Global and regional drivers of accelerating CO_2 emissions

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Author contributions: MRR, PC, CLQ, JGC, CBF designed research; MRR, GM, PC performed research; GM provided data; MRR, PC, GK analysed data; MRR, GM, CLQ, CBF wrote paper.

Category Information: Sustainability Science

Manuscript Information: 30 text pages; 1 table; 5 figures; 182 words in abstract; 45747 characters in paper (including allowances for equations, tables, figures but excluding Supporting Information).

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 nations region; D2 – Developing nations region; D3 – Least developed nations region; CDIAC – Carbon Dioxide Information and Analysis Center; EIA – Energy Information Administration; UNSD – United Nations Statistics Division; WEO – World Economic Outlook (International Monetary Fund)

Abstract

CO_2 emissions from fossil-fuel burning and industrial processes have been accelerating at global scale, with their growth rate increasing from 1.1% y^{-1} for 1990-1999 to over 3% y^{-1} for 2000-2004. The emissions growth rate since 2000 was greater than that for the most fossil-fuel-intensive of the IPCC 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 GDP-gross domestic product (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 are recently observed in both developed and developing regions. No region is decarbonising 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-eighteenth century. The results have implications for global equity.

Introduction

Atmospheric CO_2 presently contributes about 63% of the gaseous radiative forcing responsible for anthropogenic climate change (1). The mean global atmospheric CO_2 concentration has increased from 280 ppm in the 1700s to 380 ppm in 2005, at a progressively faster rate each decade (2, 3, 4, 5). This growth is governed by the global budget of atmospheric CO_2 (6), which includes two major anthropogenic forcing fluxes: (a) CO_2 emissions from fossil-fuel combustion and industrial processes, and (b) the CO_2 flux from land use change, mainly land clearing. A survey of trends in the atmospheric CO_2 budget (5) shows that these two fluxes were respectively 7.9 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 focussed on CO_2 emissions from fossil-fuel combustion and industrial processes, the dominant anthropogenic forcing flux. We undertake a regionalised 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 CO_2 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 (7, 8), 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 (9, 10), and that mitigation is not only feasible but highly desirable on economic as well as social and ecological grounds (11, 12).

The global CO_2 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 non-fuel hydrocarbons, and fuel from "international bunkers" used for shipping and air transport (separated because it is often not included in national inventories). Hence

$$F = \underset{\sim 35\%}{F_{Solid}} + \underset{\sim 36\%}{F_{Liquid}} + \underset{\sim 20\%}{F_{Gas}} + \underset{<1\%}{F_{Flare}} + \underset{\sim 3\%}{F_{Cement}} + \underset{<1\%}{F_{NonFuelHC}} + \underset{\sim 4\%}{F_{Bunkers}} \quad (1)$$

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

The Kaya identity (13, 14, 15) 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-case and lower-case symbols distinguish extensive and intensive variables, 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 [time]$^{-1}$), the counterpart of the Kaya identity for proportional growth rates is

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

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

$$r(F) = \sum_i \left(\frac{F_i}{F}\right) r(F_i) \qquad (6)$$

This analysis uses nine non-contiguous regions which span the globe and cluster nations by their emissions and economic profiles. The regions comprise four individual nations (USA, 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 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 1).

Our measure of E_i is "commercial" primary energy, including (a) fossil fuels, (b) nuclear, and (c) renewables (hydro, solar, wind, geothermal, biomass) when used to generate electricity. Total primary energy additionally includes (d) other energy from renewables, mainly as heat from biomass. Contribution (d) can be large in developing regions, but it is not included in E_i except in the USA, where it makes a small (< 4%) contribution (Supporting Information 2).

Results

Global emissions. A sharp acceleration in global emissions occurred in the early 2000s (Figure 1, lower panel). This trend is evident in two data sets (Materials and Methods): from EIA data, the proportional growth rate in global emissions [$r(F) = (1/F)dF/dt$] was 1.1% y^{-1} for the period 1990-1999 inclusive, whereas for 2000-2004 the same growth rate was 3.2%. From CDIAC data, growth rates were 1.0% y^{-1} through the 1990s and 3.3% y^{-1} for 2000-2005. The small difference arises mainly from differences in estimated emissions from China for 1996-2002 (Materials and Methods).

