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Cooling the Martian atmosphere: the spectral overlap of the CO_2 15 μm band and dust

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Abstract. Careful consideration must be given to the simultaneous treatment of the radiative transfer of the CO_2 15 μm band and dust. Calculations for the Martian winter polar region show that a simple sum of separately calculated CO_2 cooling rates and dust cooling rates can easily result in a 30% error in the net cooling, particularly near the surface. CO_2 and dust hinder each other's ability to cool the atmosphere. Even during periods of low dust opacity, dust still reduces the efficacy of CO_2 at cooling the atmosphere. At the other extreme, when dust storms occur, CO_2 still significantly impedes the ability of dust to cool the atmosphere. Hence, both CO_2 and dust must be considered in radiative transfer models.

Introduction

CO_2 is the only gas which produces appreciable infrared cooling of the Martian troposphere (Goody and Belton, 1967; Crisp, 1990; Lindner, 1991; Savijarvi, 1991; Hourdin, 1992); hence, the transmission on Mars of the CO_2 15 μm band has been well studied (Gal'tsev and Osipov, 1979; Crisp, 1990; Lindner *et al.*, 1990a,b; Savijarvi, 1991; Hourdin, 1992). Airborne dust also produces appreciable cooling, even in periods other than global dust storms (e.g. Lindner, 1985, 1993). However, virtually all previous studies of Martian radiative cooling have ignored the presence of dust when calculating CO_2 cooling rates. The effect of dust–CO_2 spectral overlap (hereafter abbreviated as dust–CO_2 interaction) was studied by Kondrat'ev and Moscalenko (1975) and Egan *et al.* (1980) for the effect on line profiles, by Pallman (1983) for the near-surface boundary layer, by Pollack *et al.* (1979) for inverting data, and by Haberle *et al.* (1982) for circulation models. However, none of these studies published or discussed dust–CO_2 interaction. The importance of both CO_2 and dust in Martian radiative transfer requires a model capable of accurately handling the scattering by dust and the complex wavelength structure of CO_2. To simplify the problem, most prior work has studied CO_2 and dust radiative transfer separately and avoided their overlapping opacities. Here I examine the errors that can result from such a treatment.

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Model

The discrete ordinate method of Stamnes *et al.* (1988) is used to treat the scattering, absorption and emission of monochromatic radiation through the Martian atmosphere. The exponential sum program of Evans *et al.* (1980) converts the banded wavelength structure of CO_2 to allow for monochromatic treatment (Freeman and Liou, 1979; Lindner, 1985; Lindner *et al.*, 1990a,b). The 15 μm band is broken into 16 subintervals to properly account for the multiple scattering (Lindner *et al.*, 1990a,b; Lacis and Oinas, 1991). Transmission functions for the 15.0 μm band of CO_2 are taken from the line-by-line model results of Gal'tsev and Osipov (1979). The transmission function, Tr, as a function of temperature T, pressure P, and CO_2 column abundance U is extrapolated from the Gal'tsev and Osipov results (subscript G) to temperatures below 200K by:

$$Tr(T, P, U) = 1 - \{[1 - Tr_G(200\text{K}, P, U)]\,(T/200\text{K})^{0.8}\}. \quad (1)$$

The exponential 0.8 is found when the temperature dependencies for the Pollack *et al.* (1981) transmission functions are recast in this form. Using a modified version of the FASCOD transmission model (Clough *et al.*, 1986), the accuracy of the transmission functions in equation (1) are confirmed for the range in temperature and pressure

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present in the atmosphere to 40 km altitude (Lindner *et al.*, 1990a,b; Pollack *et al.*, 1990). Local thermodynamic equilibrium is assumed (Gierasch and Goody, 1967; Hourdin, 1992).

Dust opacities vary from 0.2 to 1.0 for conditions other than global dust storms (Pollack *et al.*, 1979). However, dust opacities over winter polar latitudes may be slightly less (e.g. Lindner, 1990). A Gaussian profile describes the vertical distribution of dust, being well mixed to 20 km altitude for conditions other than global dust storms (Anderson and Leovy, 1978; Zurek, 1982; Korablev *et al.*, 1993). The wavelength dependence of the dust opacity and the dust single-scattering albedo are given by Toon *et al.* (1977). Scattering of radiation by dust is represented by the Haze-L phase function (Toon *et al.*, 1977). Computational difficulties which accompany highly asymmetric phase functions are removed with the Delta-L method (Wiscombe, 1977). The emissivity of airborne dust is high and has been calculated as a function of wavelength from theory and observations (Toon *et al.*, 1977; Simpson *et al.*, 1981).

