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CO_2 induced climatic change and spectral variations in the outgoing terrestrial infrared radiation

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ABSTRACT

The published temperature changes produced in general circulation model simulations of CO_2 induced climate modification are used to compute the top of the atmosphere, clear sky outgoing infrared radiance changes expected for doubled CO_2. A significant wavenumber shift is produced, with less radiance emerging in the 500–800 cm^{-1} (20.0–12.5 μm) CO_2 band and with more emerging in the 800–1200 cm^{-1} (12.5–8.3 μm) window. The effect varies greatly with latitude. The radiance shift in the 2300 cm^{-1} (4.3 μm) region is of the order of 10–30% for doubled CO_2. It is suggested that the 2300 cm^{-1} region be carefully monitored as an aid in detecting the climatic effects of increasing CO_2. The change in the wavenumber-integrated radiant exitance is at most a few %.

1. Introduction

There have been numerous attempts to model the effects of increasing CO_2 concentrations on global climate (i.e., Ramanathan *et al.*, 1979; Manabe and Stouffer, 1979). The principal result of most studies has been a prediction of a few degrees of tropospheric warming, and several degrees of stratospheric cooling, for a doubling of CO_2. The principal uncertainties in the models lie in the treatment of feedbacks involving the areal extent (Manabe and Wetherald, 1980; Paltridge, 1980) and optical properties (Charlock, 1981, 1982) of clouds, and also the ocean thermal response (Hunt and Wells, 1979; Thompson and Schneider, 1982). Hansen (1981) and Gilliland (1982) have attempted to model the observed global temperature variations of the last several decades by accounting for changes in the solar output and volcanic aerosols as well as increased CO_2; the CO_2 signal up to the present is predicted to have been small. In the upcoming decades, climate will also probably be affected by other trace gases (Wang et al., 1976; Donner and Ramanathan, 1980; Hameed et al., 1980) and tropospheric aerosols (Charlock and Sellers, 1980a, b).

While the effects of increased CO_2 on climate are anticipated to be ultimately quite large, they have been small so far, and difficult to detect because of climatic noise and non-CO_2 forcings. The natural variability of the atmosphere is very considerable in the upper stratosphere (Labitzke, 1980), where the model responses to increased CO_2 are greatest (Fels et al., 1980). Careful observational studies of surface temperatures (Madden and Ramanathan, 1980; Wigley and Jones, 1981) have concluded that a first detection of CO_2 climate effects has not yet definitively been made.

A central problem in any CO_2 first detection study is the acquisition of a data set large enough to be statistically significant. Madden and Ramanathan (1980) suggested the use of satellites. They pointed out that CO_2, with appreciable absorption/emission bands between 500–800 cm^{-1} (20.0–12.5 μm), is expected to decrease the radiant exitance (outgoing flux) to space in that wavenumber interval. As more CO_2 would cause only a small direct change in the absorption of incoming solar radiation, the infrared radiant exitance outside of 500–800 cm^{-1} should increase. Ice-albedo

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feedback would probably cause an increase in the total infrared radiant exitance, while the effect of cloud feedback is uncertain.

Kiehl (1983) has computed the change in the midlatitude infrared radiant exitance in the 500–800 cm^{-1} region for an atmosphere with doubled CO_2 (and with the anticipated CO_2 induced temperature changes, too). The radiant exitance in certain wavenumber intervals was found to change by as much as 10%. In the present work, we employ the published temperatures from a general circulation model scenario for CO_2 induced climate change and an infrared transfer band model to compute the change in the outgoing radiance throughout the terrestrial spectrum at tropical, middle, and high latitudes. The clear sky wavenumber integrated outgoing radiance decreases slightly in the tropics, and increases in high latitudes. A significant wavenumber shift in the outgoing radiance occurs. The relative shift in the radiance in the 2300 cm^{-1} (4.3 μm) CO_2 band region is of the order of 10–30% for doubled CO_2.

2. CO_2 climate change scenario and the infrared band model

The base state tropospheric temperature and humidity soundings used in this work are those compiled by the Geophysical Fluid Dynamics Laboratory (Oort and Rasmusson, 1971). Above 50 mb we employ interpolations of the Air Force Geophysics Laboratory (AFGL) model atmospheres (Kniezys et al., 1980). AFGL ozone data are also used. Computations have been made here with April data at various latitudes.