Figure 1 compares observed global emissions (including all terms in Equation (1)) with six IPCC emissions scenarios (14), and also with stabilisation trajectories describing emissions pathways for stabilisation of atmospheric CO_2 at 450 ppm and 650 ppm (16, 17, 18). 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 stabilisation trajectories for both 450 ppm and 650 ppm.

A breakdown of emissions among sources shows that solid, liquid and gas fuels contributed (for 2000-2004) about 35%, 36% and 20%, respectively, to global emissions (Equation (1)). However, this distribution varied strongly among regions: solid (mainly coal) fuels made up a larger and more rapidly growing share of emissions in developing regions (the sum of China, India, D2 and D3) than in developed regions (USA, EU, Japan, D1), and the FSU region had a much stronger reliance on gas than the world average (Supporting Information 3).

To diagnose drivers of trends in global emissions, Figure 2 superimposes time series for 1980-2004 of the Kaya factors F, P, g, e, f and $h = ef$ (Equations (2) and (3)). The left and right panels respectively use the MER and PPP forms of GDP (G_M and G_P) to calculate intensities. All quantities are normalised to 1 in the year 1990, to show the relative contributions of changes in Kaya factors to changes in emissions. Table 1 gives recent (2004) values without normalisation.

In the left (MER-based) panel of Figure 2, the Kaya identity is $F = Pg_Me_Mf = Pg_Mh_M$ (with $g_M = G_M/P$, $e_M = E/G_M$, $h_M = F/G_M$). The increase in the growth rate of F after 2000 is clear. Before 2000, F increased as a result of increases in both P and g_M at roughly equal rates, offset by a decrease in e_M, with f declining very slowly. Therefore, $h_M = e_Mf$ declined slightly more quickly than e_M. After 2000, the increases in P and g_M continued at about their pre-2000 rates but e_M and f (and therefore h_M) ceased to decrease, leading to a substantial increase in the growth rate of F. In fact, both e_M and f have increased since 2002. Similar trends are evident in the right (PPP based) panel of Figure 2, using the Kaya identity $F = Pg_Pe_Pf = Pg_Ph_P$, (with $g_P = G_P/P$, $e_P = E/G_P$, $h_P = F/G_P$). The long-term (since 1980) rate of increase of g_P and the rates of decrease of e_P and h_P were all larger than for their counterparts g_M, e_M, h_M, associated with the higher global growth rate of G_P than of G_M (Supporting Information 1). There was a change in the trajectory of e_P after 2000, similar to that for e_M but superimposed on a larger long-term rate of decrease. Hence, both panels identify the driver of the increase in the growth rate of global emissions after 2000 as a combination of reductions or reversals in long-term decreasing trends in the global carbon intensity of energy (f) and energy intensity of GDP (e).

Regional emissions. The regional distribution of emissions (Figure 3) is similar to that of (commercial) primary energy consumption (E_i) but very different from that of population (P_i), with F_i and E_i weighted toward developed regions and P_i toward developing regions. Drivers of regional emissions are shown in Figure 4 by plotting the normalised factors in the nine regional Kaya identities, using GDP (PPP). Equivalent plots with GDP (MER) are nearly identical (Supporting Information 4).

In the developed regions (USA, Europe, Japan, D1), F_i increased from 1980 to 2004 as a result of relatively rapid growth in mean income (g_i) and slow growth in population (P_i), offset in most regions by decreases in the energy intensity of GDP (e_i). Declines in e_i indicate a progressive decoupling in most developed regions between energy use and GDP growth. The carbon intensity of energy (f_i) remained nearly steady.

In the FSU, emissions decreased through the 1990s because of the fall in economic activity following the collapse of the Soviet Union. Incomes (g_i) decreased in parallel with emissions (F_i), and a shift towards resource-based economic activities led to an increase in e_i and h_i. In the late 1990s incomes started to rise again, but increases in emissions were slowed by more efficient use of energy from 2000 on, due to higher prices and shortages because of increasing exports.

In China, g_i rose rapidly and P_i slowly over the whole period 1980-2004. Progressive decoupling of income growth from energy consumption (declining e_i) was achieved up to about 2002, through improvements in energy efficiency during the transition to a market based economy. Since the early 2000s there has been a recent rapid growth in emissions, associated with very high growth rates in incomes (g_i) and a reversal of earlier declines in e_i.

In other developing regions (India, D2, D3), increases in F_i were driven by a combination of increases in P_i and g_i, with no strong trends in e_i or f_i. Growth in emissions (F_i) exceeded growth in income (g_i). Unlike China and the developed countries, strong technological improvements in energy efficiency have not yet occurred in these regions, with the exception of India over the last few years where e_i declined.

