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An Updated Estimation of Radiative Forcing due to CO_2 and Its Effect on Global Surface Temperature Change

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ABSTRACT

New estimations of radiative forcing due to CO_2 were calculated using updated concentration data of CO_2 and a high-resolution radiative transfer model. The stratospheric adjusted radiative forcing (ARF) due to CO_2 from the year 1750 to the updated year of 2010 was found to have increased to 1.95 W m^{-2}, which was 17% larger than that of the IPCC's 4th Assessment Report because of the rapid increase in CO_2 concentrations since 2005. A new formula is proposed to accurately describe the relationship between the ARF of CO_2 and its concentration. Furthermore, according to the relationship between the ARF and surface temperature change, possible changes in equilibrium surface temperature were estimated under the scenarios that the concentration of CO_2 increases to 1.5, 2, 2.5, 3, 3.5 and 4 times that of the concentration in the year 2008. The result was values of +2.2°C, +3.8°C, +5.1°C, +6.2°C, +7.1°C and +8.0°C respectively, based on a middle-level climate sensitivity parameter of 0.8 K (W $m^{-2})^{-1}$. Non-equilibrium surface temperature changes over the next 500 years were also calculated under two kinds of emission scenarios (pulsed and sustained emissions) as a comparison, according to the Absolute Global Temperature change Potential (AGTP) of CO_2. Results showed that CO_2 will likely continue to contribute to global warming if no emission controls are imposed, and the effect on the Earth-atmosphere system will be difficult to restore to its original level.

Key words: CO_2, radiative forcing, surface temperature change, Global Temperature change Potential

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1. Introduction

Many human activities involve emissions of major greenhouse gases, such as CO_2, CH_4, N_2O and halocarbons, and as such concentrations of these gases in the atmosphere have increased greatly since the Industrial Revolution (IPCC, 2007), bringing about important changes in the composition of the atmosphere and contributing significantly to global warming. In order to slow down global warming, these greenhouse gases were all identified in the Kyoto Protocol, and requirements were placed on controlling their emissions. Of these, CO_2 is the most significant greenhouse gas and is the largest radiative forcing factor. Therefore, an increase of CO_2 concentration in the atmosphere will produce the greatest impact for global climate change in the future (IPCC, 2007).

The main sources responsible for the increase of CO_2 concentration include human activities such as the combustion of fossil fuels and changes in land use. Exchanges of CO_2 with the terrestrial biosphere and surface-ocean take place rapidly after its initial release into the atmosphere, and it is then redistributed over hundreds of years, meaning it persists in the atmosphere for a relatively long period of time. Furthermore, CO_2 is very good at absorbing longwave ra-

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diation in the spectral region 500–800 cm^{-1} (15-μm band). Over the 8000 years before the Industrial Revolution, the concentration of CO_2 only increased by 20 ppmv, basically remaining at a level below 300 ppmv (IPCC, 2007). However, the Industrial Revolution broke this balance and caused a rapid increase in the concentration of CO_2 and other greenhouse gases in the atmosphere. As of 2008, the global mean mixing ratio of CO_2 had reached 385.2 ppmv (WMO, 2009), and is still growing at a rate of 1–1.5 ppmv per year.

CO_2 is the main absorbing gas in the Earth's atmosphere, and there are strong absorption bands (e.g. 15 μm and 2.7 μm) and weak absorption bands (e.g. 10 μm) where atmospheric absorption properties are affected by its concentration, which in turn has a significant influence on levels of outgoing longwave radiation. Moreover, with a lifetime of greater than 10 years, CO_2 is known to be a "long-lived" greenhouse gas that will persist in the atmosphere for anywhere between 50 and 200 years before it is totally cleaned up by natural processes. In the meantime, it continues to accumulate, and all the while persists in its influence on the atmospheric radiation balance and its contribution to global warming (IPCC, 1996).