For the CO_2 doubling calculations, we use the temperature changes computed by Manabe and Wetherald (1980). The Manabe and Wetherald results were obtained with a sector general circulation model run for mean annual conditions. The effects of both cloud radiative feedback (variations in cloud area and height, but not optical properties here) and ice albedo feedback were included in their model. Above 30 km we employ the CO_2 doubling results of Fels et al. (1980), which were also produced by a general circulation model. The composite scenario for CO_2 doubling used in this study is outlined in Table 1. Principal features of the CO_2 temperature change scenario are (1) at the surface, a 2 K rise at the equator, increasing to 4 K in middle latitudes and to almost 7 K at 75° N, (2) in the middle troposphere at 500 mb, a rise of about 2.5 K in the tropics, increasing to about 3.5 K in middle and into the high latitudes, and (3) a decrease in stratospheric temperatures, fairly uniform with latitude (~5 K) at the 25 km level. Specific humidities in the temperature change scenario were adjusted to hold the relative humidities constant. The surface specific humidity increase for the CO_2 doubling at 45° N is 30%.

Radiative transfer calculations are made with a LOWTRAN5 (Kneizys et al., 1980; Robertson et al., 1981) band model with a 5 cm^{-1} resolution. The LOWTRAN5 code evaluates the equivalent width of combined Doppler and Lorentz line shapes, and the effects of the tails of lines outside a given spectral interval are included in the calculation of transmissivity in that interval. Temperature-dependent molecular absorption coefficients are employed. The Curtis-Godson approximation is used for multi-layered pathes. Below 400 cm^{-1} (about 85% of the outgoing radiance is produced at wavenumbers above 400 cm^{-1}), we use a simpler form of the LOWTRAN5 model. In the simpler, form, the absorption coefficients are temperature independent and the resoluton is effectively cut to 20 cm^{-1}. H_2O continuum effects are still accounted for in temperature-dependent form. Below 350 cm^{-1} (28.6 μm), we assume that the H_2O rotation lines are the only effective absorbers (see Charlock, 1984).

The LOWTRAN5 provision for CO_2 is to treat it as a uniformly mixed gas along with CO, CH_4, and N_2O. When CO_2 is doubled in the model, we then really double all the other uniformly mixed gases as well. We avoid doubling CH_4, N_2O, etc., in the calculations here by using the present (current CO_2) uniformly mixed gas concentrations for the computations in those wavenumber intervals in which CH_4 and N_2O are significantly active.

The CO_2 climate change scenario will be analyzed with reference to the spectral distribution of outgoing clear sky radiances at 500 km (roughly satellite height). Radiances computed for present temperatures and CO_2 concentrations at the equator and 75° N are shown in Fig. 1. The radiances below 400 cm^{-1} (25.0 μm) show less small-scale variation with wavenumber because the simpler, lower resolution form of LOWTRAN5 is used in those wavenumbers. Peak radiance in both latitudes is obtained between 450–550 cm^{-1} (22.2–

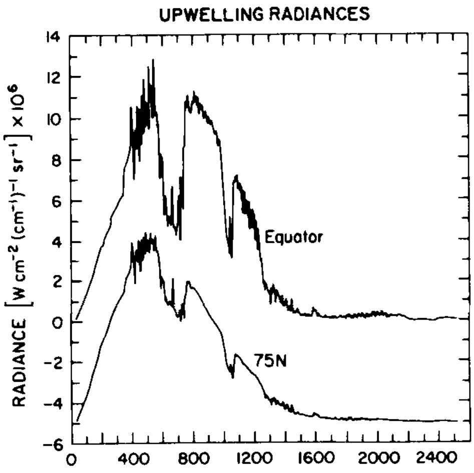


Fig. 1. Top of the atmosphere, clear sky upwelling radiances at an angle of 53° computed for the equator from April climatological data. Offset curve below (6 radiance units) is for 75° N.