Differences in intensities across regions are both large (Table 1) and persistent in time. There are enormous differences in income ($g_i = G_i/P_i$), the variation being smaller (though still large) for g_{Pi} than for g_{Mi}. The energy intensity and carbon intensity of GDP ($e_i = E_i/G_i$ and $h_i = F_i/G_i = e_i f_i$) vary significantly between regions, though less than for income (g_i). The carbon intensity of energy ($f_i = F_i/E_i$) varies much less than other intensities: for most regions it is between 15 and 20 gC/MJ, though for China and India it is somewhat higher, over 20 gC/MJ. In time, f_i has decreased slowly from 1980 to about 2000 as a global average (Figure 2) and in most regions (Figure 4). This indicates that the commercial energy supply mix has changed only slowly, even on a regional level. The global average f has increased slightly since 2002.

The regional per-capita emissions $F_i/P_i = g_i h_i$ and per-capita primary energy consumption $E_i/P_i = g_i e_i$ are important indicators of global equity. Both quantities vary greatly across regions but much less in time (Table 1, Supporting Information 5). The inter-region range, a factor of about 50, extends from the USA (for which both quantities are about 5 times the global average) to the D3 region (for which they about 1/10 of the global average). From 1980 to 1999, global average per-capita emissions ($F/P = gh$) and per-capita primary energy consumption ($E/P = ge$) were both nearly steady at about 1.1 tC/y/person and 2 kW/person respectively, but F/P rose by 8% and E/P by 7% over the five years 2000-2004.

Temporal perspectives. In the period 2000-2004, developing countries had a greater share of emissions growth than of emissions themselves (Figure 3). Here we extend this observation by considering cumulative emissions throughout the industrial era (taken to start in 1751). The global cumulative fossil-fuel emission $C(t)$ (in GtC) is defined as the time integral of the global emission flux $F(t)$ from 1751 to t. Regional cumulative emissions $C_i(t)$ are defined similarly.

Figure 5 compares the relative contributions in 2004 of the nine regions to the global cumulative emission $C(t)$, the emission flux $F(t)$ (the first derivative of $C(t)$), the emissions growth rate (the second derivative of $C(t)$), and population. The measure of regional emissions growth used here is the weighted proportional growth rate $(F_i/F)r(F_i)$, which shows the contribution of each region to the global $r(F)$ (Equation (6)). In 2004 the developed regions contributed most to cumulative emissions and least to emissions growth, and *vice versa* for developing regions. China in 2004 had a larger than pro-rata share (on a population basis) of the emissions growth, but still a smaller than pro-rata share of actual emissions and a very small share of cumulative emissions. India and the D2 and D3 regions had smaller than pro-rata shares of emissions measures on all time scales (growth, actual emissions and cumulative emissions).

Discussion

CO_2 emissions need to be considered in the context of the whole carbon cycle. Of the total cumulative anthropogenic CO_2 emission from both fossil fuels and land use change, less than half remains in the atmosphere, the rest having been taken up by land and ocean sinks (6, Supporting Information 6). For the recent period 2000-2005, the fraction of total anthropogenic CO_2 emissions remaining in the atmosphere (the airborne fraction) was 0.48. This fraction has increased slowly with time (5), implying a slight weakening of sinks relative to emissions. However, the dominant factor accounting for the recent rapid growth in atmospheric CO_2 (over 2 ppm y^{-1}) is high and rising emissions, mostly from fossil fuels.

The strong global fossil-fuel emissions growth since 2000 was driven not only by long-term increases in population (P) and per-capita global GDP (g), but also by a cessation or reversal of earlier declining trends in the energy intensity of GDP (e) and the carbon intensity of energy (f). In particular, steady or slightly increasing recent trends in f occurred in both developed and developing regions. In this sense, no region is decarbonising its energy supply.

Continuous decreases in both e and f (and therefore in carbon intensity of GDP, $h = ef$) are postulated in all IPCC emissions scenarios to 2100 (14), so that the predicted rate of global emissions growth is less than the economic growth rate. Without these postulated decreases, predicted emissions over the coming century would be up to several times greater than those from current emissions scenarios (19). In the unfolding reality since 2000, the global average f has actually increased and there has not been a compensating faster decrease in e. Consequently, there has been a cessation of the earlier declining trend in h. This has meant that even the more fossil-fuel-intensive IPCC scenarios underestimated actual emissions growth during this period.

