

# Rates of change in natural and anthropogenic radiative forcing over the past 20,000 years

Fortunat Joos\* and Renato Spahni†

Climate and Environmental Physics, Physics Institute, and Oeschger Centre for Climate Change Research, University of Bern, Sidlerstrasse 5, CH-3012 Bern, Switzerland

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**The rate of change of climate codetermines the global warming impacts on natural and socioeconomic systems and their capabilities to adapt. Establishing past rates of climate change from temperature proxy data remains difficult given their limited spatiotemporal resolution. In contrast, past greenhouse gas radiative forcing, causing climate to change, is well known from ice cores. We compare rates of change of anthropogenic forcing with rates of natural greenhouse gas forcing since the Last Glacial Maximum and of solar and volcanic forcing of the last millennium. The smoothing of atmospheric variations by the enclosure process of air into ice is computed with a firn diffusion and enclosure model. The 20th century increase in CO<sub>2</sub> and its radiative forcing occurred more than an order of magnitude faster than any sustained change during the past 22,000 years. The average rate of increase in the radiative forcing not just from CO<sub>2</sub> but from the combination of CO<sub>2</sub>, CH<sub>4</sub>, and N<sub>2</sub>O is larger during the Industrial Era than during any comparable period of at least the past 16,000 years. In addition, the decadal-to-century scale rate of change in anthropogenic forcing is unusually high in the context of the natural forcing variations (solar and volcanoes) of the past millennium. Our analysis implies that global climate change, which is anthropogenic in origin, is progressing at a speed that is unprecedented at least during the last 22,000 years.**

climate change | global warming | greenhouse gas | ice core

Measurements on atmospheric air samples and on air from ice and firn cores reveal an exceptional rise in the concentrations of the anthropogenic greenhouse gases carbon dioxide (CO<sub>2</sub>), methane (CH<sub>4</sub>), and nitrous oxide (N<sub>2</sub>O) over the past two centuries (1) (Fig. 1). Today's concentration of these greenhouse gases are higher than ever measured over the last 650 thousand years (ka), the period covered by the ice core record (2, 3). The recent rise is man-made and causes a perturbation in the radiative balance of the planet (4) leading to global warming. Concerns about the impacts and costs of anthropogenic climate change have led to legally binding agreements to avoid dangerous anthropogenic climate interference (United Nations Framework Convention on Climate Change, 1992).

An important aspect of anthropogenic climate change is its rate of change. It codetermines the magnitude and severity of the impacts on socioeconomic and natural systems. A slow rate of change in forcing and resulting climate permits more time for adaptation than a fast rate of change. However, it remains difficult to quantify rates of past global temperature change because proxy data are of limited spatiotemporal resolution (5). On the other hand, past forcing from well mixed greenhouse gases can be accurately established from ice core data. Although today's unusually high greenhouse gas concentrations are widely discussed, less attention has been paid to the rate of change in their concentrations (6, 7) and in their radiative influence (8). Here, we quantify by how much the rate of change in greenhouse gas concentrations and their radiative forcing is accelerating. We address how current rates of increase compare with past rates as recorded in the ice core records.

The effects of the enclosure process of atmospheric air into ice as well as sample frequency must be taken into account to quantify rates. Before air is enclosed in ice, it enters the porous firn column that is overlying the ice with a thickness of 80–120 m. This leads to two important effects: (i) the age difference between the air entrapped in ice and the surrounding ice and (ii) the age distribution of gas in the air bubbles within one sample. The first effect is taken into account during the construction of the age scales for the ice core. The second effect causes a smoothing of atmospheric variations. In the firn, the air exchanges with the overlying atmosphere through the open pore system by molecular diffusion (9). Therefore, the air isolated in bubbles has not a discrete age, but an age distribution. In addition, and more important at sites with a low accumulation rate, most bubbles are formed at the transition from firn to ice over a depth interval of  $\approx 15$  m, which makes the age distribution even wider. Hence, fast variations in atmospheric trace gases are smoothed in the firn column and recorded in the bubbles as attenuated signals. The width of the age distribution (width at half peak-height) depends on the accumulation rate of snow. It varies from  $\approx 20$  years in cores from sites with a high accumulation rate (10–12) to up to  $\approx 200$  years for low accumulation rate sites such as Dome C, Antarctica. During glacial conditions, when accumulation rate and temperature are lowest, the age distribution in Antarctic cores can be as wide as  $\approx 350$  years.