Atmospheric composition is taken as 95% CO_2 (Owen *et al.*, 1977). Atmospheric composition may have been quite different in past epochs, with CO_2 being perhaps a minor constituent (e.g. Lindner and Jakosky, 1985), but this study focuses on the present epoch. Season-dependent CO_2 abundances (Hess *et al.*, 1980) are corrected for circulation-induced pressure gradient (Haberle *et al.*, 1979) and elevation (Lindal *et al.*, 1979). The surface pressure is 8 mbar at 57°N latitude in late winter. Atmospheric properties are zonally averaged and are assumed azimuthally independent. The region from the surface to 40 km altitude is broken into 20 layers, each 2 km thick, to account for vertical inhomogeneity. The temperature profile rises linearly with altitude from 150K at the surface to 160K at 10 km, and then falls linearly with altitude to 130K and 40 km, typical for winter polar conditions (Lindal *et al.*, 1979; Kieffer, 1979; Martin, 1984). The albedo of the polar cap is assumed to be zero (Kieffer, 1970; Smythe, 1975; Wiscombe and Warren, 1980). An average ice emissivity of 0.9 is adopted, with the wavelength dependence given in Ditteon and Kieffer (1979) and Hunt *et al.* (1980).

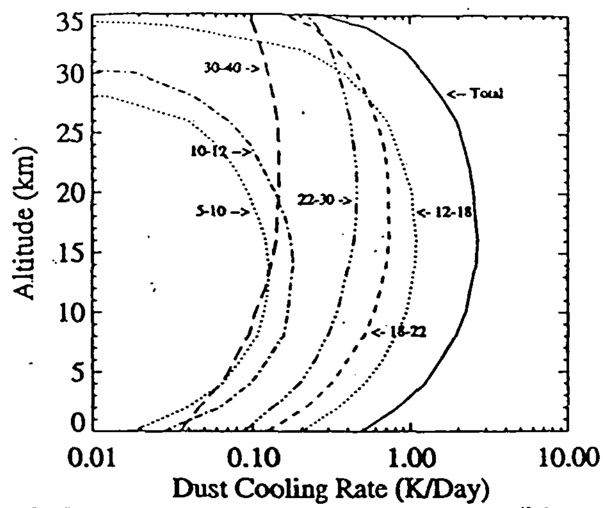

Fig. 1. Total infrared cooling rate by dust at winter polar latitudes (57°N latitude, $L_s = 343°$) as a function of altitude for dust vertical optical depth, τ_v, of 0.2, and the contribution from each wavelength interval from 5 to 40 μm (wavelength range of each bin is labeled in μm)

Results and discussion

Total atmospheric cooling rates owing to thermal emission by a vertical optical depth of dust, τ_v, of 0.2, and the contribution by various wavelength intervals are presented in Fig. 1 for winter polar conditions. The maximum cooling owing to dust below 30 km altitude occurs in the 12–18 μm wavelength interval. The strong dust cooling in the 12–18 μm range is owing to the cold temperature, to the high optical depth of dust at 12–18 μm (Toon *et al.*, 1977), and to the secondary maximum in dust emissivity at 12–18 μm (Toon *et al.*, 1977). Hence, CO_2 impedes the ability of dust to cool the atmosphere because CO_2 absorbs strongly in the 12–18 μm region where dust cools most effectively.

The presence of dust will affect CO_2 radiative transfer by increasing the optical depth, and absorbing light that is emitted by CO_2. Dust is particularly important in the radiative cooling in the line wings of CO_2. Line wings are important to cooling in that the strongly absorbing line center is often optically thick, which renders the line center ineffective at cooling (e.g. Lindner, 1993). Optically thin line wings cool effectively, in that photons emitted in the line wings can escape and cool the atmosphere. The presence of dust affects the line wings by absorbing emitted photons that would otherwise escape.

Hence, dust and CO_2 hinder each other's attempts to cool. Thus, simply adding dust cooling to CO_2 cooling is not accurate in those wavelength bands where both are important. This competition affects CO_2 cooling more than dust cooling. Dust cooling occurs over the entire infrared spectrum, which is mostly free of CO_2 absorption. However, CO_2 absorption and emission must always compete with the absorption by dust. Figure 2 shows that the cooling is overestimated up to 30% if dust and CO_2 cooling rates are computed separately and then summed. The effect is strongest near the surface where the optical depth is largest. CO_2 cooling is optically thick, making it very difficult for emitted photons to escape in the lowest 10 km. Some of the photons emitted by CO_2 line wings that would normally escape and cool are being absorbed by dust, which results in a lower cooling rate. CO_2 also absorbs some of the photons emitted by dust that would normally escape and cool.

The error induced by ignoring dust–CO_2 interaction is increased at higher dust loading (Fig. 3). Dust is now even more capable of choking off the escape of emitted photons, not only those of CO_2, but also photons emitted by dust itself. Dust–CO_2 interaction is highest near the surface for all three cases. The relative importance of the line wings for cooling is greater at lower altitudes. Since dust has its strongest effect on the line wings, dust–CO_2 interaction is strongest near the surface. Note that the errors do not change as much when dust opacity is changed from