The recent growth rate in emissions was strongest in rapidly developing economies, particularly China, because of very strong economic growth (g_i) coupled with post-2000 increases in e_i, f_i and therefore $h_i = e_i f_i$. These trends reflect differences in trajectories between developed and developing nations: developed nations have used two centuries of fossil-fuel emissions to achieve their present economic status, while developing nations are currently experiencing intensive development with a high energy requirement, much of the demand being met by fossil fuels. A significant factor is the physical movement of energy-intensive activities from developed to developing countries (20, 21) with increasing globalisation of the economy.

Finally, we note (Figure 5) that the developing and least developed economies (China, India, D2 and D3) representing 80% of the world's population) accounted for 73% of global emissions *growth* in 2004. However, they accounted for only 41% of global *emissions* in that year, and only 23% of global *cumulative emissions* since the start of the industrial revolution. A long-term (multi-decadal) perspective on emissions is essential because of the long atmospheric residence time of CO_2. Therefore, Figure 5 has implications for long-term global equity and for burden sharing in global responses to climate change.

Materials and Methods

Annual time series at national and thence regional scale (for 1980-2004 except where otherwise stated) were assembled for CO_2 emissions (F_i), population (P_i), GDP (G_{Mi} and G_{Pi}) and primary energy consumption (E_i), from four public sources (Supporting Information 7): the Energy Information Administration, US Department of Energy (EIA), for F_i and E_i; the Carbon Dioxide Information and Analysis Center, US Department of Energy (CDIAC) (22, 23), for F_i (1751-2005); the United Nations Statistics Division (UNSD) for P_i and G_{Mi}; and the World Economic Outlook of the International Monetary Fund (WEO) for G_{Pi}. We inferred G_{Pi} from country shares of global G_P and the annual growth rate of global G_P in constant-price US dollars, taking $G_M = G_P$ in 2000.

We analysed nine non-contiguous regions (USA, EU, Japan, D1, FSU, China, India, D2, D3; see Introduction and Supporting Information 8). Because only aggregated data were available for FSU provinces before 1990, all new countries issuing from the FSU around 1990 remained allocated to the FSU region after that date, even though some (Estonia, Latvia, Lithuania) are now members of the EU. European nations who are not members of the EU (Norway, Switzerland) were placed in group D1. Regions D1 and D3 were defined using UNSD classifications. Region D2 includes all other nations.

Comparisons were made between three different emissions datasets: CDIAC global total emissions, CDIAC country-level emissions, and EIA country-level emissions. These revealed small discrepancies with two origins. First, different datasets include different components of total emissions, Equation (1). The CDIAC global total includes all terms, CDIAC country-level data omit $F_{Bunkers}$ and $F_{NonFuelHC}$, 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) which are within 1% of each other although they include slightly different components of Equation (1), and the CDIAC global total is 4-5% larger than both sums over countries. The second kind of discrepancy arises from differences at country level, the main issue being with data for China. Emissions for China from the EIA and CDIAC datasets both show a significant slowdown in the late 1990s, which is a recognised event (24) associated mainly with closure of small factories and power plants and with policies to improve energy efficiency (25). However, the CDIAC data suggest a much larger emissions decline for from 1996 to 2002 than the EIA data (Supporting Information 9). The CDIAC emissions estimates are based on the UN energy dataset, which is currently undergoing revisions for China. Therefore we use EIA as the primary source for emissions data subsequent to 1980.

Acknowledgments

This work has been a collaboration under the Global Carbon Project (GCP, www.globalcarbonproject.org) of the Earth System Science Partnership (www.essp.org). Support for the GCP from the Australian Climate Change Science Program is appreciated. We thank Mr Peter Briggs for assistance with preparation of figures.

References

See end of paper.

Figure Legends and Table Caption

Figure 1: Observed global CO_2 emissions including all terms in Equation (1), from both the EIA (1980-2004) and global CDIAC (1751-2005) data, compared with emissions scenarios (14) and stabilisation trajectories (16, 17, 18). EIA emissions data are normalised 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 dataset are provisional. The six IPCC scenarios (14) are spline fits to projections (initialised with observations for 1990) of possible future emissions for four scenario families, A1, A2, B1 and B2, which emphasise globalised versus regionalised development on the A,B axis and economic growth versus environmental stewardship on the 1,2 axis. Three variants of the A1 (globalised, 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 stabilisation trajectories (16) are spline fits approximating the average from two models (17, 18) which give similar results. They include uncertainty because the emissions pathway to a given stabilisation target is not unique.