Today, anthropogenic and natural factors exert changing radiative influences. The concept of radiative forcing is used to compare these (13). Anthropogenic factors are changes in the well mixed greenhouse gases CO<sub>2</sub>, CH<sub>4</sub>, and N<sub>2</sub>O, in halocarbons and SF<sub>6</sub>, in soot, tropospheric ozone (O<sub>3</sub>), and stratospheric water vapor, all causing warming, aerosols, the surface albedo due to land use, and stratospheric O<sub>3</sub> (globally causing cooling). Natural forcing factors include changes in stratospheric sulfate loading caused by explosive volcanism (14) and changes in solar energy output (15, 16).

The goals of this paper are to (i) discuss the recent anthropogenic rise in greenhouse gases in the context of the ice core records, (ii) analyze the rate of change in atmospheric greenhouse gas concentration as recorded in the ice core record, taking into account uncertainties arising from sampling frequency and smoothing occurring during the enclosure of air in firn and ice, and (iii) compare radiative forcing and the recent rate of change in radiative forcing by greenhouse gases and other forcing factors.

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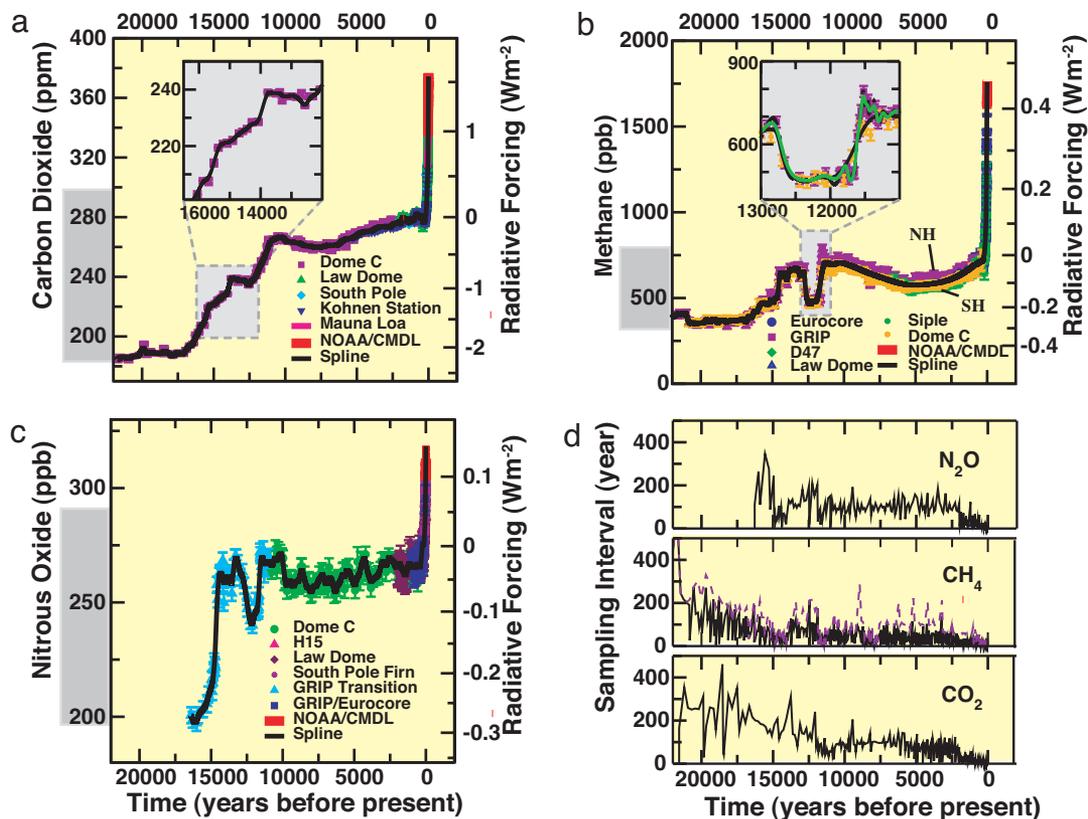
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\*To whom correspondence should be addressed. E-mail: joos@climate.unibe.ch.