Radiative forcing is used to assess and compare anthropogenic and natural drivers of climate change, which is defined as the change of net irradiance at the tropopause due to changes in concentrations of greenhouse gases, and other factors. WMO (1986) indicated that changes in global mean surface temperature are related to the net radiation flux at the tropopause. Thus, radiative forcing is an important index and measure for evaluating global warming. The IPCC (1996) defined radiative forcing into two categories, according to whether the stratospheric temperature is allowed to be adjusted: (1) Instantaneous Radiative Forcing (IRF), which does not consider temperature change in the stratosphere; and (2) Adjusted Radiative Forcing (ARF), which is the change of net radiation flux at the tropopause after allowing stratospheric temperature to readjust to radiative equilibrium, but with surface and tropospheric temperatures and states held at unperturbed values. It is known from these definitions that radiative forcing could reveal the general trend of climate change; positive (negative) radiative forcing would warm up (cool down) the surface–troposphere system, causing an increase (decrease) in mean surface temperature. Therefore, we can quantitatively estimate the influence of CO_2 concentration changes on the Earth's climatic system by analyzing the radiative forcing due to CO_2, which then forms the basis for studying the climatic effects of greenhouse gases. For example, when calculating Global Warming Potentials (GWPs) and Global Temperature-change Potentials (GTPs) of greenhouse gases, the values of CO_2 radiative forcing, as a reference gas, are required to be provided. In addition, the ARF of greenhouse gases can be directly related to the change of surface temperature (Hansen et al., 1997; Stuber et al., 2001), so the ARF of CO_2 can be used for evaluating its contribution to surface temperature change.

Since the 4th Assessment Report of the IPCC (IPCC, 2007), the concentration of CO_2 has again increased rapidly. As of 2008, the global mean mixing ratio of CO_2 had reached 385.2 ppmv. It is thus necessary to update the situation regarding CO_2 radiative forcing data and the corresponding global surface temperature changes. In the work reported in the present paper, we used a high-accuracy radiative transfer model (998-band scheme) developed by Zhang et al. (2006a, b) and up-to-date CO_2 concentration data to obtain the IRF and ARF of CO_2 based on previous studies (Zhang et al., 2011a, b), taking into account the influence of its persistence (lifetime) in the atmosphere on its radiative efficiency. We also studied the updated radiative forcing data due to CO_2 changes from the Industrial Revolution until 2010, and propose a new simplified fitting formula to calculate the ARF of CO_2 according to its radiative forcing values generated from different scenario concentrations. Furthermore, we estimated the equilibrium surface temperature change with prescribed scenarios of CO_2 concentration change and non-equilibrium surface temperature change from the Industrial Revolution to 500 years in the future. Together, this work provides new information on how CO_2 acts to affect global warming.

The remainder of the paper is organised as follows. Section 2 introduces the radiation model and its input dataset. Section 3 describes the calculation scheme of radiative forcing (RF), evaluates the radiation model, and discusses the calculated RF. Section 4 applies the new formula to describe the relationship between the ARF of CO_2 and its concentration. Section 5 reports the results from the experiment to predict global mean equilibrium and non-equilibrium surface temperature changes under the chosen prescribed scenarios. And finally, section 6 presents the conclusions of the study.

2. Model and data

The longwave radiative transfer model adopted in this work was developed by Zhang et al. (2003, 2006a, b). The effective absorption coefficients in the model were calculated with the correlated k-distribution method proposed by Shi (1981), the optimal approach to overlapping bands by Zhang et al. (2003), the k-interval number-choosing method by Zhang et al. (2006a), and the band division method by

Table 1. The parameters of 15 cloud categories.

