

Global and regional drivers of accelerating CO₂ emissions

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CO₂ emissions from fossil-fuel burning and industrial processes have been accelerating at a global scale, with their growth rate increasing from 1.1% y⁻¹ for 1990–1999 to >3% y⁻¹ for 2000–2004. The emissions growth rate since 2000 was greater than for the most fossil-fuel intensive of the Intergovernmental Panel on Climate Change emissions scenarios developed in the late 1990s. Global emissions growth since 2000 was driven by a cessation or reversal of earlier declining trends in the energy intensity of gross domestic product (GDP) (energy/GDP) and the carbon intensity of energy (emissions/energy), coupled with continuing increases in population and per-capita GDP. Nearly constant or slightly increasing trends in the carbon intensity of energy have been recently observed in both developed and developing regions. No region is decarbonizing its energy supply. The growth rate in emissions is strongest in rapidly developing economies, particularly China. Together, the developing and least-developed economies (forming 80% of the world's population) accounted for 73% of global emissions growth in 2004 but only 41% of global emissions and only 23% of global cumulative emissions since the mid-18th century. The results have implications for global equity.

carbon intensity of economy | carbon intensity of energy | emissions scenarios | fossil fuels | Kaya identity

Atmospheric CO₂ presently contributes ≈63% of the gaseous radiative forcing responsible for anthropogenic climate change (1). The mean global atmospheric CO₂ concentration has increased from 280 ppm in the 1700s to 380 ppm in 2005, at a progressively faster rate each decade (2, 3).^{‡‡} This growth is governed by the global budget of atmospheric CO₂ (4), which includes two major anthropogenic forcing fluxes: (i) CO₂ emissions from fossil-fuel combustion and industrial processes and (ii) the CO₂ flux from land-use change, mainly land clearing. A survey of trends in the atmospheric CO₂ budget (3) shows these two fluxes were, respectively, 7.9 gigatonnes of carbon (GtC) y⁻¹ and 1.5 GtC y⁻¹ in 2005 with the former growing rapidly over recent years, and the latter remaining nearly steady.

This paper is focused on CO₂ emissions from fossil-fuel combustion and industrial processes, the dominant anthropogenic forcing flux. We undertake a regionalized analysis of trends in emissions and their demographic, economic, and technological drivers, using the Kaya identity (defined below) and annual time-series data on national emissions, population, energy consumption, and gross domestic product (GDP). Understanding the observed magnitudes and patterns of the factors influencing global CO₂ emissions is a prerequisite for the prediction of future climate and earth system changes and for human governance of climate change and the earth system. Although the needs for both understanding and governance have been emerging for decades (as demonstrated by the United Nations Framework Convention on Climate Change in 1992 and the Kyoto Protocol in 1997), it is now becoming widely perceived that climate change is an urgent challenge requiring globally

concerted action, that a broad portfolio of mitigation measures is required (5, 6), and that mitigation is not only feasible but highly desirable on economic as well as social and ecological grounds (7).

The global CO₂ emission flux from fossil fuel combustion and industrial processes (F) includes contributions from seven sources: national-level combustion of solid, liquid, and gaseous fuels; flaring of gas from wells and industrial processes; cement production; oxidation of nonfuel hydrocarbons; and fuel from “international bunkers” used for shipping and air transport (separated because it is often not included in national inventories). Hence

$$F = F_{\text{Solid}} + F_{\text{Liquid}} + F_{\text{Gas}} + F_{\text{Flare}} + F_{\text{Cement}} + F_{\text{NonFuelHC}} + F_{\text{Bunkers}}, \quad [1]$$

$\approx 35\%$ $\approx 36\%$ $\approx 20\%$ $<1\%$
 $\approx 3\%$ $<1\%$ $\approx 4\%$

where the fractional contribution of each source to the total F for 2000–2004 is indicated.

The Kaya identity^{§§} (8, 9) expresses the global F as a product of four driving factors:

$$F = P \left(\frac{G}{P} \right) \left(\frac{E}{G} \right) \left(\frac{F}{E} \right) = Pgef, \quad [2]$$

where P is global population, G is world GDP or gross world product, E is global primary energy consumption, $g = G/P$ is the per-capita world GDP, $e = E/G$ is the energy intensity of world GDP, and $f = F/E$ is the carbon intensity of energy. Upper- and lowercase symbols distinguish extensive and intensive variables,

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Abbreviations: GDP, gross domestic product; MER, market exchange rate; PPP, purchasing power parity; IPCC, Intergovernmental Panel on Climate Change; EU, European Union; FSU, Former Soviet Union; D1, developed countries; D2, developing countries; D3, least-developed countries; CDIAC, U.S. Department of Energy Carbon Dioxide Information and Analysis Center; EIA, U.S. Department of Energy Energy Information Administration.