†Present address: Department of Earth Sciences, University of Bristol, Wills Memorial Building, Queen's Road, Bristol BS8 1RJ, United Kingdom.

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**Fig. 1.** Evolution of atmospheric CO<sub>2</sub> (a), methane (b), and nitrous oxide (c), and sampling intervals (d) over the past 20,000 years. The gray bar denotes the range of the preindustrial, natural variability in the concentrations of CO<sub>2</sub>, CH<sub>4</sub>, and N<sub>2</sub>O as measured for the past 650,000 years. The green line in *b* Inset is a spline to the Greenland CH<sub>4</sub> data only that preserves multidecadal variability. Sampling intervals for the Greenland CH<sub>4</sub> data are shown by the dashed line in *d*. Data sources are given in *SI Text*.

## Results

**Greenhouse Gas Concentrations and Radiative Forcing.** Atmospheric concentrations of CO<sub>2</sub>, CH<sub>4</sub>, and N<sub>2</sub>O, as measured in the ice cores, have varied within restricted ranges over the past 650 ka before the Industrial Era (Fig. 1) (2, 3). CO<sub>2</sub> concentrations varied naturally between the lowest glacial values of 180 ppm and interglacial values of up to 300 ppm. Natural CH<sub>4</sub> variations were between 320 and 790 ppb, and natural N<sub>2</sub>O variations between 195 and 290 ppb over the last 650 ka. Within the last 200 years, the maximum of the late Quaternary natural range has been exceeded by at least 25% for CO<sub>2</sub>, 120% for CH<sub>4</sub>, and 9% for N<sub>2</sub>O. All three records show effects of the large and increasing growth in anthropogenic emissions during the Industrial Era.

Sample frequency [Fig. 1*d* and supporting information (SI) Fig. 5*d*] in the ice core is generally high enough to capture multidecadal to century scale variations over the past 22 ka and to record multidecadal variations over the past millennium. Many samples have been analyzed around periods of large variations, such as the transition to the Bølling, the end of the Younger Dryas, and the 8.2 ka event, when data spacing is sometimes as short as 30 years (SI Fig. 6).

A gas diffusion and enclosure model (17) is used to calculate the width of the age distribution for the different trace gases and ice cores and the attenuation of atmospheric signals during the enclosure process. The width of the age distribution is  $\approx 200$  years in the Antarctic data for the last transition, whereas the CH<sub>4</sub> data from Greenland are from samples with a small width of the age distribution (20–25 year) (SI Fig. 7). The comparison between the two hemispheric data sets reveals that decadal-to-

century scale concentration changes are recorded also in Antarctic cores, at least over the past 22 ka (Fig. 1*b* and SI Fig. 6).

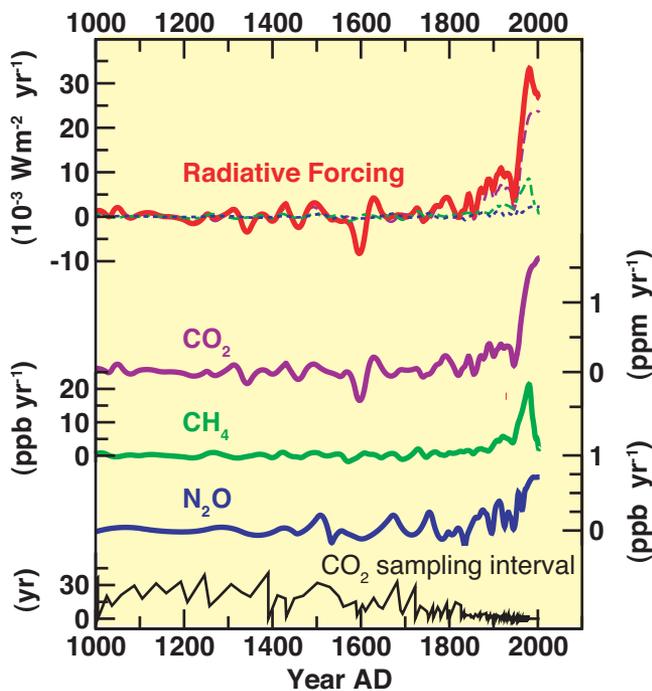
Using the available data and considering the smoothing effect of the ice archive, the data resolution is sufficient to exclude with very high confidence a peak similar to the anthropogenic rise for the past 50,000 years for CO<sub>2</sub>, for the past 80,000 years for CH<sub>4</sub>, and for the past 16,000 years for N<sub>2</sub>O (SI Text).