Category	Tropical Atmosphere Cloud amount (%)	Water or ice content (g m^{-3})	Effective radius (μm)	Midlatitude Atmosphere Cloud amount (%)	Water or ice content (g m^{-3})	Effective radius (μm)	Subarctic Atmosphere Cloud amount (%)	Water or ice content (g m^{-3})	Effective radius (μm)
Cu (water)	11.43	0.03	10	9.50	0.03	10	2.43	0.03	10
Sc (water)	9.38	0.07	10	10.48	0.09	10	5.36	0.11	10
St (water)	0.75	2.47	10	2.26	2.79	10	5.17	4.11	10
Cu (ice)	0.00	0.01	30	2.03	0.03	30	3.42	0.04	30
Sc (ice)	0.00	0.20	30	1.12	0.17	30	5.76	0.22	30
St (ice)	0.00	5.90	30	0.30	4.26	30	2.85	3.76	30
Ac (water)	5.55	0.05	10	2.55	0.05	10	0.38	0.06	10
As (water)	4.43	0.09	10	3.67	0.10	10	0.82	0.13	10
Ns (water)	1.14	0.07	10	1.66	0.08	10	1.03	0.10	10
Ac (ice)	0.95	0.06	30	9.02	0.09	30	9.48	0.10	30
As (ice)	0.18	0.14	30	6.43	0.18	30	12.99	0.22	30
Ns (ice)	0.06	0.11	30	2.20	0.11	30	4.93	0.10	30
Ci (ice)	15.36	0.01	30	13.27	0.01	30	6.49	0.01	30
Cs (ice)	5.25	0.06	30	6.89	0.08	30	1.59	0.09	30
Dc (ice)	2.49	0.27	30	3.54	0.25	30	0.64	0.24	30

Zhang et al. (2006b). Zhang et al. (2006a, b) divided the whole spectral region (10–49000 cm^{-1}) into different bands; for example, 17, 21, 27, 55, 998 etc. Among them, the high-accuracy 998-band scheme divided the spectral region 10–49000 cm^{-1} (0.2–1000 μm) into 998 bands, with 498 bands in the longwave region 10–2500 cm^{-1} (4–1000 μm), and with a spectral resolution of about 5 cm^{-1}. The k-interval number was optimized for each band and the values ranged from 2 to 16. For detailed information about band division, k-interval numbers and absorbing gases in each band, see Zhang et al. (2006b) and references therein.

Five main greenhouse gases (H_2O, CO_2, O_3, CH_4, N_2O and CFCs) were included in the model, which assumes that CO_2, CH_4, N_2O and CFCs are evenly mixed in the atmosphere. The concentrations of CO_2, CH_4 and N_2O were their values as of 2008, which were 385.2, 1.797 and 0.3218 ppmv, respectively. CO_2 absorptions were from 4 to 18.9 μm in the longwave region, located in bands 105–498 in the 998-band scheme. Almost all the strong and weak bands were considered in the scheme, and thus the corresponding results were comparable to those of the precise line-by-line integration (LBL) model (Zhang and Shi, 2000; Zhang et al., 2005, 2008). Zhang et al. (2011b) also confirmed that radiative forcings calculated by the 998-band scheme are much more accurate than the 17-band scheme designed for climate models. Therefore, the high-accuracy 998-band scheme was adopted to calculate the radiative forcing due to CO_2 in this work.

The whole atmosphere was divided into 100 layers with a vertical resolution of 1 km. The surface height was set at 0 km, and the top of atmosphere (TOA) at 100 km. As for the calculation of radiation flux and heating rate, six kinds of model atmosphere (Garand et al., 2001) were used for the required profiles of temperature, pressure and gas (water vapor and O_3) concentration: tropical (TRO), mid-latitude summer (MLS), mid-latitude winter (MLW), sub-arctic summer (SAS), sub-arctic winter (SAW), and United States Standard (USS). Based on these, the instantaneous radiative efficiency (IRE) (RF per unit concentration) and the stratospheric adjusted radiative efficiency (ARE) of CO_2 were calculated, and the arithmetic mean and area-weighted zonal mean were separately used to obtain the corresponding global mean results for clear and all-sky conditions.