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^{‡‡}CO₂ data are available at www.cmdl.noaa.gov/gmd/ccgg/trends.

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respectively. Combining e and f into the carbon intensity of GDP ($h = F/G = ef$), the Kaya identity can also be written as

$$F = P \left(\frac{G}{P} \right) \left(\frac{F}{G} \right) = Pgh. \quad [3]$$

Defining the proportional growth rate of a quantity $X(t)$ as $r(X) = X^{-1}dX/dt$ (with units $[\text{time}]^{-1}$), the counterpart of the Kaya identity for proportional growth rates is

$$\begin{aligned} r(F) &= r(P) + r(g) + r(e) + r(f) \\ &= r(P) + r(g) + r(h), \end{aligned} \quad [4]$$

which is an exact, not linearized, result.

The world can be disaggregated into regions (distinguished by a subscript i) with emission F_i , population P_i , GDP G_i , energy consumption E_i , and regional intensities $g_i = G_i/P_i$, $e_i = E_i/G_i$, $f_i = F_i/E_i$, and $h_i = F_i/G_i = e_i f_i$. Writing a Kaya identity for each region, the global emission F can be expressed by summation over regions as:

$$F = \sum_i F_i = \sum_i P_i g_i e_i f_i = \sum_i P_i g_i h_i, \quad [5]$$

and regional contributions to the proportional growth rate in global emissions, $r(F)$, are

$$r(F) = \sum_i \left(\frac{F_i}{F} \right) r(F_i). \quad [6]$$

This analysis uses nine noncontiguous regions that span the globe and cluster nations by their emissions and economic profiles. The regions comprise four individual nations (U.S., China, Japan, and India, identified separately because of their significance as emitters); the European Union (EU); the nations of the Former Soviet Union (FSU); and three regions spanning the rest of the world, consisting respectively of developed (D1), developing (D2), and least-developed (D3) countries, excluding countries in other regions.

GDP is defined and measured by using either market exchange rates (MER) or purchasing power parity (PPP), respectively denoted as G_M and G_P . The PPP definition gives more weight to developing economies. Consequently, wealth disparities are greater when measured by G_M than G_P , and the growth rate of G_P is greater than that of G_M [supporting information (SI) Fig. 6].

Our measure of E_i is “commercial” primary energy, including (i) fossil fuels, (ii) nuclear, and (iii) renewables (hydro, solar, wind, geothermal, and biomass) when used to generate electricity. Total primary energy additionally includes (iv) other energy from renewables, mainly as heat from biomass. Contribution iv can be large in developing regions, but it is not included in E_i except in the U.S., where it makes a small (<4%) contribution (SI Text, Primary Energy).

Results

Global Emissions. A sharp acceleration in global emissions occurred in the early 2000s (Fig. 1 Lower). This trend is evident in two data sets (Materials and Methods): from U.S. Department of Energy Energy Information Administration (EIA) data, the proportional growth rate in global emissions [$r(F) = (1/F)dF/dt$] was $1.1\% \text{ y}^{-1}$ for the period 1990–1999 inclusive, whereas for 2000–2004, the same growth rate was 3.2% . From U.S. Department of Energy Carbon Dioxide Information and Analysis Center (CDIAC) data, growth rates were $1.0\% \text{ y}^{-1}$ through the 1990s and $3.3\% \text{ y}^{-1}$ for 2000–2005. The small difference arises mainly from differences in estimated emissions from China for 1996–2002 (Materials and Methods).

