

# Methane and Climate

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## Abstract

Atmospheric methane (CH<sub>4</sub>) contributes to the *radiative forcing* of Earth's atmosphere. Radiative forcing is the difference in the net upward thermal radiation from the Earth through a transparent atmosphere and radiation through an otherwise identical atmosphere with greenhouse gases. Radiative forcing, normally specified in units of W m<sup>-2</sup>, depends on latitude, longitude and altitude, but it is often quoted for a representative temperate latitude, and for the altitude of the tropopause, or for the top of the atmosphere. For current concentrations of greenhouse gases, the radiative forcing at the tropopause, per added CH<sub>4</sub> molecule, is about 30 times larger than the forcing per added carbon-dioxide (CO<sub>2</sub>) molecule. This is due to the heavy saturation of the absorption band of the abundant greenhouse gas, CO<sub>2</sub>. But the rate of increase of CO<sub>2</sub> molecules, about 2.3 ppm/year (ppm = part per million by mole), is about 300 times larger than the rate of increase of CH<sub>4</sub> molecules, which has been around 0.0076 ppm/year since the year 2008. So the contribution of methane to the annual increase in forcing is one tenth (30/300) that of carbon dioxide. The net forcing increase from CH<sub>4</sub> and CO<sub>2</sub> increases is about 0.05 W m<sup>-2</sup> year<sup>-1</sup>. Other things being equal, this will cause a temperature increase of about 0.012 C year<sup>-1</sup>. Proposals to place harsh restrictions on methane emissions because of warming fears are not justified by facts.

# 1 Introduction

This is a summary of a more detailed paper on radiative forcing by greenhouse gases that the authors plan to publish in the near future[1], and which we will refer to as “WH.” We assume most readers of this paper will have little background in quantitative sciences, but since much of the concern over climate change and greenhouse gases comes from misunderstanding basic physics, we have included a few fundamental equations. We explain the physical meaning of all equations in plain English.

The paper is focused on the greenhouse effects of atmospheric methane, since there have recently been proposals to put harsh restrictions on any human activities that release methane. The basic radiation-transfer physics outlined in this paper gives no support to the idea that greenhouse gases like methane, CH<sub>4</sub>, carbon dioxide, CO<sub>2</sub> or nitrous oxide, N<sub>2</sub>O are contributing to a climate crisis. Given the huge benefits of more CO<sub>2</sub> to agriculture, to forestry, and to primary photosynthetic productivity in general, more CO<sub>2</sub> is almost certainly benefitting the world. And radiative effects of CH<sub>4</sub> and N<sub>2</sub>O, another greenhouse gas produced by human activities, are so small that they are irrelevant to climate.

## 2 The methane molecule

Methane, CH<sub>4</sub> is the simplest *hydrocarbon* molecule. It has a single carbon atom, C, bonded to four hydrogen atoms, H, as sketched in Fig. 1. Natural-gas is mostly methane[2]. Large amounts methane are found in some coal seams[3]. Methane is produced by the anaerobic decomposition of organic matter as marsh gas [4], and huge amounts of methane can be found as methane clathrates [5] in seafloor sediments, the Arctic tundra and other locations on Earth. Methane is produced in the digestive tracts of ruminants, like cattle and sheep, where symbiotic, anaerobic bacteria convert some of the cellulose of plant material to nutritionally useful fatty acids and other compounds [6], with methane as a byproduct. Similar bacteria in the digestive tracts of termites also produce large amounts of methane [7]. Methane has a half-life of about 10 years in the atmosphere, before it is oxidized to carbon dioxide and water [8].

## 3 Greenhouse gases in the atmosphere

Radiation transfer in the cloud-free atmosphere of the Earth is controlled by only two factors: (1) the temperature  $T = T(z)$  as a function of the altitude  $z$ , and (2) the number densities,  $N^{(i)} = N^{(i)}(z)$  of the  $i$ th type of greenhouse-gas molecule. Although the altitude profiles of temperature and number densities vary with latitude and longitude, the horizontal variation is normally small enough to neglect when calculating local radiative forcing. The dependence of the temperature on altitude is as important as the concentration of greenhouse gases. If the temperature were the same from the surface to the top of the atmosphere, there would be no radiative forcing, no matter how high the concentration of greenhouse gases.

Representative midlatitude altitude profiles of temperature [9], and concentrations of greenhouse gases[10], are shown in Fig. 2. Altitude profiles directly measured by radiosondes in ascending balloons [11] are always much more complicated than those of Fig. 2,

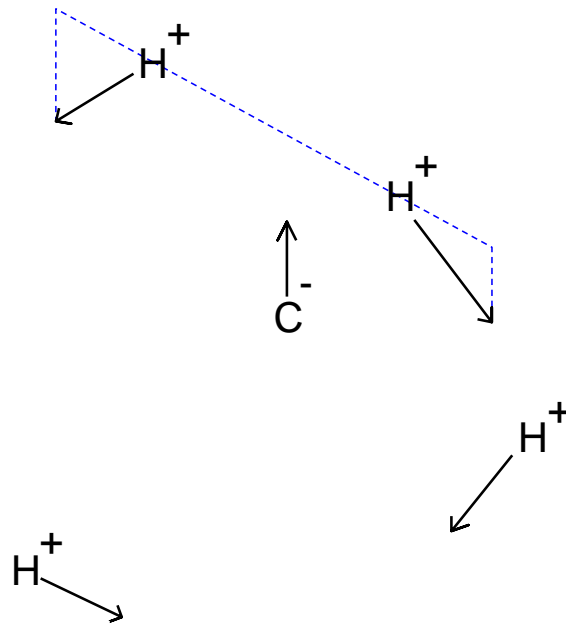


Figure 1: Geometry of a methane molecule,  $\text{CH}_4$ . The four hydrogen atoms H are centered at the corners of a cube and the carbon atom C is at the center. Near the H atoms the molecule has a slightly positive electrical charge, and near the central carbon atom the atom has a slightly negative charge. Also shown is a representative asymmetric bending vibration of the molecule, which dominates the greenhouse forcing. The carbon atom moves up while the top two hydrogen atoms bend outward, and the bottom two hydrogen atoms bend inward. The accelerating charges emit radiation with a spatial frequency of  $1306 \text{ cm}^{-1}$  (waves per cm). Thermally excited molecular rotations spread the emission frequencies from about  $1200$  to  $1400 \text{ cm}^{-1}$ .

which can be thought of as time-averaged profiles. Collision rates of molecules in the Earth's troposphere and stratosphere are sufficiently fast that a single local temperature  $T = T(z)$  provides an excellent description of the distribution of molecules between translational, vibrational and rotational energy levels. However, radiation in the atmosphere is almost never in full thermal equilibrium because at many frequencies, the mean-free paths of thermal photons can exceed the atmospheric thickness.