3. CO_2 radiative forcing

3.1 *Radiative forcing calculation scheme*

In order to calculate the ARF, an iterative method in the longwave radiative transfer model was needed, as proposed in previous work (Zhang et al., 2011a, b). If the convergence condition is satisfied, then the stratosphere reaches a new radiation equilibrium after the temperature adjustment, and the net radiative flux at the tropopause is the ARF. Whereas, the net radiative flux at the tropopause caused by a perturbing concentration change of gas without temperature adjustment in the stratosphere is the IRF. For special cases, if the perturbing concentration of gas is the unit concentration (e.g. 1 ppmv or 1 ppbv), then the cor-

Table 2. Comparison of longwave radiative forcings due to CO_2 under different scenarios and different models (units: m^{-2}).

	scenario 1: Doubling the concentration of CO_2			scenario 2: Water vapor content increases by 20% after doubling the concentration of CO_2		
Model Layer	998-band	AOGCMs	LBLs	998-band	AOGCMs	LBLs
TOA	3.03	2.45	2.8	3.26	3.57	3.78
200 hPa	5.6	5.07	5.48	4.13	4.45	4.57
Surface	1.7	1.12	1.64	11.14	11.95	11.52

responding radiative forcing per unit concentration is called the radiative efficiency of the gas.

Clouds are an important factor affecting the radiative forcing due to greenhouse gases. In the present study, the method described in Zhang et al. (2011a and b) was used to consider the effect of clouds. Accordingly, the parameters of 15 cloud categories are shown in Table 1 [see Zhang et al. (2011a, b) for further details]. Zhang et al. (2011a, b) also provide the stratospheric ARE of CO_2 for all-sky cases by the follow formula:

$$R=\sum_{i=1}^{15} C_{\mathrm{d}i}R_i+(1-C_{\mathrm{d}})R_{\mathrm{clear}}\ . \tag{1}$$

Here, $C_{\mathrm{d}i}$ (cloud category: i=1–15) is the cloud cover of each cloud category; $C_{\mathrm{d}}=\sum C_{\mathrm{d}i}$ is total cloud cover; and R_{clear} and R_i are the AREs for a clear and cloudy atmosphere, respectively. Then, the global mean ARE (R_{mean}) of CO_2 for all-sky cases was adopted (Zhang et al., 2011a, b):

$$R_{\mathrm{mean}}=\frac{1}{2}\times R_{\mathrm{tro}}+\left(\frac{\sqrt{3}}{2}-\frac{1}{2}\right)\times R_{\mathrm{mid}}+\left(1-\frac{\sqrt{3}}{2}\right)\times R_{\mathrm{sub}}\ . \tag{2}$$

Here, R_{tro}, R_{mid} and R_{sub} are the AREs of the tropical, mid-latitude and subarctic atmosphere types, respectively.

3.2 *Evaluation of the radiative transfer model*

In order to assess the radiative transfer model adopted in this study, the radiative forcings due to CO_2 under two different concentration hypotheses were calculated, and the results compared with those given by the atmosphere-ocean general circulation models (AOGCMs) in Collins et al. (2006). The two scenarios were: (1) doubling the concentration of CO_2 from 287 ppmv in 1860 to 574 ppmv (scenario 1); (2) increasing the water vapor content to 1.2 times the original after doubling the concentration of CO_2(scenario 2). The IRF results under these two scenarios included: (1) net longwave radiative flux at the TOA for clear sky; (2) longwave net radiative flux at 200 hPa for clear sky; (3) longwave net radiative flux at the surface for clear sky. In the calculation, MLS was chosen to make all the calculations under the same conditions for comparison purposes, within which the model atmosphere was divided into 40 layers, and the TOA was set at 80 km (0.01 hPa). The surface was assumed to be a black body with an emissivity of 1.0. The temperature of the surface was 294 K, and the influence of cloud and aerosol was neglected.

Table 2 shows the comparison between the results of this work and those given by the different models in Collins et al. (2006) under the above scenarios. The longwave radiative forcing values at the surface, 200 hPa, and model top under scenario 1 were 1.7, 5.6 and 3.03 W m^{-2}, respectively, and the longwave radiative forcing values under scenario 2 were 11.14, 4.13 and 3.26 W m^{-2}, respectively. The results were basically located in the range of the different AOGCMs, as well as those of the line-by-line integration models (LBLs). However, under scenario 1 the results were closer to those of the LBLs, while under scenario 2 they were closer to the results of the AOGCMs (with the exception of the results for the surface), but still only a little different from the results of the LBLs. In view of the values and magnitude, all the results can be regarded as being sufficiently similar, indicating that it is reasonable to calculate the longwave radiative forcing due to CO_2 using the 998-band model.