Figure 2: Factors in the Kaya identity, $F = Pgef = Pgh$, as global averages. All quantities are normalised to 1 at 1990. Intensities are calculated using G_M (left) and G_P (right). In each panel, the black line (F) is the product of the red (P), orange (g), green (e) and light blue (f) lines (Equation (2)), or equivalently of the red (P), orange (g), dark blue (h) lines (Equation (3)). Since $h = ef$, the dark blue line is the product of the green and light blue lines. Sources as in Table 1.

Figure 3: Fossil-fuel CO_2 emissions (MtC y^{-1}), for nine regions. Data source: EIA.

Figure 4: Factors in the Kaya identity, $F = Pgef = Pgh$, for nine regions. All quantities are normalised to 1 at 1990. Intensities are calculated with G_{Pi} (PPP). For FSU, normalising G_{Pi} in 1990 was back-extrapolated. Other details as for Figure 2.

Figure 5: Relative contributions of nine regions to cumulative global emissions (1751-2004), current global emission flux (2004), global emissions growth rate (5-year smoothed for 2000-

2004) and global population (2004). Data sources as in Table 1, with pre-1980 cumulative emissions from CDIAC.

Table 1: Values of extensive and intensive variables in 2004. All dollar amounts ($) are in constant-price (2000) US dollars. Data sources: EIA (F_i, E_i), UNSD (P_i, G_{Mi}), WEO (G_{Pi}).

Tables

	F_i	P_i	E_i	G_{Mi}	G_{Pi}	$g_{Pi} = G_{Pi}/P_i$	$e_{Pi} = E_i/G_{Pi}$	$f_i = F_i/E_i$	$h_{Pi} = F_i/G_{Pi}$	F_i/P_i	E_i/P_i
	MtC/y	million	EJ/y	G$/y	G$/y	k$/y	MJ/$	gC/MJ	gC/$	tC/y	kW
USA	1617	295	95.4	9768	7453	25.23	12.80	16.95	217.0	5.47	10.24
EU	1119	437	70.8	10479	7623	17.45	9.29	15.81	146.8	2.56	5.14
Japan	344	128	21.4	4036	2412	18.85	8.89	16.05	142.7	2.69	5.31
D1	578	127	37.3	2941	2553	20.14	14.63	15.47	226.3	4.56	9.34
FSU	696	285	42.8	726	1423	4.99	30.08	16.25	488.7	2.44	4.76
China	1306	1293	57.5	1734	5518	4.27	10.43	22.70	236.6	1.01	1.41
India	304	1087	14.6	777	2130	1.96	6.86	20.77	142.5	0.28	0.43
D2	1375	2020	80.9	4280	7044	3.49	11.49	16.99	195.2	0.68	1.27
D3	37	656	2.2	255	609	0.93	3.66	16.78	61.4	0.06	0.11
World	7376	6328	423.1	34997	36765	5.81	11.51	17.43	200.6	1.17	2.12

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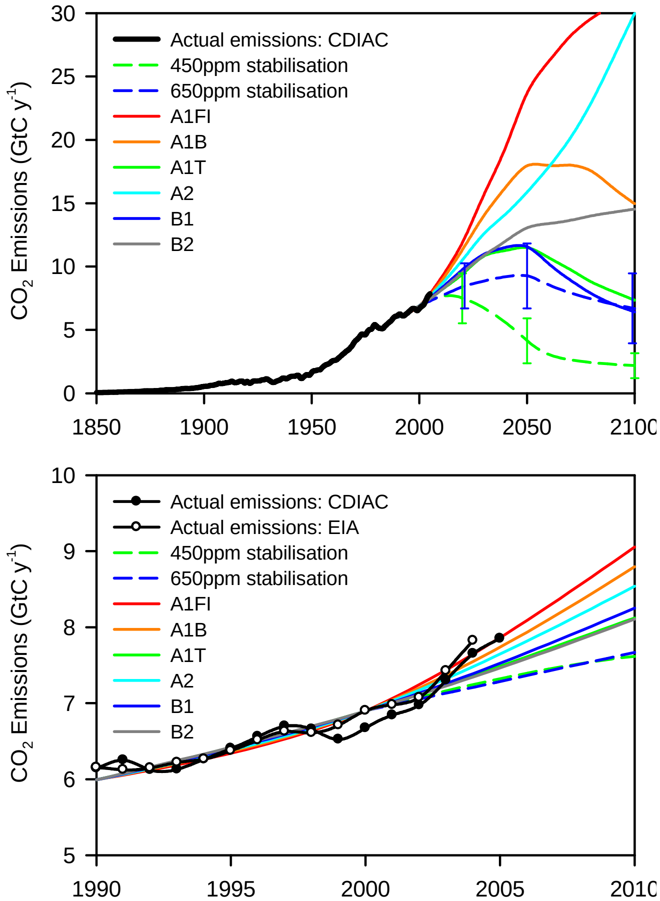
Figures