18.2 μm), where H_2O is the principal absorber and the upper troposphere is effectively sensed. CO_2 effects are in evidence between 550–800 cm^{-1} (18.2–12.5 μm). The radiances in 600–720 cm^{-1} (6.7–13.9 μm) at 75° N generally exceed those at the equator because here (near the CO_2 band center) we sense the stratosphere, which is warmer at 75° N. Radiances in the 800–1200 cm^{-1} (12.5–8.3 μm) window are of course much larger (factor of 2 between 1050 and 1200 cm^{-1}) at the equator. The relative drop in radiance at ~1040 cm^{-1} (9.6 μm) due to O_3 is less pronounced at 75° N because conditions there are more nearly isothermal. A detailed discussion of the wavenumber variation of outgoing radiance as a function of latitude for the present CO_2 concentration is given by Charlock (1984).

3. Spectral changes below 1800 cm^{-1}

We now consider the change in the spectral distribution of the out-going clear sky terrestrial infrared radiance attendant on CO_2 induced climatic change. We compare the differences of present climatological (computed) radiances and radiances for (1) doubled CO_2 with no temperature or specific humidity change (ΔCO_2), (2) present CO_2 but with changes in temperature and specific humidity computed according to the doubled CO_2 scenario (ΔT), and (3) doubled CO_2 with the temperature and specific humidity computed as in the doubled CO_2 scenario (ΔCO_2, ΔT). Three sets of radiance computations are presented because of the uncertainty in the general circulation model simulation of the climatic effects of CO_2. In the real atmosphere, we may increase CO_2 but obtain a smaller or larger temperature change than that predicted by the GCM. The effects contributing to the full, doubled CO_2 radiance shifts (ΔCO_2, ΔT) can be best analyzed with reference to the component (ΔCO_2) and (ΔT) calculations.

Doubling CO_2 while holding temperatures fixed (ΔCO_2) at 45° N results in a slight decrease in the wavenumber integrated upwelling radiance. Weak CO_2 bands in the 800–1200 cm^{-1} (12.5–8.3 μm) window decrease radiances by 1–2%, while radiances in the wings of the 500–800 cm^{-1} (20.0–12.5 μm) band decrease by 8–10% (fig. 2). The CO_2 band center (~670 cm^{-1}) is very opaque, and radiances at 670 cm^{-1} (14.9 μm) essentially sound the stratosphere. Adding more CO_2 means that we sound a higher, warmer level of the stratosphere, resulting in an increase in the 670 cm^{-1} radiance. The weaker bands in the wings (~600 and 740 cm^{-1}) and window sound the troposphere, and their radiances decrease as CO_2 is increased at fixed temperature.

Holding CO_2 fixed at the present level while increasing tropospheric and decreasing stratospheric temperatures (ΔT) as per a doubled CO_2 climate change (Table 1) yields a large increase in the wavenumber integrated outgoing radiance. The ΔT effect across the spectrum at 45° N is more significant than the ΔCO_2 effect (Fig. 2). The increase in the surface temperature causes a general increase in 800–1200 cm^{-1} window radiance by 5–8%. Below about 600 cm^{-1}, the radiances are generally upwelling from the upper troposphere where the scenario increases the temperature by less than that at the surface; the radiance increases are thus not as large as in the window. The sub-600 cm^{-1} radiances also show a smaller proportional sensitivity to the temperature change, because the logarithmic derivative of the Planckian radiance with respect to temperature is smaller at low wavenumbers. Large decreases in radiance are noted in the 670 cm^{-1} CO_2 band center (12%) and