3.3 CO_2 *radiative efficiency and heating rate*

The IRE and ARE of CO_2 for clear sky obtained by the 998-band scheme were 1.992×10^{-5} and 1.878×10^{-5} W m^{-2} $ppbv^{-1}$, respectively, and the ARE for all-sky was 1.638×10^{-5} W m^{-2} $ppbv^{-1}$, becoming 1.567×10^{-5} W m^{-2} $ppbv^{-1}$ after lifetime-adjustment (120-yr CO_2 lifetime). In order to compare with the corresponding result (1.4×10^{-5} W m^{-2} $ppbv^{-1}$) given by the IPCC (IPCC, 2007), the radiative efficiency was used (units of W m^{-2} $ppbv^{-1}$). Among the results, those for clear sky were the arithmetic mean of the values under the six model atmosphere types, and those for all-sky were the zonal area-weighted means of the above three

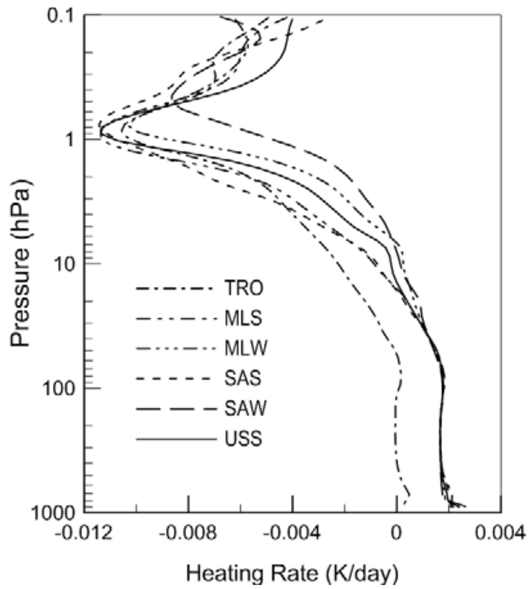

Fig. 1. The heating rates of 1 ppmv perturbation of CO_2 for the six model atmosphere types.

model atmosphere types in Eq. (2). By comparing the IRE for clear sky with the ARE, it was found that the radiative efficiency of CO_2 was reduced by 5.7% after stratospheric temperature adjustment.

Whether the effect of stratospheric temperature adjustment on radiative forcing was an increase or decrease depends on the influence of the temperature profile on the net radiative flux at the tropopause after the adjustment (Jain et al., 2000). In Fig. 1, the heating rates in the longwave region were induced by the disturbance of 1 ppmv under the six kinds of model atmosphere. It can be seen that the heating rates varied under different model atmosphere types, but the magnitudes and the vertical distributions were similar. Among the results, those of the USS model atmosphere were located basically in the middle of the results of all the model atmosphere types, thus representing an approximation of the average of heating rates for all kinds of model atmosphere. Therefore, the results from USS were taken as an example to analyze. It can be seen that the heating rates of CO_2 were all negative in the stratosphere above the tropopause, which played a cooling role in these atmosphere layers. When the stratosphere reached a new thermal balance after adjustment, the stratosphere temperature would fall, and the downward radiation flux from the lower stratosphere toward the troposphere would then be reduced, causing the decrease of net radiation flux of the tropopause, resulting in the decrease of the ARF of CO_2.

The global mean of CO_2 ARE was 1.638×10^{-5} W m^{-2} ppbv^{-1} for all-sky, which was 12.8% less than the corresponding value for clear sky, owing to the decreasing of the upward longwave radiative flux caused by clouds (Collins et al., 2006). The final lifetime-adjusted radiative efficiency in this work was a little bit larger (1.14%–12.8%) than that of the IPCC (IPCC, 2007) due to the use of a different radiative model, cloud scheme etc. Detailed analysis can be found in Zhang et al. (2011a).