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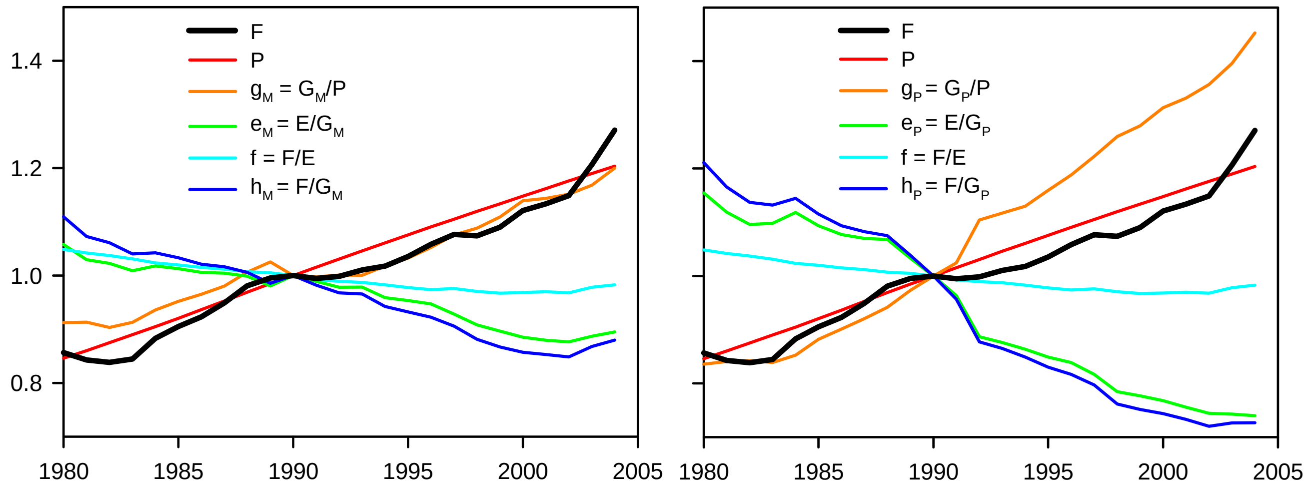

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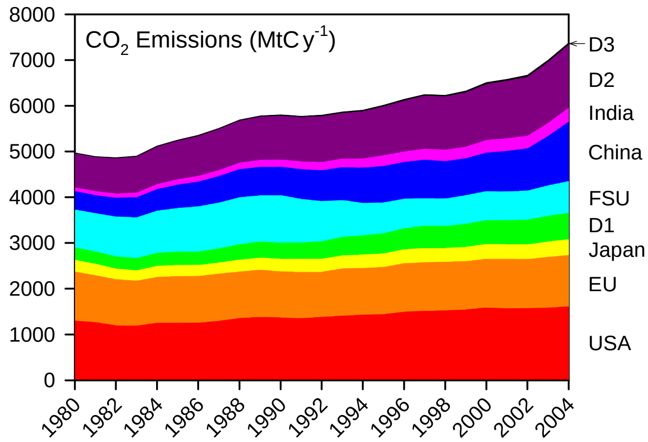