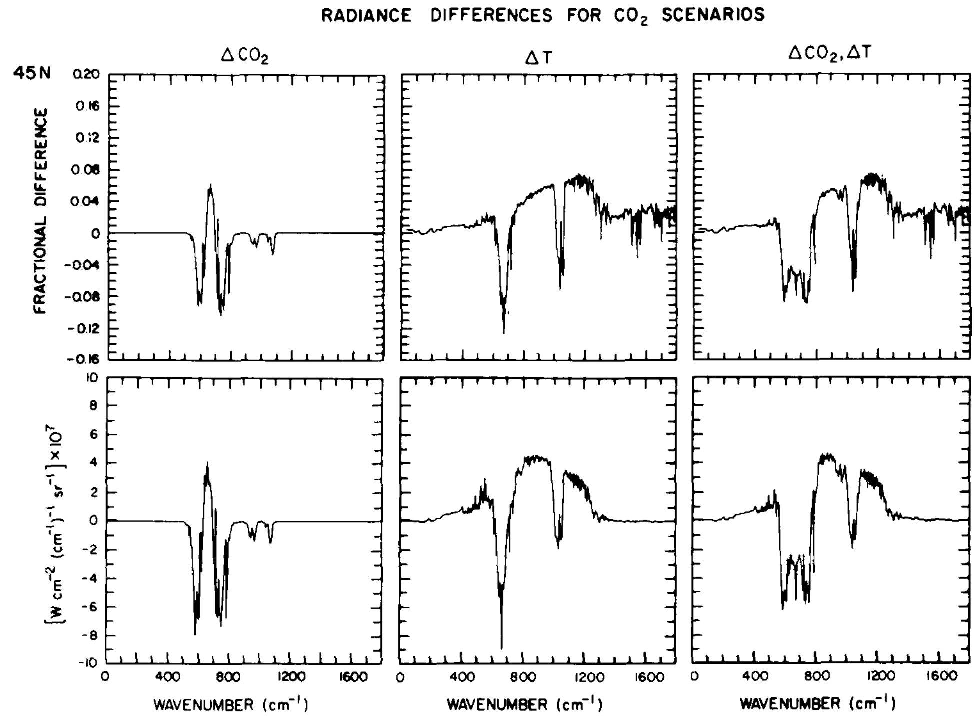


Fig. 2. Differences between the present clear sky 45° N radiances and radiances for each of the 3 scenarios (ΔCO_2), (ΔT), and (ΔCO_2, ΔT). Fractional differences in the top row and absolute differences in the bottom row. (ΔCO_2) in the first column refers to radiances computed with doubled CO_2 and present temperatures. (ΔT) is computed with present CO_2 but with temperatures and specific humidities adjusted to the doubled CO_2 scenario. (ΔCO_2, ΔT) is the full doubled CO_2, changed temperature and specific humidity scenario.

Table 1. *Temperature changes ΔT (°K) at selected levels applied to soundings to simulate the climatological effect of doubled CO_2*

	Latitude		
Height	0°N	45°N	75°N
0 km	2.0	3.8	6.8
5 km	2.3	3.5	3.3
10 km	2.8	2.4	2.0
15 km	1.8	0.3	−0.3
20 km	−1.7	−1.7	−3.0
25 km	−5.6	−4.5	−4.8
30 km	−8.7	−7.3	−6.5

in the 1040 cm^{-1} O_3 band; both are in response to the large decrease in stratospheric temperature. The fairly opaque CH_4 and N_2O bands (~1300, 1500, and 1700 cm^{-1}) are also seen to have radiance decreases. The widths of these latter bands are small. The Planck function begins to tail off at these higher wave-numbers, so the contribution of CH_4 and N_2O to the absolute radiance change (lower panel in Fig. 2) is not significant.

The difference in radiance at 45° N between the full doubled CO_2 scenario (changed CO_2 and temperature both: ΔCO_2, ΔT) and the present CO_2 and temperature scenario is almost just the sum of the radiance difference in the two previous cases. In the wings of the CO_2 band, the effect of doubling the gas concentration (rather than changing the temperature) dominates, so the radiance decreases. For the CO_2 band center itself, we have opposing effects, and the radiance comes down by 6–8%. Kiehl (1983) has produced similar results between 500–800 cm^{-1} with a midlatitude calculation. The drop in absolute radiance in the 1040 cm^{-1} O_3

band is not as large as that in the CO_2 band because, while the relative drops are about the same, the absolute radiance in the O_3 band is small (in fact a minimum for the interval 200–1200 cm $^{-1}$). The relative changes in the window are as large as those in the CO_2 bands. The doubled CO_2, temperature-changed scenario at 45° N emits 3W m $^{-2}$ more wavenumber integrated radiant exitance to space than does the present climatological scenario.