Until today, the Industrial Era increase in CO<sub>2</sub>, and in the radiative forcing by all three gases, is similar in magnitude to the increase over the transitions from glacial to interglacial periods, but started from an interglacial level and occurred much faster (Fig. 1). Radiative forcing from the three greenhouse gases increased by 2.3 W m<sup>-2</sup> over the 6,000 years of the last glacial–interglacial transition, by 0.3 W m<sup>-2</sup> over the Holocene, and by 2.2 W m<sup>-2</sup> from 1750 to 2004 AD.

Variations in atmospheric CO<sub>2</sub> dominate the radiative forcing by all three gases over the industrial period and glacial interglacial cycles (Fig. 1). Radiative forcing by CO<sub>2</sub> increased by 3.8 W m<sup>-2</sup> since the Last Glacial Maximum, but only by 0.6 and 0.4 W m<sup>-2</sup> for CH<sub>4</sub> and N<sub>2</sub>O. Consequently, most emphasis must be given to variations in CO<sub>2</sub> when reconstructing rates of change in forcing.

**Rates of Change.** We start our discussion of rates of change by determining average rates for distinct periods of the last 20 ka using the simplest approach. The records are divided into 8 and 11 distinct periods of different lengths for CO<sub>2</sub> and CH<sub>4</sub>, respectively. Periods are selected such that the rate of change is approximately steady during each period. An average rate is determined by subtracting the measurement at the end from that





**Fig. 3.** Decadal-scale rates of change for the three greenhouse gases  $\text{N}_2\text{O}$ ,  $\text{CH}_4$ ,  $\text{CO}_2$  and their combined radiative forcing over the past millennium. Rates were computed from the spline fits to the Law Dome (11) and atmospheric data shown in the main panels of *SI Fig. 5*. The thin lines at the top indicates the rate of change in forcing from  $\text{CO}_2$  (violet, dash),  $\text{CH}_4$  (green, dash-dot), and  $\text{N}_2\text{O}$  (blue, dot).

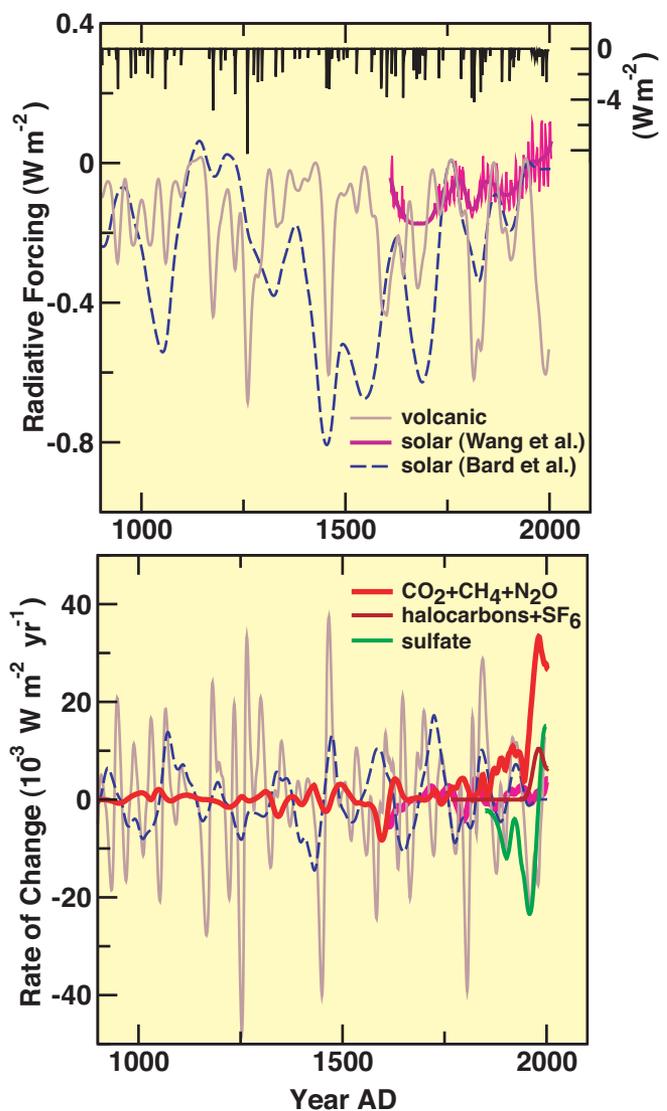
reflected by a slight decrease in the rate of the combined radiative forcing.