On the left of Fig. 2 we have indicated the three most important atmospheric layers for radiative heat transfer. The lowest atmospheric layer is the troposphere, where parcels of air, warmed by contact with the solar-heated surface, float upward, much like hot-air balloons. As they expand into the surrounding air, the parcels do work at the expense of internal thermal energy. This causes the parcels to cool with increasing altitude, since heat flow in or out of parcels is usually slow compared to the velocities of ascent or descent. If the parcels consisted of dry air, the cooling rate would be  $9.8 \text{ C km}^{-1}$  the *dry adiabatic lapse rate*[12]. But rising air has usually picked up water vapor from the land or ocean. The condensation of

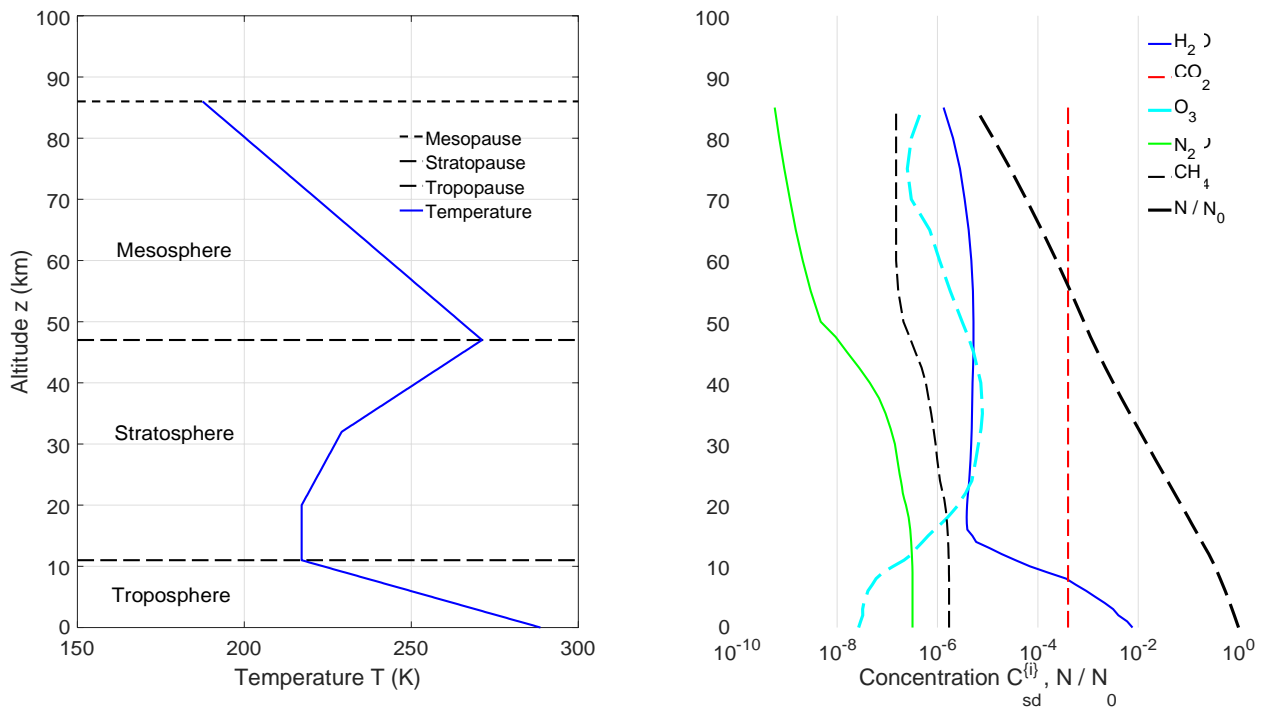


Figure 2: **Left.** A standard atmospheric temperature profile[9],  $T = T(z)$ . The surface temperature is  $T(0) = 288.7$  K. **Right.** Standard concentrations[10],  $C_{sd}^{(i)} = N_{sd}^{(i)}/N$  for greenhouse molecules versus altitude  $z$ . The total number density of atmospheric molecules is  $N$ . At sea level the concentrations are 7750 ppm of  $H_2O$ , 1.8 ppm of  $CH_4$  and 0.32 ppm of  $N_2O$ . The  $O_3$  concentration peaks at 7.8 ppm at an altitude of 35 km, and the  $CO_2$  concentration was approximated by 400 ppm at all altitudes. The data is based on experimental observations.

water vapor to droplets of liquid or to ice crystallites in clouds, releases so much latent heat that the lapse rates are less than  $9.8 \text{ C km}^{-1}$  in the lower troposphere. A representative lapse rate for midlatitudes is  $dT/dz = 6.5 \text{ K km}^{-1}$  as shown in Fig. 2. The tropospheric lapse rate is familiar to vacationers who leave hot areas near sea level for cool vacation homes at higher altitudes in the mountains. On average, the temperature lapse rates are small enough to keep the troposphere buoyantly stable[13]. Tropospheric air parcels that are displaced in altitude will oscillate up and down around their original position with periods of a few minutes. However, at any given time, large regions of the troposphere (particularly in the tropics) are unstable to moist convection because of exceptionally large temperature lapse rates.

Above the troposphere is the stratosphere, which extends from the tropopause to the stratopause, at a typical altitude of  $z_{sp} = 47$  km, as shown in Fig. 2. Stratospheric air is much more stable to vertical displacements than tropospheric air, and negligible moist convection occurs there. For mid latitudes, the temperature of the lower stratosphere is nearly constant, at about 220 K, but it increases at higher altitudes, reaching a peak temperature not much less than the surface temperature at the stratopause. The stratospheric heating is due to the

absorption of solar ultraviolet radiation by ozone molecules,  $O_3$ . The average solar flux at the top of the atmosphere is about 1350 Watts per square meter ( $W m^{-2}$ )[14]. Approximately 9 % consists of ultraviolet light (with wavelengths shorter than  $\lambda = 405$  nanometers (nm)) which can be absorbed in the upper atmosphere.

Above the stratosphere is the mesosphere, which extends from the stratopause to the mesopause at an altitude of about  $z_{mp} = 86$  km. With increasing altitudes, radiative cooling, mainly by  $CO_2$ , becomes increasingly more important compared to heating by solar ultraviolet radiation. This causes the temperature to decrease with increasing altitude in the mesosphere.

Above the mesopause, is the extremely low-pressure thermosphere, where convective mixing processes are negligible. Temperatures increase rapidly with altitude in the thermosphere, to as high as 1000 K, due to heating by extreme ultraviolet sunlight, the solar wind and atmospheric waves. Polyatomic gases break up into individual atoms, and there is gravitational stratification, with lighter gases increasingly dominating at higher altitudes.