The change in the clear sky wavenumber integrated radiant exitance requires some explanation (aside from the use of different radiation models in this work and the GCM). In an equilibrium model, an increase in IR emission to space would be anticipated only if the absorption of solar radiation also increased, and the doubling of CO_2 has only a small direct effect on absorption in solar wavelengths. The GCM scenario used here includes the indirect effects of ice-albedo, water vapor, dynamical, and cloud feedback for increased CO_2. The temperature increase melts ice, lowering the albedo and increasing the absorption of solar radiation, especially in the higher latitudes. The increased specific humidity for doubled CO_2 also increases absorption in solar wavelengths. Dynamical feedback causes a meridional redistribution of heat which increases the radiant exitance in some latitude belts and decreases it in others. Changes in cloud height and areal extent modify the GCM temperature distribution, thus affecting the outgoing flux over both clear and cloudy skies. While the (ΔCO_2, ΔT) scenario for 45° N produced an increase in the clear sky wavenumber integrated radiant exitance, an increase would not necessarily have been obtained if full account for cloud effects had in fact been made. Here, we focus on the clear sky effect because, for remote sensing purposes, it is less ambiguous.

It should also be noted that the (ΔT) and (ΔCO_2, ΔT) radiance changes were significantly affected by increases in specific humidity (30% near the surface at 45° N). To investigate this, the (ΔCO_2, ΔT) computations of Fig. 2 were repeated, but with specific humidities fixed at the original values. With the lower, fixed specific humidities, the radiances between 300–500 cm $^{-1}$ increased by 2–4% in the (ΔCO_2, ΔT) scenario, as opposed to only 1–2% in that interval for (ΔCO_2, ΔT) with increased specific humidities. 800–1200 cm $^{-1}$ window radiances with fixed specific humidities displayed additional increases of about 1% for (ΔCO_2, ΔT). The increase in radiance with increased specific humidity is generally below 4% in 1400–1800 cm $^{-1}$ for (ΔCO_2, ΔT), but with fixed specific humidity it exceeds 10% over part of that interval. Specific humidity does not have a very significant effect near the CO_2 band center.

The differences between the present radiances and those for the three scenarios vary considerably with latitude. Fig. 3 displays these differences for the equator and 75° N. While doubling CO_2 and holding temperatures and specific humidities constant (ΔCO_2), we essentially sound to different levels; the response at 75° N is smaller than at the equator, because in high latitudes the vertical temperature gradient is smaller than in the tropics.

A comparison of the radiance changes at the equator and 75° N for the case of changed temperatures and specific humidities (as per the CO_2 scenario) with present CO_2 (ΔT) is more intricate. The temperature and specific humidity changes, as well as the base temperatures and specific humidities, are different at the two latitudes. In the stratosphere, the variation of temperature with latitude is smaller than in the troposphere, and the predicted gradient of CO_2 induced temperature change is smaller in the stratosphere, too. Hence, the response in the CO_2 band center (~670 cm $^{-1}$) is similar at the equator (−14%) and 75° N (−12%). The 800–1200 cm $^{-1}$ window response is largely due to the surface temperature change, which is much larger at 75° N. In fact, at 75° N, the 1200 cm $^{-1}$ radiance effect exceeds that in the CO_2 band center. The response in the tropical window is also small because water vapor specific humidity increases with temperature; the quantity of water vapor in the lower tropical troposphere is sufficiently large as to cause an appreciable opacity because of continuum effects. (One caveat in regard to the tropical window continuum effect is that it is quite model dependent. Kneizys et al. (1980) have noted the uncertainties concerning the H_2O continuum in the window.) The response in the O_3 window "plug" is similar at both latitudes.

For the full CO_2 temperature change, doubled CO_2 scenario (ΔCO_2, ΔT), we have a dramatic variation of response with latitude. The effects of changing CO_2 and changing temperature are almost additive, as at 45° N. The wavenumber integrated radiant exitance decreases by 3.5 W m $^{-2}$