The global mean concentration of CO_2 was adopted to calculate the global mean radiative forcing (efficiency) in this work. However, in the real atmosphere, the vertical distribution of CO_2 concentration also varies with altitude. Many studies (e.g. Christidis et al., 1997; Freckleton et al., 1998; Jain et al., 2000) have indicated that the vertical distribution of greenhouse gas concentrations has a significant influence on their radiative forcing, and that differences will exist between the radiative forcings caused by uniform and non-uniform concentration profiles. Therefore, an adjustment factor relevant to the atmospheric lifetime was put forward by Sihra et al. (2001) based on the work by Jain et al. (2000) for correcting the influence of a concentration decrease of greenhouse gas in the stratosphere on radiative forcing. Sihra et al. (2001) reported that the coefficient is $1-0.241\times l^{-0.358}$ if the atmospheric lifetime (l, in yr) of a gas is longer than 0.25. It should be noted that radiative forcing after lifetime-correction can also have errors. However, these errors are much less than if no lifetime-correction is applied. Using this coefficient, the radiative efficiency of CO_2 after lifetime-correction (120 years in this study) was 1.567×10^{-5} W m^{-2} ppbv^{-1}, which was reduced by 4.3% compared with the radiative efficiency without correction. Therefore, as far as CO_2 is concerned, lifetime-correction is necessary when calculating its radiative forcing.

The IPCC (2007) reported an estimated value of radiative forcing due to the increase of CO_2 by human beings from the Industrial Revolution (1750) to 2005 to be 1.66 ± 0.17 W m^{-2}. Taking the concentration of CO_2 in 1750 and 2005 as 280 ppmv and 379 ppmv, the ARF of CO_2 calculated in this work was 1.89 W m^{-2} for all-sky, which then became 1.81 W m^{-2} after lifetime-correction, which was within the estimation range of the IPCC (2007). Based on the above, we further calculated the updated ARF of CO_2 from the Industrial Revolution to the year 2010, the result of which was 2.04 W m^{-2}, and then 1.95 W m^{-2} after lifetime-correction. The updated CO_2 concentration of 391 ppmv in 2010 given by NOAA/ESRL (Earth Systems Research Laboratory) was 17% more than that of the IPCC (2007). This can be mainly attributed to the increase in CO_2 concentration since the IPCC's 4th Assessment Report (IPCC, 2007).

4. A new fitting formula for the ARF of CO_2

To calculate the radiative forcings of greenhouse gases, a variety of radiative transfer models can be employed, including LBL models, band models etc., and there are radiation-convection models and various climate models that can be applied too. Calculation of the ARF has to be completed at least with an iterative program for adjusting the stratospheric temperature profile shown in Zhang et al. (2011a, b). Therefore, the calculation of ARF is more complicated than that of the IRF; the computation burden is heavier and much more time-consuming. It has been found that the values of radiative forcing generated by changing the concentrations of greenhouse gases will change correspondingly, and there is a resultant relationship between them. Therefore, this relationship could be expressed with a simple empirical formula in order to quickly and easily calculate radiative forcing due to different future concentration changes of gases.

The concentration of CO_2 in the atmosphere has been being increased rapidly since the Industrial Revolution. Also, CO_2 absorbs infrared radiation well in the 15 μm band. It is generally agreed that the radiative forcing due to CO_2 has an approximate logarithmic relationship with its concentration. CO_2 also has several weak absorption bands, which, together with the wing parts of the central strong absorption bands, will contribute more and more to its radiative forcing with increases in its concentration. Thus, Shi (1991) and Yu and Shi (2001) added a square root of concentration variable term into their simplified formula describing the relationship between the ARF and concentration, besides a logarithmic term [see Eq. (3)], to improve its accuracy. We adopted the same form of formula as Eq. (3) (Shi, 1991; Yu and Shi, 2001), but the ARFs were calculated using the updated concentration of CO_2 and high spectral resolution 998-band scheme used in the present study.

$$\Delta F_{\mathrm{CO_2}} = \alpha \ln \frac{C}{C_0} + \beta(\sqrt{C} - \sqrt{C_0}) \,. \tag{3}$$

Here, $\Delta F_{\mathrm{CO_2}}$ is the ARF due to CO_2; C_n is the target concentration of CO_2; and C_0 is the reference concentration of 385.2 ppmv. Then, the fitting coefficients obtained in this work were used as α (6.2554) and β (6.2783×10^{-2}). The absolute error of this fitting formula was $\leqslant$0.1 W m^{-2}, and the relative error was $\leqslant$1%, as shown in Fig. 2.