The vertical radiation flux  $Z$ , which is discussed below, can change rapidly in the troposphere and stratosphere. There can be a further small change of  $Z$  in the mesosphere. Changes in  $Z$  above the mesopause are small enough to be neglected, so we will often refer to the mesopause as “the top of the atmosphere” (TOA), with respect to radiation transfer. As shown in Fig. 2, the most abundant greenhouse gas at the surface is water vapor,  $H_2O$ . However, the concentration of water vapor drops by a factor of a thousand or more between the surface and the tropopause. This is because of condensation of water vapor into clouds and eventual removal by precipitation.

Carbon dioxide,  $CO_2$ , the most abundant greenhouse gas after water vapor, is also the most uniformly mixed because of its chemical stability. Methane, the main topic of this discussion is much less abundant than  $CO_2$  and it has somewhat higher concentrations in the troposphere than in the stratosphere where it is oxidized by OH radicals and ozone,  $O_3$ . The oxidation of methane[8] is the main source of the stratospheric water vapor shown in Fig. 2.

Ozone molecules,  $O_3$ , are produced from  $O_2$  molecules by ultraviolet sunlight in the upper atmosphere, and this is the reason that  $O_3$  concentrations peak in the stratosphere, and are hundreds of times smaller in the troposphere, as shown in Fig.2.

## 4 Fluxes and forcings.

How greenhouse gases affect energy transfer through Earth’s atmosphere is quantitatively determined by the *radiative forcing*,  $F$ , the difference between the flux  $\sigma T_0^4$  of thermal radiant energy from a black surface through a hypothetical, transparent atmosphere, and the flux  $Z$  through an atmosphere with greenhouse gases, particulates and clouds, but with the same surface temperature,  $T_0$ . [15],

$$F = \sigma T_0^4 - Z. \quad (1)$$

Here the Stefan-Boltzmann constant is

$$\sigma = 5.67 \times 10^{-8} W m^{-2} K^{-4} \quad (2)$$

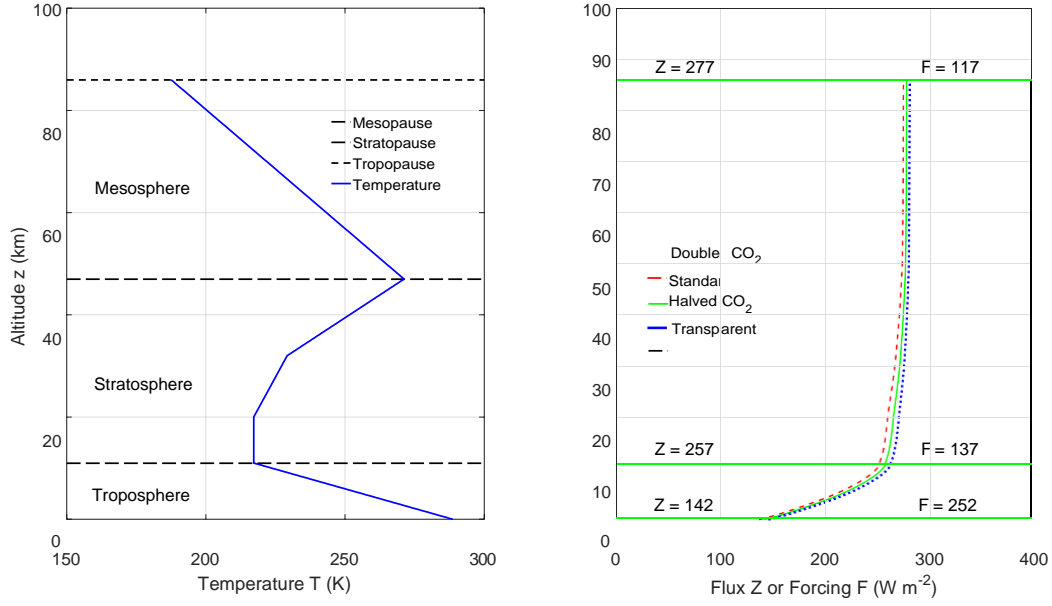


Figure 3: **Left:** The altitude dependence of temperature from Fig. 2. **Right** The flux  $Z$  increases with increasing altitude as a result net upward energy radiation from the greenhouse gases  $\text{H}_2\text{O}$ ,  $\text{O}_3$ ,  $\text{N}_2\text{O}$  and  $\text{CH}_4$ , and  $\text{CO}_2$ . The middle, green curve is the flux for current concentrations. The forcings  $F$  are the differences between the altitude-independent flux  $\sigma T_0^4$  through a transparent atmosphere with no greenhouse gases, for a surface temperature of  $T_0 = 288.7$  K (the vertical, dashed black line), and the flux  $Z$  for an atmosphere with the greenhouse gas concentrations of Fig. 2. Fluxes and forcings for halved and doubled concentrations of  $\text{CO}_2$ , but with the same concentrations of all other greenhouse gases, are shown as dotted blue and dashed red curves, which barely differ from the green curve, the flux for current concentrations. We used doubled and halved  $\text{CO}_2$  rather than  $\text{CH}_4$  for this illustration since the flux changes for doubling or halving methane concentrations would be ten times smaller and would not be distinguishable on the figure.

The forcing  $F$  and the flux  $Z$  are usually specified in units of  $\text{W m}^{-2}$ . The radiative heating rate,

$$R = \frac{dF}{dz}, \quad (3)$$

is equal to the rate of change of the forcing with increasing altitude  $z$ . Over most of the atmosphere,  $R < 0$ , so thermal infrared radiation is a cooling mechanism that transfers internal energy of atmospheric molecules to space or to the Earth's surface. Forcing depends on latitude, longitude and on the altitude,  $z$ .

The right panel of Fig. 3 shows the altitude dependence of the net upward flux  $Z$  and the forcing  $F$  for the greenhouse gas concentrations of Fig. 2. The temperature profile of Fig 2 is reproduced in the left panel. The altitude-independent flux,  $\sigma T_0^4 = 394 \text{ W m}^{-2}$ , from the surface with a temperature  $T_0 = 288.7$  K, through a hypothetical transparent atmosphere, is shown as the vertical dashed line in panel on the right. The fluxes for current concentrations of  $\text{CO}_2$  and for doubled or halved concentrations are shown as the continuous green line,

the dashed red line and dotted blue line.

At current greenhouse gas concentrations the surface flux,  $142 \text{ W m}^{-2}$ , is less than half the surface flux of  $394 \text{ W m}^{-2}$  for a transparent atmosphere because of downwelling radiation from greenhouse gases above. The surface flux has nearly doubled to  $257 \text{ W m}^{-2}$  at the tropopause altitude, 11 km in this example. The  $115 \text{ W m}^{-2}$  increase in flux from the surface to the tropopause has been radiated by greenhouse gases in the troposphere. Most of the energy needed to replace the radiated power comes from convection of moist air. Direct absorption of sunlight in the troposphere makes a much smaller contribution.