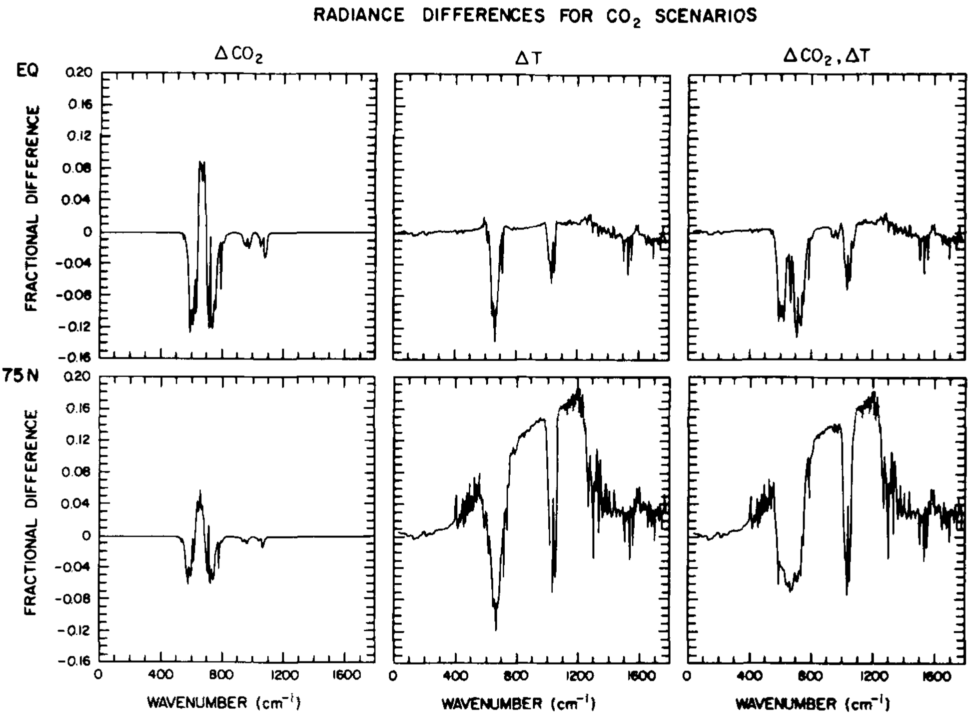


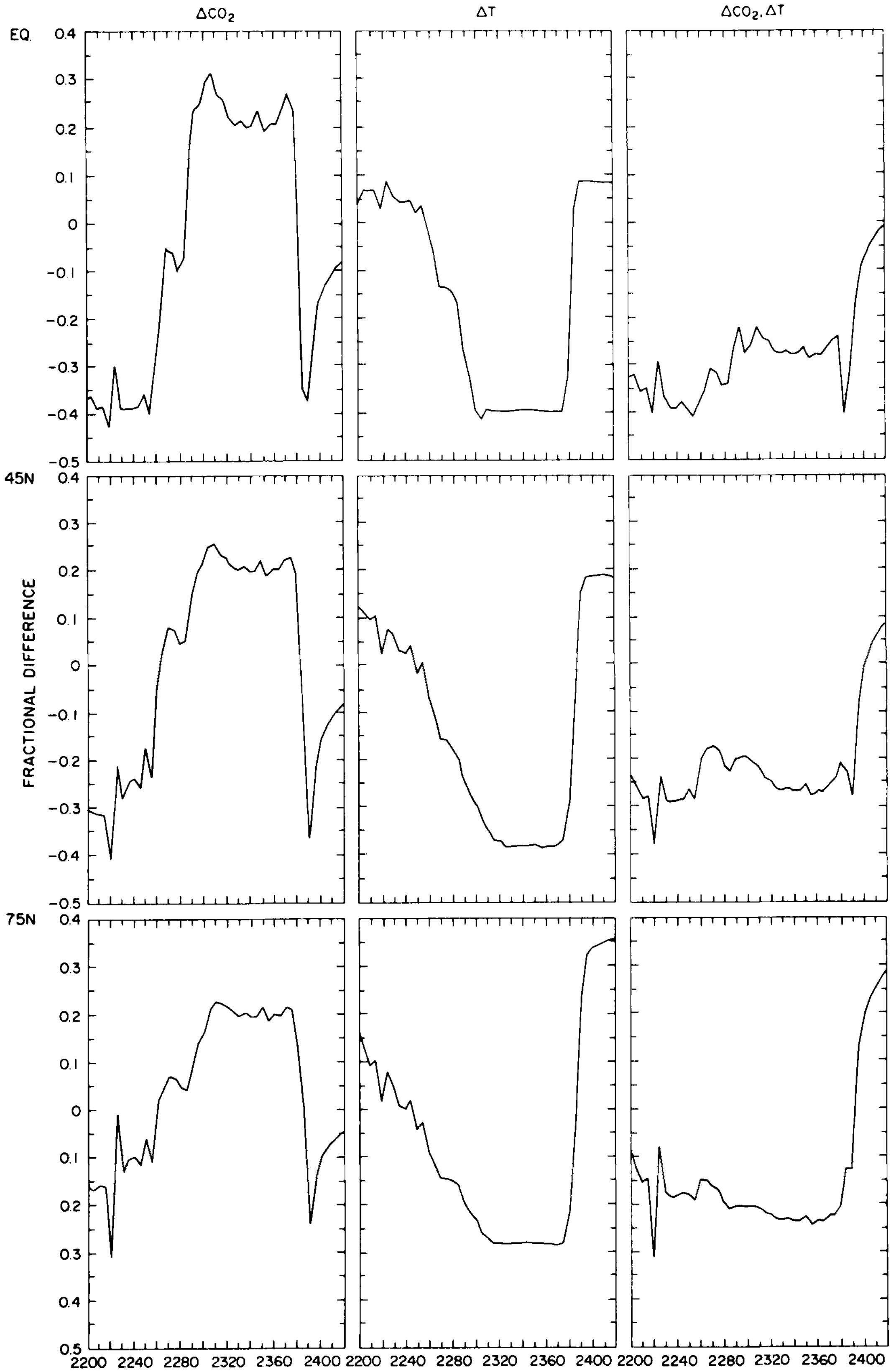
Fig. 3. Fractional differences between present clear sky radiances and radiances for each of the 3 scenarios (ΔCO_2), (ΔT), and (ΔCO_2, ΔT). Equator in top row and 75° N in bottom row. (ΔCO_2), (ΔT), and (ΔCO_2, ΔT) as in Fig. 2.