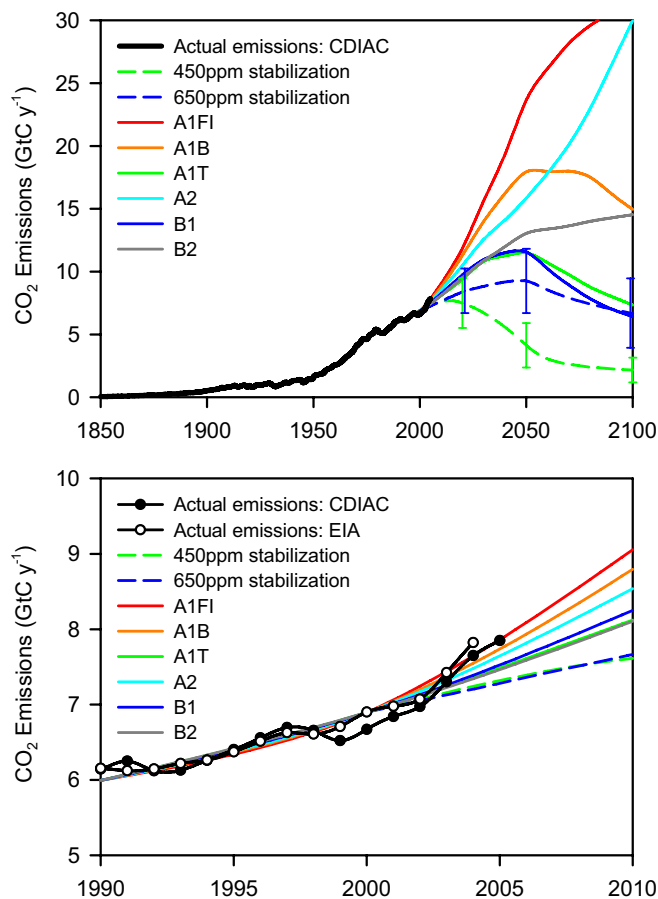


Fig. 1. Observed global CO₂ emissions including all terms in Eq. 1, from both the EIA (1980–2004) and global CDIAC (1751–2005) data, compared with emissions scenarios (8) and stabilization trajectories (10–12). EIA emissions data are normalized to same mean as CDIAC data for 1990–1999, to account for omission of F_{Cement} in EIA data (see Materials and Methods). The 2004 and 2005 points in the CDIAC data set are provisional. The six IPCC scenarios (8) are spline fits to projections (initialized with observations for 1990) of possible future emissions for four scenario families, A1, A2, B1, and B2, which emphasize globalized vs. regionalized development on the A,B axis and economic growth vs. environmental stewardship on the 1,2 axis. Three variants of the A1 (globalized, economically oriented) scenario lead to different emissions trajectories: A1FI (intensive dependence on fossil fuels), A1T (alternative technologies largely replace fossil fuels), and A1B (balanced energy supply between fossil fuels and alternatives). The stabilization trajectories are spline fits approximating the average from two models (11, 12), which give similar results. They include uncertainty because the emissions pathway to a given stabilization target is not unique.

Fig. 1 compares observed global emissions (including all terms in Eq. 1) with six Intergovernmental Panel on Climate Change (IPCC) emissions scenarios (8) and also with stabilization trajectories describing emissions pathways for stabilization of atmospheric CO₂ at 450 and 650 ppm (10–12). Observed emissions were at the upper edge of the envelope of IPCC emissions scenarios. The actual emissions trajectory since 2000 was close to the highest-emission scenario in the envelope, A1FI. More importantly, the emissions growth rate since 2000 exceeded that for the A1FI scenario. Emissions since 2000 were also far above the mean stabilization trajectories for both 450 and 650 ppm.

A breakdown of emissions among sources shows that solid, liquid, and gas fuels contributed (for 2000–2004) $\approx 35\%$, 36% , and 20% , respectively, to global emissions (Eq. 1). However, this distribution varied strongly among regions: solid (mainly coal) fuels made up a larger and more rapidly growing share of

nia) are now members of the EU. European nations who are not members of the EU (Norway and Switzerland) were placed in group D1. Regions D1 and D3 were defined by using United Nations Statistics Division classifications. Region D2 includes all other nations.

Comparisons were made among three different emissions data sets: CDIAC global total emissions, CDIAC country-level emissions, and EIA country-level emissions. These revealed small discrepancies with two origins. First, different data sets include different components of total emissions, Eq. 1. The CDIAC global total includes all terms, CDIAC country-level data omit F_{Bunkers} and $F_{\text{NonFuelHC}}$, and EIA country-level data omit F_{Cement} but include F_{Bunkers} by accounting at country of purchase. The net effect is that the EIA and CDIAC country-level data yield total emissions (by summation) that are within 1% of each other, although they include slightly different components of Eq. 1, and the CDIAC global total is 4–5% larger than both sums over countries. The second kind of

discrepancy arises from differences at the country level, the main issue being with data for China. Emissions for China from the EIA and CDIAC data sets both show a significant slowdown in the late 1990s, which is a recognized event (16) associated mainly with closure of small factories and power plants and with policies to improve energy efficiency (17). However, the CDIAC data suggest a much larger emissions decline from 1996 to 2002 than the EIA data (SI Fig. 10). The CDIAC emissions estimates are based on the UN energy data set, which is currently undergoing revisions for China. Therefore, we use EIA as the primary source for emissions data subsequent to 1980.

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