From Fig. 3 we see that the flux  $Z$  increases by another  $20 \text{ W m}^{-2}$ , from  $257 \text{ W m}^{-2}$  to  $277 \text{ W m}^{-2}$  between the tropopause and the top of the atmosphere. The energy needed to replace the  $20 \text{ W m}^{-2}$  increase in flux comes from the absorption of solar ultraviolet light by ozone,  $\text{O}_3$  in the stratosphere and mesosphere. Convective heat transport above the tropopause is small enough to be neglected.

## 5 Spectral forcings

In Eq. (1), the fluxes,  $Z$ , and forcings,  $F$ , of Fig. 3 can be thought of as sums of contributions,  $\tilde{Z}dv$  and  $\tilde{F}dv$ , from *spectral fluxes*,  $\tilde{Z}$ , or *spectral forcings*,  $\tilde{F}$ , carried by infrared radiation of spatial frequencies between  $\nu$  and  $\nu + d\nu$ . As one can see from Fig. 3, at the top of the atmosphere, the sums (integrals) of the spectral fluxes and spectral forcings are

$$Z = \int_0^{\infty} \tilde{Z} dv = 277 \text{ W m}^{-2}, \quad (4)$$

and

$$F = \int_0^{\infty} \tilde{F} dv = 117 \text{ W m}^{-2}. \quad (5)$$

Representative spectral fluxes and forcings at the top of the atmosphere are plotted in Fig. 4. The integral (4) is the area under the jagged black curve. The spectral fluxes and forcings are related by a formula analogous to (1)

$$\tilde{F} = \pi\tilde{B}_0 - \tilde{Z}. \quad (6)$$

Here  $\tilde{B}_0 = \tilde{B}(\nu, T_0)$ , is the surface value of the spectral Planck intensity,

$$\tilde{B} = \frac{2h_P c^2 \nu^3}{e^{hc\nu/(k_B T_0)} - 1}, \quad (7)$$

which depends on the spatial frequency  $\nu$  and the temperature  $T$  of the radiation. In (6), Boltzmann's constant has the value,  $k_B = 1.3806 \times 10^{-16} \text{ erg K}^{-1}$ , Planck's constant,  $h_P$ , has the value  $h_P = 6.6261 \times 10^{-27} \text{ erg s}$ , and the speed of light,  $c$ , has the value  $c = 2.9979 \times 10^{10} \text{ cm s}^{-1}$ . The spatial frequency of the radiation,  $\nu = 1/\lambda$  (usually given in units of  $\text{cm}^{-1}$ ) is the inverse of the wavelength  $\lambda$  of the radiation. Spectral densities, equivalent to (7), but in terms of wavelength  $\lambda$  or temporal frequency ( $c\nu \rightarrow \nu$ ), instead of spatial frequency, are often given in the literature[16]. The spectral flux from the "black" surface of a hypothetical transparent atmosphere is  $\pi\tilde{B}_0$ , where the factor of  $\pi$  comes from integrating  $\tilde{B}_0 \cos \theta$  over

$2\pi$  steradians of upwardly directed solid-angle increments, in accordance with a Lambertian [17] angular dependence.

Planck's formula (7) for the spectral intensity of thermal radiation is one of the most famous equations of physics. It finally resolved the paradox that classical physics predicted infinite fluxes of heat radiation, in clear contradiction to observations, and it gave birth to quantum mechanics [16].

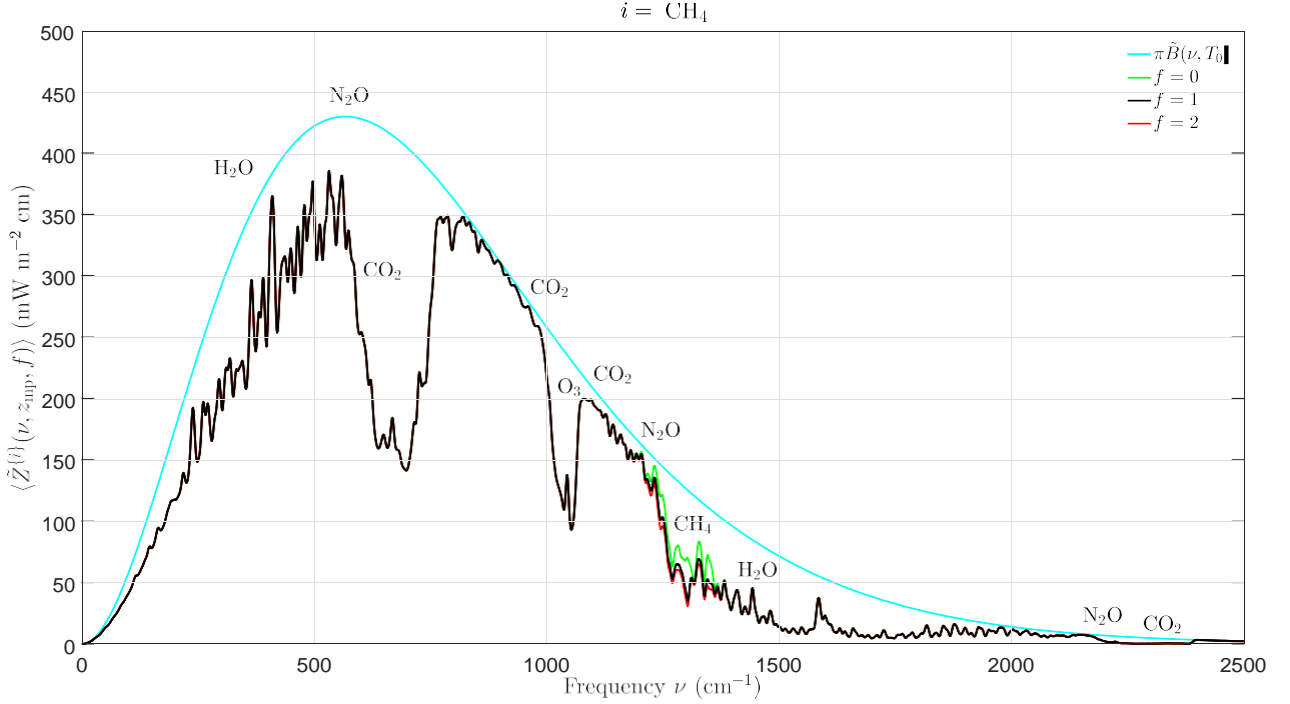


Figure 4: The spectral forcing at current levels of methane,  $\text{CH}_4$ , (the black curve with  $f = 1$ ), or if concentrations of methane are doubled (the red curve with  $f = 2$ ), or if all methane is removed (the green curve with  $f = 0$ ). The area under the black, jagged curve is  $227 \text{ W m}^{-2}$  and is the frequency-integrated flux at the top of the atmosphere of Fig. 3. The area under the Planck spectral intensity (the smooth cyan curve) is  $394 \text{ W m}^{-2}$ . It is the flux<sub>0</sub>  $\sigma T^4$ , that would be radiated to space by a black surface at the temperature  $T_0 = 288.7 \text{ K}$  for an atmosphere that contained no greenhouse gases and was transparent to thermal radiation.