for doubled CO_2 at the equator, while it increases by 8.5W m^{-2} at 75° N. These changes in wavenumber integrated radiant exitance are at most a few %. In particular wavenumber intervals, the changes are proportionally much larger. At the equator, the greatest response is in the CO_2 band, while the largest response at 75° N is in the window. In the 500–800 cm^{-1} CO_2 band itself, the wavenumber shape of the response varies with latitude; at 75° N, the shift in radiance at the band center is not minimized relative to the shift in the wings as is the case at the equator and 45° N. The radiances in the wings of the CO_2 band at 75° N do not decrease by as much as those at lower latitudes because of the smaller tropospheric vertical lapse rate at 75° N.

4. Changes in the 2300 cm^{-1} CO_2 band

While the radiance shifts in the terrestrial infrared expected for CO_2 doubling are of general geophysical interest, the fact that the magnitude of the shifts are only about 10% indicates that they may be of limited utility in serving as a first detector for the climatic effects of smaller (than doubling) increases in CO_2. A stronger response would be desirable. This is provided by the 2300 cm^{-1} (4.3 μm) region, where an opaque CO_2 band is adjacent to an atmospheric window. Relatively little energy is emitted in this region because of the tailing off of the Planck function above 1400 cm^{-1} (Fig. 1). The Planck function does, however, exhibit a larger temperature dependence in the

Fig. 4. Fractional differences between present clear sky radiances and radiances for each of the 3 scenarios (ΔCO_2), (ΔT), and (ΔCO_2, ΔT). Equator in the top row, 45° N in the middle, and 75° N at the bottom. (ΔCO_2), (ΔT), and (ΔCO_2, ΔT) as in Fig. 2.


ΔCO2
ΔT
ΔCO2, ΔT
EQ.
45N
75N
0.4
0.3
0.2
0.1
0
-0.1
-0.2
-0.3
-0.4
-0.5
FRACTIONAL DIFFERENCE
2200 2240 2280 2320 2360 2400
WAVENUMBER (cm⁻¹)

higher wavenumbers. The 2300 cm^{-1} region has been found to have considerable potential for atmospheric sounding (Kaplan et al., 1977).

The response of the 2310–2420 cm^{-1} interval to a doubling of CO_2 for fixed temperature (ΔCO_2) at 45° N (Fig. 4) is qualitatively similar to the response in the 670–1000 cm^{-1} interval considered earlier. 2310 and 670 cm^{-1} are located in the band centers, and radiances at these wavenumbers increase (26% for 2310 cm^{-1} and 7% for 670 cm^{-1}) as a higher, warmer stratospheric level is sounded. At slightly higher wavenumbers (2390 and 750 cm^{-1}), radiances fall for doubled CO_2 at fixed temperatures. 2420 and 1000 cm^{-1} are near window wavenumbers, and their radiances show only small variations for doubled CO_2 at fixed temperatures.