The advantages of using Eq. (3) to calculate the ARF of CO_2 are that it is very easy and simple to apply when the concentration changes, and the use of iteration (like that in Zhang et al., 2011a, b) and other complicated models is not necessary.

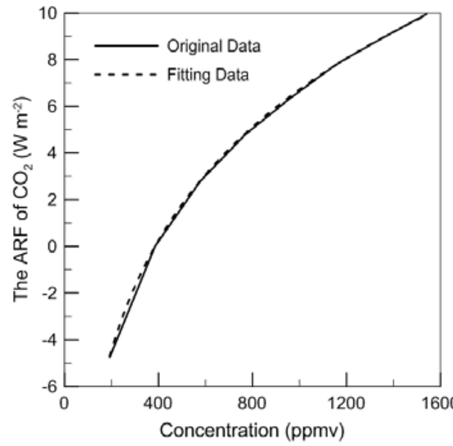

Fig. 2. The stratospheric-adjusted radiative forcing of CO_2 and its fitting curve.

5. Surface temperature change

Radiative forcing can be related by a linear relationship to the global mean equilibrium temperature change at the surface Eq. (4), providing a simple measure for both quantifying and ranking the different influences of gas concentration changes on climate change. It also offers a limited measure of climate change, as it does not attempt to represent the overall climate response. According to Eq. (3), the global mean equilibrium surface temperature change can be estimated according to radiative forcing (IPCC, 2007):

$$\Delta T_{\mathrm{s}} = \lambda \Delta F \,. \tag{4}$$

Here, ΔT_{s} is the global mean equilibrium surface temperature change; ΔF is the global mean ARF; and λ is the climate sensitivity parameter, which mainly depends on whether cloud feedback is strong or weak, depending on different climate models, and ranges from 0.3 to 1.4 K (W m^{-2})$^{-1}$. We took a typical median value of 0.8 K (W m^{-2})$^{-1}$. According to the calculated results above, when the concentration of CO_2 rises from 385.2 ppmv to 1.5, 2, 2.5, 3, 3.5 and 4 times the original value, the calculated ARF values were 2.79, 4.80, 6.37, 7.79, 8.90 and 9.95 W m^{-2}, respectively. Thus, the corresponding global mean equilibrium surface temperature changes were +2.2°C, +3.8°C, +5.1°C, +6.2°C, +7.1°C and +8.0°C, respectively. It should be noted that these temperature responses were obtained with a middle value of λ. As climate sensitivity and other aspects of the climate response to external forcings remain inadequately quan-

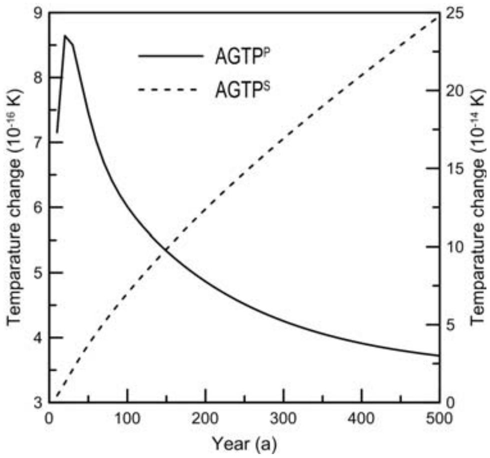

Fig. 3. Surface temperature changes caused by pulsed and sustained emissions of CO_2. The solid line represents AGTP^P (left y-axis) and the dashed line AGTP^S (right y-axis), both after atmospheric lifetime-adjustment.

tified, Eq. (4) has the advantage of being more readily calculable and comparable than estimates of the climate response.