The Stefan-Boltzman flux,  $\sigma T_0^4 = 394 \text{ W m}^{-2}$  of (1), for a surface temperature of  $T_0 = 288.7 \text{ K}$ , is the frequency integral of the Planck spectral flux,  $\pi \tilde{B}_0$ ,

$$\int_0^{\infty} \pi \tilde{B}_0 d\nu = \sigma T_0^4 = 394 \text{ W m}^{-2}. \quad (8)$$

The integral (8) is the area in Fig. 4 beneath the smooth blue curve, the spectral flux for a transparent atmosphere.

As one can see from Fig. 3, the flux at the top of the atmosphere,  $227 \text{ W m}^{-2}$  is only 70.3% of the flux  $\sigma T_0^4 = 394 \text{ W m}^{-2}$  emitted by a black surface at a temperature of



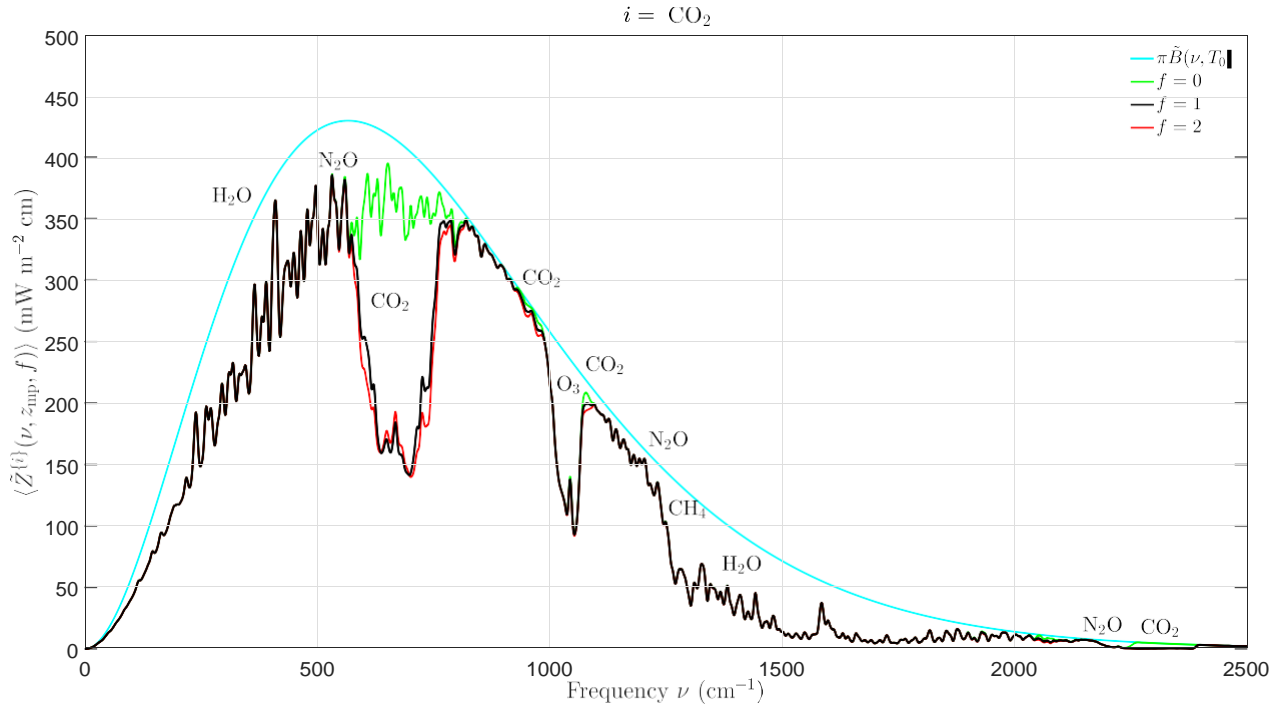


Figure 5: The spectral forcing at current levels of carbon dioxide,  $\text{CO}_2$ , (the black curve with  $f = 1$ ), or if concentrations of carbon dioxide are doubled (the red curve with  $f = 2$ ), or if all carbon dioxide is removed (the green curve with  $f = 0$ ). See the caption of Fig. 4.

$T_0 = 288.7 \text{ K}$ . So without greenhouse gases, the surface would only need to radiate 70.3% of its current value to balance the same amount of solar heating. Since the Stefan-Boltzman flux is proportional to the fourth power of the surface temperature, without greenhouse gases the surface temperature could be smaller by a factor of  $(0.703)^{1/4} = 0.916$ . For this example, the greenhouse warming of the surface by all the greenhouse gases of Fig. 2 is  $\Delta T = (1 - 0.916)T_0 = 24.3 \text{ K}$ . The warming would be different at different latitudes and longitudes, or in summer or winter, or if clouds are taken into account. But 20 C to 30 C is a reasonable estimate of how much warming is caused by current concentrations of greenhouse gases, compared to a completely transparent atmosphere.

## 6 Temperature changes caused by forcing changes

Instantaneous forcing changes due to changes in the concentrations of greenhouse gases, but with no other changes to the atmosphere, can be calculated accurately for a given temperature profile. The next step, using instantaneous forcing changes to calculate temperature changes, is fraught with difficulties and is a major reason that climate models predict much more warming than observed[18]. As shown in Fig. 3, increasing the concentration of greenhouse gases (doubling the  $\text{CO}_2$  concentration for the example in the figure) slightly decreases the radiation flux through the atmosphere. In response, the atmosphere will slightly change

its properties to ensure that the average energy absorbed from sunlight is returned to space as thermal radiation. Since both the surface and greenhouse molecules radiate more intensely at higher temperatures, temperature increases are an obvious way to restore the equality of incoming and outgoing energy. But the amount of water vapor and clouds in the atmosphere will also change, since water vapor is evaporated from the oceans and from moist land. Water is also precipitated from clouds as condensed rain or snow. Low, warm clouds reflect more sunlight and reduce solar heating, with little hindrance of thermal radiation to space. High, cold cirrus clouds reduce the thermal radiation to space, but are wispy and do little to hinder solar heating of the Earth.