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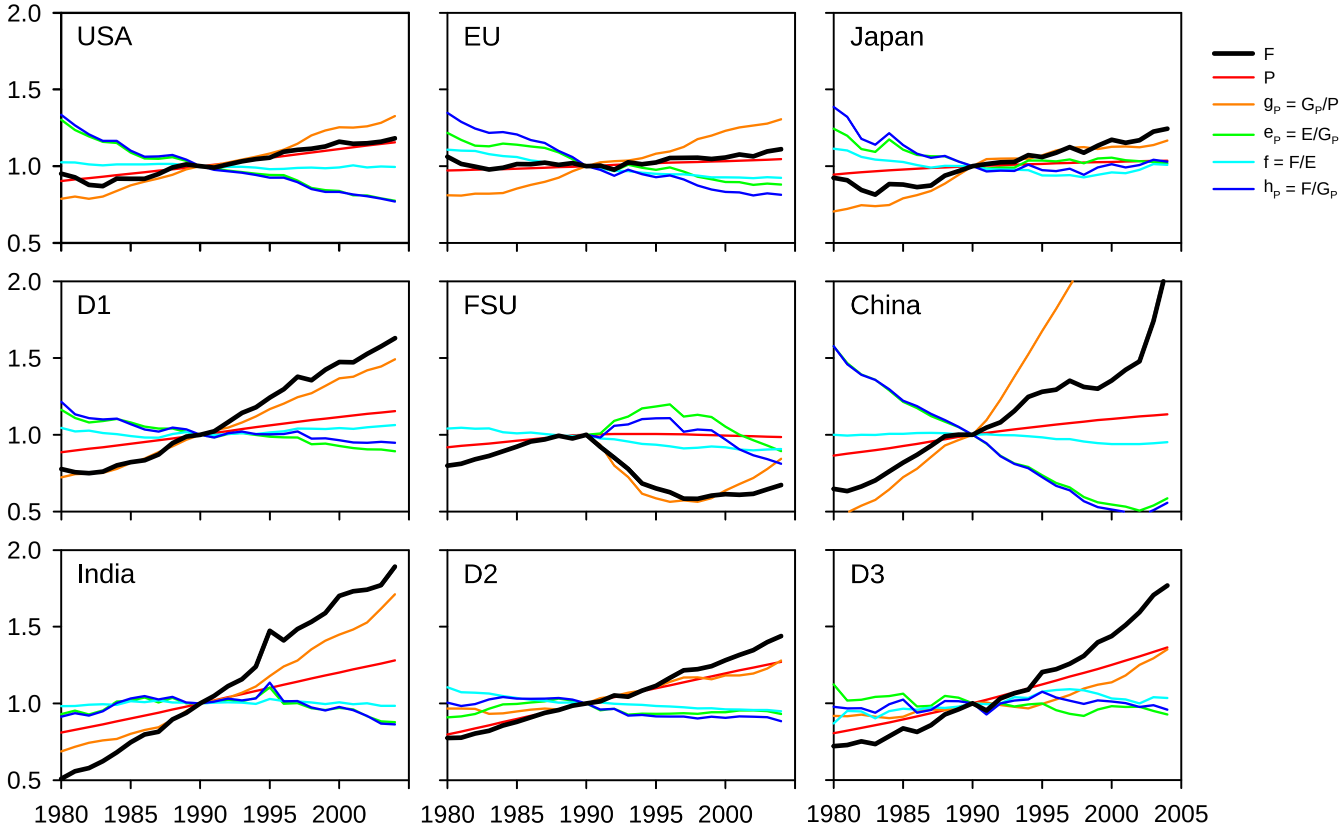


Figure 4: Factors in the Kaya identity, $F = Pgef = Pgh$, for nine regions. All quantities are normalised to 1 at 1990. Intensities are calculated with G_{Pi} (PPP). For FSU, normalising G_{Pi} in 1990 was back-extrapolated. Other details as for Figure 2.