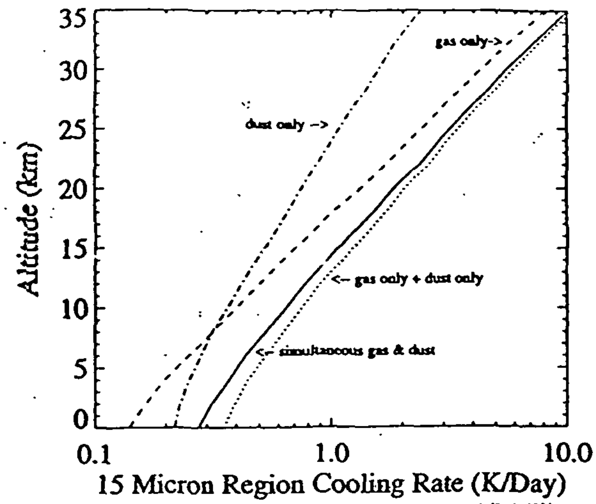

Fig. 2. Total 15 μm region (12–18 μm) cooling rates as a function of altitude for a pure CO_2 atmosphere (labeled "gas only") and for a pure dust ($\tau_v = 0.2$) atmosphere (labeled "dust only") at winter polar latitudes. Also shown are the cooling rates for a simple sum of the CO_2 only and dust only cooling rates (labeled "gas only + dust only"), and the cooling rates calculated when dust and CO_2 are treated simultaneously (labeled "simultaneous gas & dust")

$\tau_v = 0.5$ to 1.0 as they do when dust opacity is changed from $\tau_v = 0.2$ to 0.5 or from 0.0 to 0.2. This occurs because line wings are effective in optically thin media. Once large dust opacity is reached, further increases in dust opacity do not affect line wing optical depths as much.

Note that the error increases with dust optical depth, even when dust cooling exceeds CO_2 cooling. The explanation lies in the two-fold nature of dust–CO_2 interaction, and underlies the importance of its inclusion even for

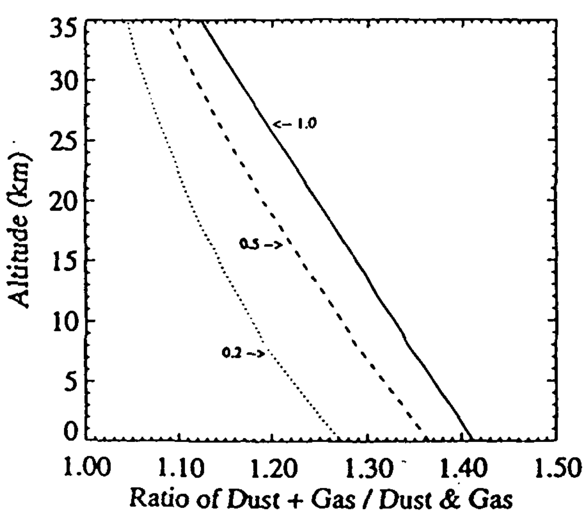

Fig. 3. Ratio of the 15μm region (12–18 μm) thermal cooling rates computed ignoring dust–CO_2 interaction (labeled "gas only+dust only" in Fig. 2) to those computed including dust–CO_2 interaction (labeled "simultaneous gas & dust" in Fig. 2) for τ_v(dust) of 0.2, 0.5 and 1.0 at winter polar latitudes. Hence, these curves represent the overestimation error of computing cooling rates in the 12–18 μm wavelength interval without proper simultaneous treatment of dust and CO_2, as a function of altitude and dust opacity

calculations for dust storm conditions. For low dust opacities, dust–CO_2 interaction involves the effect of dust in choking off emission in the line wings of the CO_2 15 μm band. However, for large dust opacities, it is CO_2 that is the parasite. For large dust opacities, dust cooling is dominant and as much as half of all dust cooling occurs in the 15 μm wavelength interval (Fig. 1). However, dust is unable to cool effectively in the 15 μm wavelength interval because emitted photons are quickly reabsorbed by CO_2. In fact, the parasitic effect of CO_2 grows as dust opacity increases, as shown in Fig. 3. The error reaches an asymptote at large dust opacities.

Summary and conclusions

As much as half of all atmospheric cooling owing to thermal emission by dust occurs in the 12–18 μm wavelength range. Since this is also the wavelength region where most cooling owing to thermal emission by CO_2 occurs, it is important to consider the spectral overlap between dust and CO_2. CO_2 infrared cooling and dust infrared cooling are both overestimated if CO_2 and dust cooling are computed separately and then summed. Indeed, if dust–CO_2 interaction is ignored, then the total 12–18 μm cooling is overestimated by almost 30% for minimal dust loading at winter polar latitudes. Furthermore, for one vertical optical depth of dust at winter polar latitudes, a simple sum of dust cooling and CO_2 cooling from 12–18 μm will overestimate the actual total 12–18 μm cooling by over 40% near the surface. Hence, dust–CO_2 interaction is important not only for calculating CO_2 cooling rates, since dust opacities overlap the CO_2 15 μm band, but also for calculating dust cooling rates, since the 15 μm band of CO_2 overlaps a significant portion of the infrared region where dust cooling is most effective. In other words, even when the Martian atmosphere is very dusty, when CO_2 cooling and heating rates are minor compared with dust (e.g. Lindner, 1993), the interaction of CO_2 will significantly affect the ability of dust to cool the atmosphere.

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