The simplest response to changes in radiative forcing would be a uniform temperature increase  $dT$ , at every altitude and at the surface. The rate of increase of top-of-the-atmosphere flux with a uniform temperature is then [1]

$$\frac{dZ}{dT} = 3.9 \text{ W m}^{-2} \text{ K}^{-1}. \quad (9)$$

For a uniform temperature increase, the forcing increase  $\Delta F = 0.23 \text{ W m}^{-2}$  after 50 years, that would result if methane concentrations continued to rise at the rate of the previous 10 years as shown in Fig. 9, would cause a surface-temperature increase of  $\Delta T = \Delta F / (dZ/dT) = 0.05 \text{ C}$ . The forcing increase  $\Delta F = 2.2 \text{ W m}^{-2}$  after 50 years, if carbon dioxide concentrations continued to rise at the rate of the previous 10 years, would cause a surface-temperature increase of  $\Delta T = \Delta F / (dZ/dT) = 0.59 \text{ C}$ . Both temperature increments are small and probably beneficial.

But there are persuasive reasons to expect that the temperature changes will be altitude dependent, like the forcing changes shown in Fig. 3, and that the water-vapor concentrations and cloud cover will change in response to changes in the surface temperature. Fig. 6 illustrates a more complicated “feedback” calculation. On the left panel of Fig. 6, the continuous blue line labeled  $T$  is the midlatitude temperature profile of Fig. 3. The dashed red line labeled  $T'$  is the adjustment of the temperature profile in response to doubling the concentration of  $\text{CO}_2$ , with a simultaneous increase in the concentration of water vapor in the troposphere.

The right panel of Fig. 6 summarizes forcing increments, with and without feedbacks. The continuous blue line is the instantaneous flux change from doubling  $\text{CO}_2$  concentrations, with no other changes to the atmosphere. It is the difference between the dashed red curve and the continuous green curve on the right of Fig. 3, but plotted on an expanded scale. The instantaneous forcing,  $\Delta F = -\Delta Z$ , is  $5.5 \text{ W m}^{-2}$  at the tropopause altitude of 11 km, and  $3.0 \text{ W m}^{-2}$  at the 86 km altitude of the top of the atmosphere. The dashed red curve on the right of Fig. 6, labeled  $\delta Z$  is the “residual forcing” for the dashed-red temperature profile  $T'$  on the left, for doubled  $\text{CO}_2$  concentrations, and for the same relative humidity as before doubling  $\text{CO}_2$ . The same lapse rate,  $dT/dz = 6.5 \text{ K km}^{-1}$ , was used before and after doubling  $\text{CO}_2$  concentrations, as proposed by Manabe and Wetherald[19] in their model of “radiative-convective equilibrium.” This feedback prescription approximately doubles the surface warming, compared to a uniform temperature adjustment and no change in water-vapor concentration. There is stratospheric cooling and surface warming. Variants of the radiative-convective equilibrium recipes illustrated in Fig. 6 are widely used in climate models. Unlike forcing calculations, which can be uniquely and reliably calculated, there

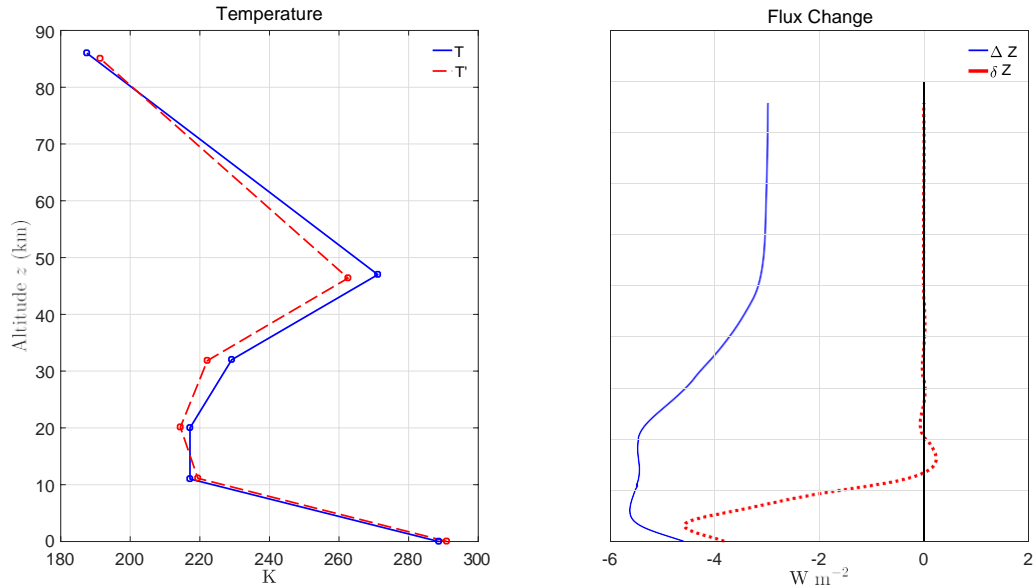


Figure 6: **Left.** An initial temperature profile  $T$  (continuous blue line), the mid latitude profile of Fig. 3. The dashed red line is the adjusted temperature profile  $T'$ , after a doubling of the  $\text{CO}_2$  concentration. **Right.** The continuous blue line is the altitude profile of the “instantaneous” flux change  $\Delta Z$ , caused by doubling  $\text{CO}_2$  concentrations. The concentrations of all other greenhouse gases, and the temperature profile are held fixed for the blue line. The dashed red curve  $\delta Z$  on the right of this Figure is the difference between the initial flux and the flux for doubled concentrations of  $\text{CO}_2$  and for the adjusted temperature profile  $T'$  on the left of the figure. See the text for more details of the adjustments.

is lots of room for subjective adjustments of the temperature changes caused by forcing changes.

## 7 Future forcing from $\text{CH}_4$ and $\text{CO}_2$

Methane levels in Earth’s atmosphere are slowly increasing, as shown in Fig. 7. If the current rate of increase, about 0.007 ppm/year for the past decade or so, were to continue unchanged it would take about 270 years to double the current concentration of  $C^{i3} = 1.8$  ppm. But, as one can see from Fig.7, methane levels have stopped increasing for years at a time, so it is hard to be confident about future concentrations. Methane concentrations may never double, but if they do, WH[1] show that this would only increase the forcing by  $0.8 \text{ W m}^{-2}$ . This is a tiny fraction of representative total forcings at midlatitudes of about  $140 \text{ W m}^{-2}$  at the tropopause and  $120 \text{ W m}^{-2}$  at the top of the atmosphere.

