upward flux is defined as the upward flux at each atmospheric level minus the upward flux due to the ground at the bottom of the atmosphere.
- Figure 10. The downward flux (a), the heating rate (b), the upward flux (c), and the net upward flux (d), as a function of altitude for the wave number interval $950\text{--}1650\text{ cm}^{-1}$, using a 25 cm^{-1} subinterval size, for the pure CH_4 calculation. The solid lines represent a gas containing 3.44 ppmv of CH_4 , at all altitudes. The dotted lines represent the results for a gas containing 1.72 ppmv of CH_4 . The net upward flux is defined as the upward flux at each atmospheric level minus the upward flux due to the ground at the bottom of the atmosphere.
- Figure 11. The downward flux (a), the heating rate (b), the upward flux (c), and the net upward flux (d), as a function of altitude for the wave number interval $950\text{--}1650\text{ cm}^{-1}$, using a 25 cm^{-1} subinterval size, for the CH_4 calculation. The solid lines represent a mixture containing 3.44 ppmv of CH_4 , at all altitudes, plus the current atmospheric abundances of H_2O , CO_2 , O_3 , and N_2O , treated as a single combined gas. The dotted lines represent the results for the same mixture with a CH_4 mixing ratio of 1.72 ppmv. The net upward flux is defined as the upward flux at each atmospheric level minus the upward flux due to the ground at the bottom of the atmosphere.

SF₆

Pressure	945.2
Temperature	291.66
Band Low	940.00
Band High	955.00

Figure 1.

Pressure	178.5
Temperature	217.28
Band Low	940.00
Band High	955.00

Figure 2.

SF6

Pressure	1.480
Temperature	272.23
Band Low	940.00
Band High	955.00

Figure 3.

Figure 4.

No SF₆

Pressure	945.2
Temperature	291.66
Band Low	940.00
Band High	955.00

Figure 5.

No SF₆

(a)

(c)

(b)

Pressure	178.5
Temperature	217.28
Band Low	940.00
Band High	955.00

Figure 6.

No SF₆

Pressure	1.480
Temperature	272.23
Band Low	940.00
Band High	955.00

Figure 7.

Figure 8.

SF₆/MIXTURE, 940-955 cm⁻¹

Figure 9.

CH₄, 950-1650 cm⁻¹

Figure 10.

CH₄/MIXTURE, 950-1650 cm⁻¹

Figure 11.

END

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