

Warming from fossil fuels

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Abstract.

Carbon cycle models have been used to estimate the rate of change in atmospheric CO₂ concentration with time. Climate models have been used to estimate the radiative forcing of climate from CO₂ additions to the atmosphere. From these two results, we calculate the time integrated radiative forcing of the climate system from an emission of carbon dioxide. We estimate this time integrated radiative forcing to be about 4.5×10^{10} J per mol of CO₂ emitted. The direct warming from the burning of organic carbon is about 4.8×10^5 J per mol CO₂ released. Thus the burning of organic carbon warms the Earth about 100,000 times more from climate effects than it does through the release of chemical energy in combustion.

Introduction

The Earth is heated both when reduced carbon is oxidized to carbon dioxide and when outgoing longwave radiation is trapped by carbon dioxide in the atmosphere (i.e., the CO₂ “greenhouse effect”). The purpose of this work is to compare the relative magnitude of these two effects.

Comparison for year 2002

How does the heating from the production of energy (principally the burning of coal, oil, and gas) compare with the radiative forcing from carbon dioxide?

In the year 2002, total world energy consumption was 411.5 Quadrillion Btu (EIA, 2005), for an average heating rate from energy consumption of 13.76 TW, or about 0.027 W m^{-2} averaged across the area of the Earth.

In year 2002, the annual average atmospheric CO₂ concentration observed at Mauna Loa was 373.1 ppm. This compares with the pre-industrial value of about 280 ppm. The increase in atmospheric CO₂ concentration is a consequences of historical CO₂ emissions from fossil-fuel burning and land-cover change (IPCC TAR 2001).

The heating effect from increased atmospheric CO₂ content can be described using the concept of radiative forcing. The radiative forcing from CO₂ in the atmosphere increases with the logarithm of atmospheric CO₂ content, with an increase of about 3.7 W m⁻² for a doubling of atmospheric CO₂ (IPCC TAR 2001). Since the pre-industrial atmospheric CO₂ concentration was about 280 ppm, this implies that the radiative forcing from CO₂ in year 2002 was about 1.53 W m⁻².

Thus we can estimate that in year 2002, the trapping of heat by CO₂ added to the atmosphere by human activities warmed the Earth about 57 times more than the heat released directly to the environment by our energy system.

In year 2002, about 1.4 PgC of carbon was released from the burning of natural gas, 2.9 PgC was released from the burning of oil, and 2.5 from the burning of coal (Marland et al., 2005). Upon combustion, coal releases about 90 g CO₂ per MJ of heat, oil about 70 g CO₂ MJ⁻¹, and natural gas about 50 g CO₂ MJ⁻¹ (IPCC, 2005). Using these numbers we can estimate that

Approximately $\sim 4.8 \times 10^5$ J/mol is released during oxidation of reduced carbon ($\text{CH}_2\text{O} + \text{O}_2 \rightarrow \text{CO}_2 + \text{H}_2\text{O}$).

The rate of chemical energy release from fossil fuel burning in year 2000 was $\sim 1.2 \times 10^{13}$ W (1). We can estimate the heating rate from anthropogenic CO₂ in the atmosphere in year 2000 to be $\sim 9.0 \times 10^{14}$ W, based on radiative forcing from increased CO₂ of 4.4 W/m² per CO₂-doubling and scaling with the log of CO₂ (2), pre-industrial and year 2000 atmospheric CO₂ contents of ~ 280 ppm and ~ 370 ppm, respectively, and Earth's surface area of $\sim 5.1 \times 10^{14}$ m². Therefore, in year 2000, the Earth was heated >75 times more by anthropogenic CO₂ in the atmosphere than by direct heating from fossil-fuel combustion.

The fossil fuel is burned in an instant, but some of the CO₂ remains in the atmosphere for many thousands of years. If we integrate the radiative forcing from a CO₂ emission over the surface of the Earth and over the lifetime of the CO₂ in the atmosphere, we can calculate the total amount

of heating from that CO₂ in joules, and compare that with the number of joules released from the oxidation of the carbon to CO₂. To estimate the lifetime of CO₂ in the atmosphere, we used an ocean box model embedded within a representation of the carbonate-silicate cycle (3, 4). We simulated this release in an undisturbed pre-industrial atmosphere. The radiative forcing decays away on a range of time scales that can be roughly associated with a variety of physical processes (Figure 1). A multiple exponential fit to the radiative forcing resulting from a unit pulse of CO₂ in this model yields

$$RF(t) = \sum_{n=1}^5 a_n \exp(-t/t_n) , \quad (1)$$

where $a_1 = 1.37 \times 10^{-2}$ W/mol, $a_2 = 1.34 \times 10^{-2}$ W/mol, $a_3 = 2.67 \times 10^{-2}$ W/mol, $a_4 = 6.51 \times 10^{-3}$ W/mol, and $a_5 = 3.76 \times 10^{-3}$ W/mol. Time constants $t_1 = 1.9$ yr, $t_2 = 90.1$, $t_3 = 269$ yr, $t_4 = 10,739$ yr, and $t_5 = 356,878$ yr, correspond roughly to time scales for carbon to mix into the oceanic mixed layer, thermocline, and interior, and time scales for neutralization by carbonate and silicate mineral weathering, respectively. Integrating the radiative forcing from zero to infinity yields $\sim 4.5 \times 10^{10}$ J of global warming per mol CO₂ released to the atmosphere. Calculations of radiative forcing from a CO₂ release are somewhat insensitive to background scenario because at high CO₂ concentrations the chemical effect of the increased ocean carbon buffer factor is largely offset by the lower sensitivity of radiative forcing to added CO₂ (5).