### Discussion and Conclusion

Rates of change in greenhouse gas concentrations and in radiative forcing have been reconstructed for the past 20 ky. Uncertainties arise from the attenuation of atmospheric gas signals during the enclosure process of air into ice (17, 20, 21) and from sampling resolution. The results show that the 20th century rise in the concentration of  $\text{CO}_2$  and  $\text{CH}_4$  and in the combined radiative forcing from  $\text{CO}_2$ ,  $\text{CH}_4$ , and  $\text{N}_2\text{O}$  is exceptionally high in the context of the past 20 ka.

Are the rates of anthropogenic forcing higher than those of natural forcing factors? We further analyze radiative forcing from solar irradiance changes and explosive volcanisms as well as from anthropogenic sulfate aerosols and from halocarbons and  $\text{SF}_6$  to put the anthropogenic rise in forcing into the perspective of decadal-to-century scale natural forcing variability of the last millennium (Fig. 4; *SI Text* and *SI Table 3*). Changes in orbital parameters vary over multimillennial periods and were small for the last 1,000 years. Considerable uncertainties exist in the temporal evolution and the magnitude of solar irradiance changes, volcanic forcing, and tropospheric aerosol forcing (4). These uncertainties affect any comparison with the well defined 20th century greenhouse gas record.

The anthropogenic sulfur emission history of ref. 22 shows an increase over the industrial period with a peak in the late 1980s and a subsequent decrease by 24% until 2000 AD. The rate of change in (negative) sulfate aerosol forcing is estimated to increase from  $-23 \times 10^{-3} \text{ W m}^{-2} \text{ yr}^{-1}$  around 1960 to  $+15 \times 10^{-3} \text{ W m}^{-2} \text{ yr}^{-1}$  in year 2000 (Fig. 4b) with an average of  $\approx 3 \times 10^{-3} \text{ W m}^{-2} \text{ yr}^{-1}$  over this period. The high and positive rates estimated for the past years may be biased high as the sulfate burden decreased less than sulfur emissions (23). Forcing



**Fig. 4.** Forcings and their rates of change during the last millennium. (*Upper*) Decadal-scale solar (15, 27) and volcanic (28) forcing during the last millennium expressed relative to 1750 AD. Data were splined with a 40-year cutoff period. The original reconstructions of volcanic forcing (28) (black) and of solar forcing from (15) (thin, magenta) are shown as well. (*Lower*) Rates of change in radiative forcing from explosive volcanism, solar changes, the three greenhouse gases ( $\text{CO}_2$ ,  $\text{CH}_4$ , and  $\text{N}_2\text{O}$ ), sulfate aerosols, halocarbons, and  $\text{SF}_6$ .

from halocarbons and  $\text{SF}_6$  has also increased over the industrial period and the implied rate is  $\approx 8 \times 10^{-3} \text{ W m}^{-2} \text{ yr}^{-1}$  over the past 40 years, with a very recent slowing of growth (Fig. 4b). We estimate that other anthropogenic forcing factors such as ozone, soot, and albedo changes contribute a few  $10^{-3} \text{ W m}^{-2} \text{ yr}^{-1}$  to the recent trend (*SI Text*). Furthermore, the average rate of increase in anthropogenic forcing is estimated to total  $\approx 35 \times 10^{-3} \text{ W m}^{-2} \text{ yr}^{-1}$  for the period 1960–2000. We conclude that the recent decrease in sulfate aerosol emissions as well as emissions of halocarbon and  $\text{SF}_6$  contribute substantially to the current growth trend in anthropogenic forcing.

Turning to natural forcings, there is an ongoing debate on the importance of solar forcing. The latest summaries of the various uncertainties can be found in two recent reviews (16, 24). Model-based analyses comparing results from simulations with different magnitudes of solar forcing and the Northern Hemisphere temperature and atmospheric  $\text{CO}_2$  proxy records suggest



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