We also calculated the Absolute Global Temperature change Potential (AGTP) of CO_2, AGTP^P for pulsed emissions, and AGTP^S for sustained emissions for 500 years into the future. The results are given in Fig. 3, which shows the global mean non-equilibrium surface temperature change caused by the two kinds of emissions for the next 500 years. AGTP^P and AGTP^S [units: K kg^{-1} and K (kg yr^{-1})$^{-1}$] are the global mean non-equilibrium surface temperature change at time t induced by pulsed and sustained emissions of CO_2 at the initial time. They were calculated by Eq. (5) (Shine et al., 2005), which represents the relationship between the global mean non-equilibrium surface temperature change (ΔT_s) and ARF (ΔF):

$$C_y \frac{d\Delta T_s(t)}{dt} = \Delta F(t) - \frac{\Delta T_s(t)}{\lambda} \quad (5)$$

Here, t is the developing-time of change (units: d); C_y is the thermal capacity (13.3 J K^{-1} m^{-2} kg^{-1}); λ is the climate sensitivity parameter, as above, but here it is set as 0.8 K (W m^{-2})$^{-1}$.

It can be seen from Fig. 3 that the surface temperature induced by pulsed emission of CO_2 increases quickly in the initial stage and reaches a peak after around 30 years. Then, the surface temperature begins to decrease rapidly before 200 years and continues to reduce slowly between 200 and 400 years, but does not come back to the initial state by 500 years. Figure 3 indicates that the surface temperature change caused by sustained emission involves a continuous rise during the whole 500 years. It can also be seen that the surface temperature change caused by a sustained emission of CO_2 is two orders of magnitude larger than that by pulsed emission, so sustained emission has a much greater influence on surface temperature change. It can be concluded that CO_2 will have a sustained influence on surface temperature change in the future if no controls are exerted on CO_2 emissions, and that the Earth-atmosphere system will therefore be difficult to restore to its original state.

6. Conclusions

An updated assessment of radiative forcing due to CO_2 has been recalculated according to its new concentration in the atmosphere by using a high spectral resolution radiative transfer model. The calculated radiative forcing caused by the increase of atmospheric CO_2 from 1750 to 2005 was 1.81 W m^{-2}, which was within the range of 1.66±0.17 W m^{-2} given by the IPCC (2007). Based on this, we calculated the new ARF of CO_2 from the year 1750 to 2010, and obtained a value of 1.95 W m^{-2}, which was 17% higher than the range given by the IPCC (IPCC, 2007), and which was mainly caused by the rapid increase in the concentration of CO_2 since the IPCC's 4th Assessment Report (IPCC, 2007). To simplify the calculation of the ARF of CO_2 under its changed concentrations in the future, a new fitting formula for the relationship between CO_2 ARF and its concentration has been proposed in this work.

Finally, according to the relationship between surface temperature change and the ARF, the global mean equilibrium surface temperature change caused by changes in atmospheric concentrations of CO_2 under different scenarios was estimated. If the global mean concentration of CO_2 rises to 1.5, 2, 2.5, 3, 3.5 and 4 times the value of 385.2 ppmv in the year 2008, then the corresponding global mean equilibrium surface temperature will become +2.2°C, +3.8°C, +5.1°C, +6.2°C, +7.1°C and +8.0°C higher, respectively, based on a middle level climate sensitivity parameter of 0.8 K (W m^{-2})$^{-1}$. Meanwhile, the non-equilibrium surface temperature change caused by pulsed and sustained emissions of CO_2 over the next 500 years was also calculated. This illustrated that the driving of global warming by CO_2 will remain over the next 500 years if emissions are not controlled, starting from now. Subsequently, the Earth–atmosphere system will be difficult to restore to its original state. However, attention should be paid to the fact that the results of this work were obtained under the assumption of a medium-level climate sensitivity parameter.

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