If we compare this $\sim 4.5 \times 10^{10}$ J/mol with the $\sim 4.8 \times 10^5$ J/mol released during oxidation of reduced carbon ($\text{CH}_2\text{O} + \text{O}_2 \rightarrow \text{CO}_2 + \text{H}_2\text{O}$), we can see that over time, the burning of carbon heats the Earth about 100,000 times more through the trapping of outgoing longwave radiation than it does by direct heating through the release of chemical energy. In other words, when we burn carbon and release CO₂ to the atmosphere, only 0.001 % of the total warming comes directly from the release of chemical energy during burning. The remaining 99.999 % of the warming is associated with the trapping of outgoing longwave radiation by that CO₂ in the atmosphere.

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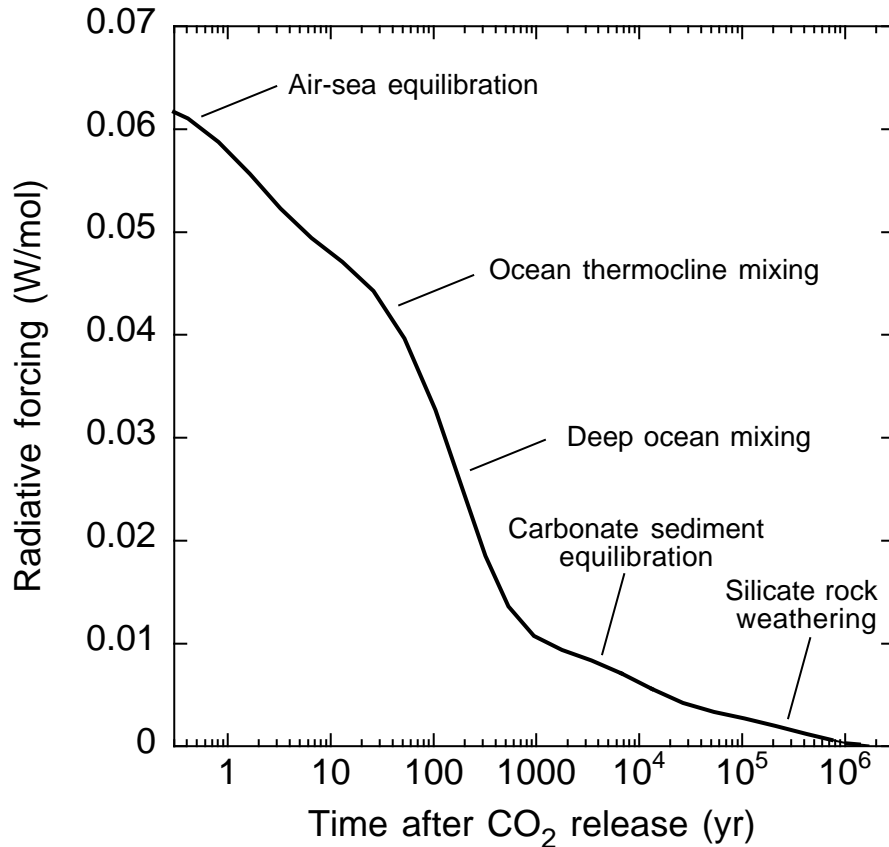


Figure 1. Globally integrated radiative forcing per mol CO₂ released to the atmosphere as a function of time. Radiative forcing reduction results from removal of excess atmospheric CO₂ by processes occurring on a range of time scales. Release of CO₂ to the atmosphere yields an initial radiative forcing of ~0.064 W/mol. A multiple exponential fit to the radiative forcing results indicates that 21% of the perturbation in radiative forcing decays away on the 1.9 yr time scale (atmosphere-ocean equilibration), 21% on the 90 yr time scale (ocean mixed layer-upper thermocline equilibration), 42% on the 270 yr time scale (ocean thermocline-deep ocean equilibration), 10% on the 11,000 yr time scale (carbonate weathering), and the remaining 6% on the 360,000 yr time scale (silicate weathering). The integrated radiative forcing is $\sim 4.5 \times 10^{10}$ J/mol. Dividing this by the initial radiative forcing gives a characteristic time-scale for CO₂ removal from the atmosphere of ~22,000 yr.