Carbon dioxide levels in the atmosphere have been steadily increasing over the past half century and at a much faster rate than those of methane. Thanks to pioneering work by Charles Keeling [21], there are a number of observatories at various latitudes around the Earth, from the South Pole to the Arctic, that provide measurements of  $\text{CO}_2$  like those of Fig. 8. In WH[1] it is shown that the forcing increment  $\Delta F$ , caused by a small increase,

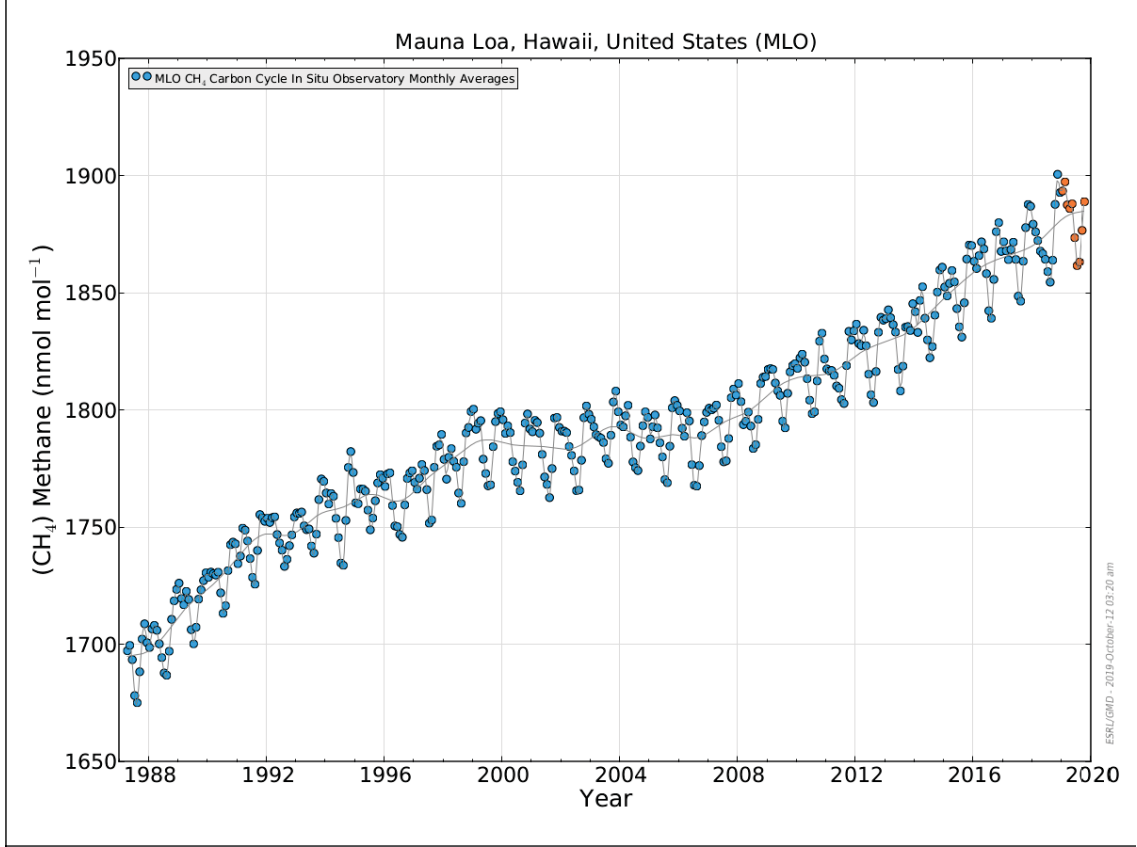


Figure 7: Atmospheric concentrations  $\bar{C}^{\{i\}}$  of methane molecules ( $i = \text{CH}_4$ ) versus time[8]. For the past 10 years, the average rate of increase has been about  $d\bar{C}^{\{i\}}/dt = 0.0076$  ppm/year.

$\Delta\hat{N}^{\{i\}}$ , in the column density of a greenhouse gas of type  $i$  is

$$\Delta F^{\{i\}} = P^{\{i\}} \Delta\hat{N}^{\{i\}}. \quad (10)$$

The column density of the greenhouse gas is determined from the concentrations,  $C^{\{i\}}(z)$  and total atmospheric number density  $N(z)$  (like those of Fig. 2) by the equation

$$\hat{N}^{\{i\}} = \int_0^{\infty} C^{\{i\}} N dz = \bar{C}^{\{i\}} \hat{N}. \quad (11)$$

Here  $\bar{C}^{\{i\}}$  is the altitude-averaged concentration of the greenhouse gas, and the column density of all atmospheric molecules is

$$\hat{N} = \int_0^{\infty} N dz = 2.15 \times 10^{29} \text{ m}^{-2}. \quad (12)$$

For the tropopause, WH [1] show that for current atmospheric concentrations of greenhouse gases, the forcing power per molecule for  $\text{CH}_4$  and  $\text{CO}_2$  are

$$P^{\{i\}} = 2.8 \times 10^{-24} \text{ W}, \quad \text{for } i = \text{CH}_4, \quad (13)$$

$$P^{\{i\}} = 9.0 \times 10^{-26} \text{ W}, \quad \text{for } i = \text{CO}_2. \quad (14)$$