For temperature changes as per doubled CO_2 but with CO_2 itself held fixed (ΔT) at 45° N, the response near 2300 cm^{-1} is again much stronger than at the lower wavenumbers. The decreased stratospheric temperatures pull down 2320 cm^{-1} radiances by 40%. Increased surface temperatures cause an increase in 2420 cm^{-1} window radiances of 20%.

Considering the full scenario of doubled CO_2 and changed temperature (ΔCO_2, ΔT) at 45° N, the temperature effect (stratospheric cooling) dominates at 2320 cm^{-1}, decreasing radiances by ~25%. Similar decreases in 2320 cm^{-1} radiance are noted for the full scenario at the equator and at 75° N. The near window channel at 2420 cm^{-1} shows successively larger radiance increases when going from the equator to 75° N with the full scenario.

5. Discussion

The general circulation model scenario for CO_2 induced climatic change involves increases in tropospheric temperatures, decreases in stratospheric temperatures, and changes in the outgoing infrared radiation budget with latitude. A calculation with doubled CO_2 at present temperatures (ΔCO_2) gives a decrease in the wavenumber integrated radiance to space at all latitudes, while a calculation with changed temperature according to the CO_2 doubling scenarios but with present CO_2 (ΔT) yields an increase in the wavenumber integrated radiance at all latitudes.

The change in the outgoing wavenumber integrated IR for the full changed CO_2 and changed temperature scenario (ΔCO_2, ΔT) involves a crossover with latitude; wavenumber integrated radiances in the tropics fall, while those in the middle and high latitude rise. At all latitudes, decreases in the 500–800 cm^{-1} CO_2 band emission and increases in the 800–1200 cm^{-1} window emission are obtained, as suggested by Madden and Ramanathan (1980). The wavenumber integrated radiant exitance changes are at most a few Wm^{-2}. Because the changes in the wavenumber integrated radiant exitance are small on a % basis, monitoring of the wavenumber integrated radiant exitance would be of only limited use in a CO_2 climate change detection scheme.

Large fractional changes in the spectral radiance are obtained, especially near the 2300 cm^{-1} CO_2 band, for the full CO_2 doubling scenario. Careful monitoring of the 2300 cm^{-1} band may afford a first detection capability for CO_2 effects on climate if the radiances are matched to general circulation model results obtained for small (~10%) changes in CO_2. The 2300 cm^{-1} band suffers from contamination by reflection of incoming solar radiation, and the radiances in that region (as in many of the wavenumber intervals discussed in this paper) would also be affected by clouds. Solar contamination can be avoided by scans on the night side of the planet. The cloud problem can probably be overcome by a sampling of clear sky areas only. Cloudy sky can be sorted out with spatial coherence techniques using scanner data (Coakley and Bretherton, 1982).

It should be noted that the present generation of satellite temperature sounding units may in fact be adequate for the task of narrow band monitoring of the terrestrial infrared budget. The HIRS instrument, currently operational on TIROS-N satellites, has 19 channels between 669 and 2660 cm^{-1}. Temperature retrievals by the same HIRS channels on different satellites are consistent to within 1 K, indicating that the narrow band radiances are measured to a consistenty of 1% (the absolute accuracy is probably not within 1%, however). It would thus be fortunate if the calibration of the HIRS instruments on subsequent satellites were maintained.

Computations by Kiehl (1983) show that satellite monitoring of the 500–800 cm^{-1} interval would be of use in detecting the climatic effects of

CO_2. Here, the concept is extended to other intervals. It should be noted that the results do not give a solid, unambiguous "fingerprint" for the climatic effects of CO_2. Climatic noise, or deterministic changes due to aerosols or non-CO_2 trace gases, could cause radiance shifts similar to those anticipated for CO_2 in certain intervals. A selected monitoring of the spectral characteristics of the emitted radiation would be a powerful aid, however, to a surface-based system for the early detection of systematic climate changes.

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