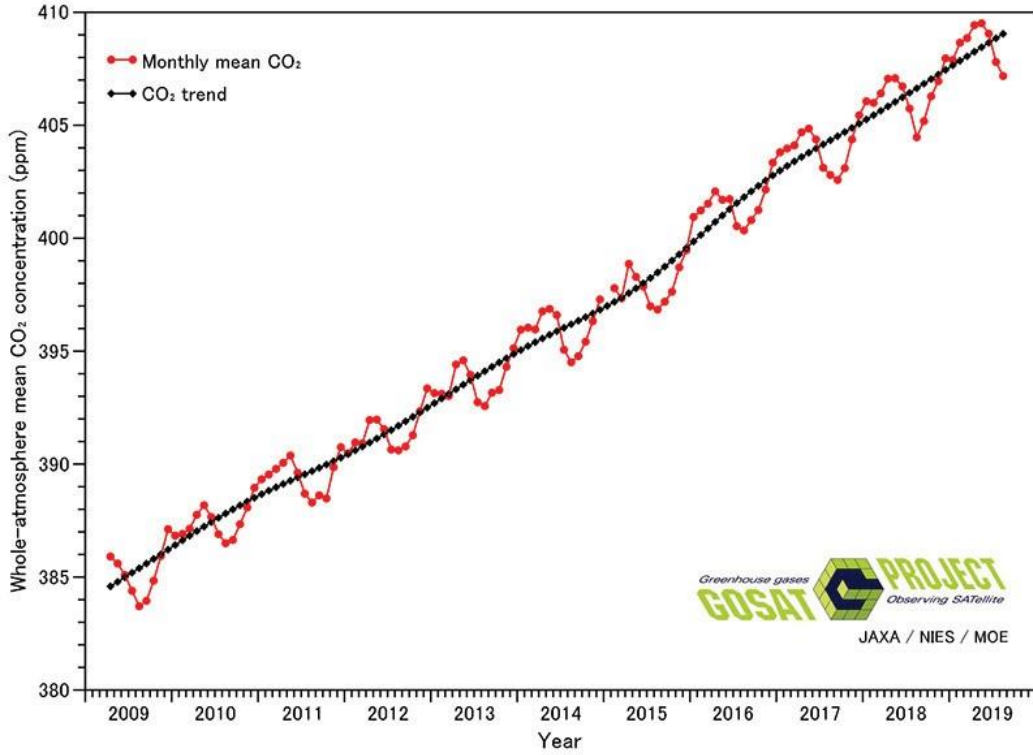


Figure 8: Atmospheric concentrations  $\bar{C}^{\{i\}}$  of carbon dioxide ( $i = \text{CO}_2$ ) molecules versus time[20]. For the past 10 years, the rate of increase has been about  $d\bar{C}^{\{i\}}/dt = 2.3$  ppm/year.

Assuming that the concentration growth rates  $d\bar{C}^{\{i\}}/dt$  of Fig 7 and Fig. 8 remain the same, the forcing after a time  $\Delta t$  will be

$$\Delta F^{\{i\}} = \hat{N} P^{\{i\}} \left( \frac{d\bar{C}^{\{i\}}}{dt} \right) \Delta t \quad (15)$$

The per-molecule forcings  $P^{\{i\}}$  of (13) and (14) have been used with the column density  $\hat{N}$  of (12) and the concentration increase rates  $d\bar{C}^{\{i\}}/dt$ , noted in Fig. 7 and Fig. 8, to evaluate the future forcing (15), which is plotted in Fig. 9. Even after 50 years, the forcing increments from increased concentrations of methane ( $\Delta F = 0.23 \text{ W m}^{-2}$ ), or the roughly ten times larger forcing from increased carbon dioxide ( $\Delta F = 2.2 \text{ W m}^{-2}$ ) are very small compared to the total forcing,  $\Delta F = 137 \text{ W m}^{-2}$ , shown in Fig. 3.

The reason that the per-molecule forcing of methane is some 30 times larger than that of carbon dioxide for current concentrations is “saturation” of the absorption bands. The current density of  $\text{CO}_2$  molecules is some 200 times greater than that of  $\text{CH}_4$  molecules, so the absorption bands of  $\text{CO}_2$  are much more saturated than those of  $\text{CH}_4$ . In the dilute “optically-thin” limit, WH[1] show that the tropospheric forcing power per molecule is  $P^{\{i\}} = 0.15 \times 10^{-22} \text{ W}$  for  $\text{CH}_4$ , and  $P^{\{i\}} = 2.73 \times 10^{-22} \text{ W}$  for  $\text{CO}_2$ . Each  $\text{CO}_2$  molecule in the dilute limit causes about 5 times more forcing increase than an additional molecule of  $\text{CH}_4$ ,

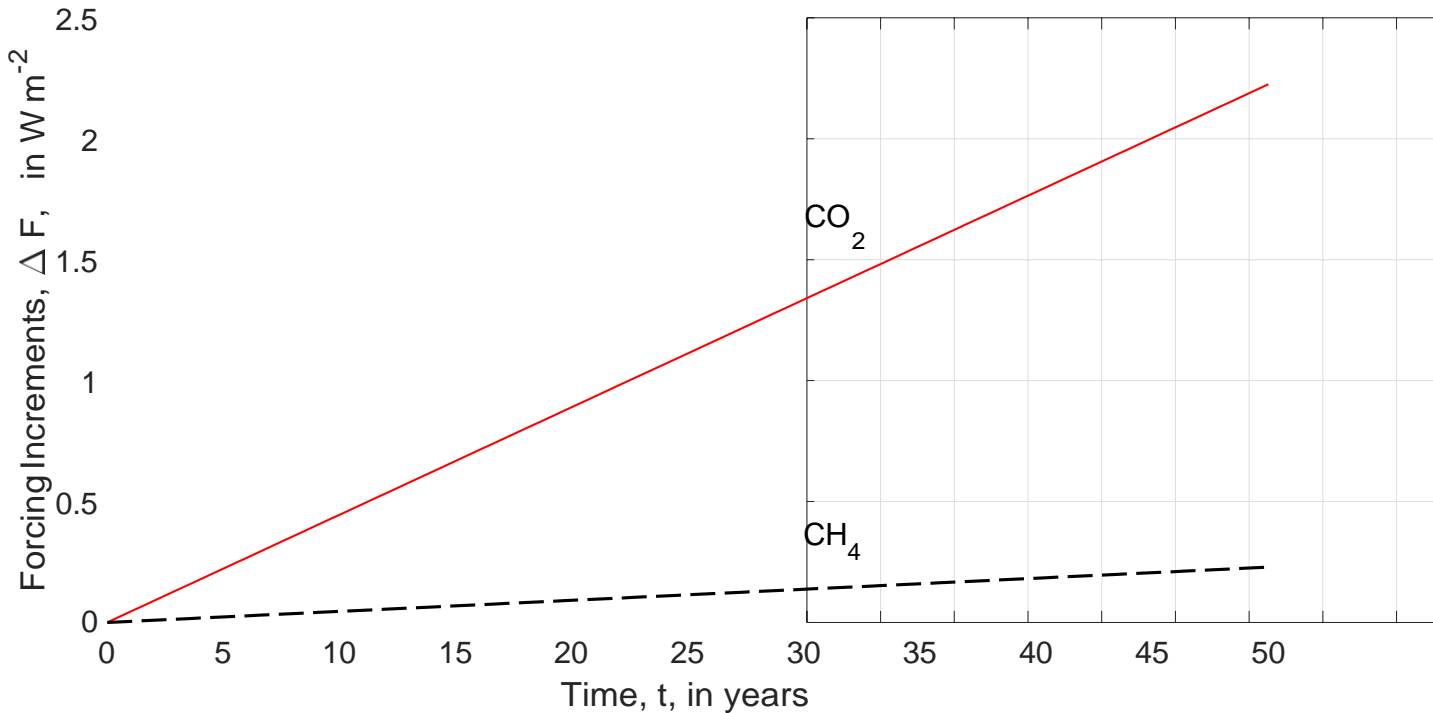


Figure 9: Projected mid-latitude forcing increments at the tropopause from continued increases of CO<sub>2</sub> and CH<sub>4</sub> at the rates of Fig. 7 and Fig. 8 for the next 50 years. The projected forcings are very small, especially for methane, compared to the current tropospheric forcing of 137 W m<sup>-2</sup>.

which is only a "super greenhouse gas" because there is so little in the atmosphere, compared to CO<sub>2</sub>.

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