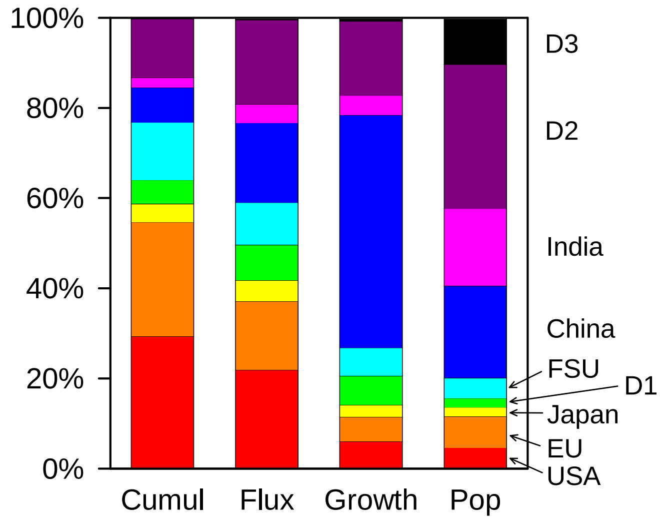
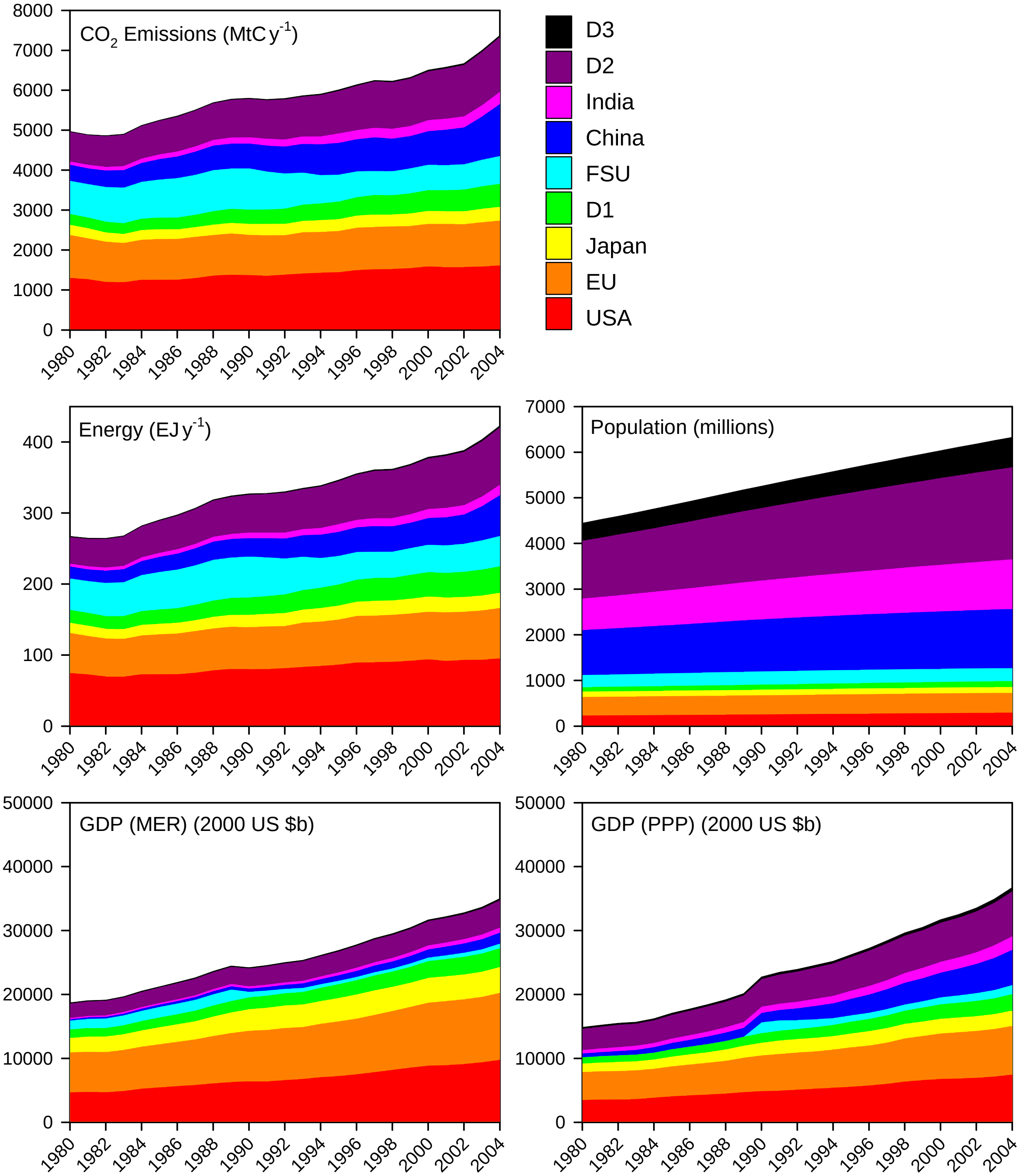


Figure 5: Relative contributions of nine regions to cumulative global emissions (1751-2004), current global emission flux (2004), global emissions growth rate (5-year smoothed for 2000-2004) and global population (2004). Data sources as in Table 1, with pre-1980 cumulative emissions from CDIAC.

On-line Supporting Information



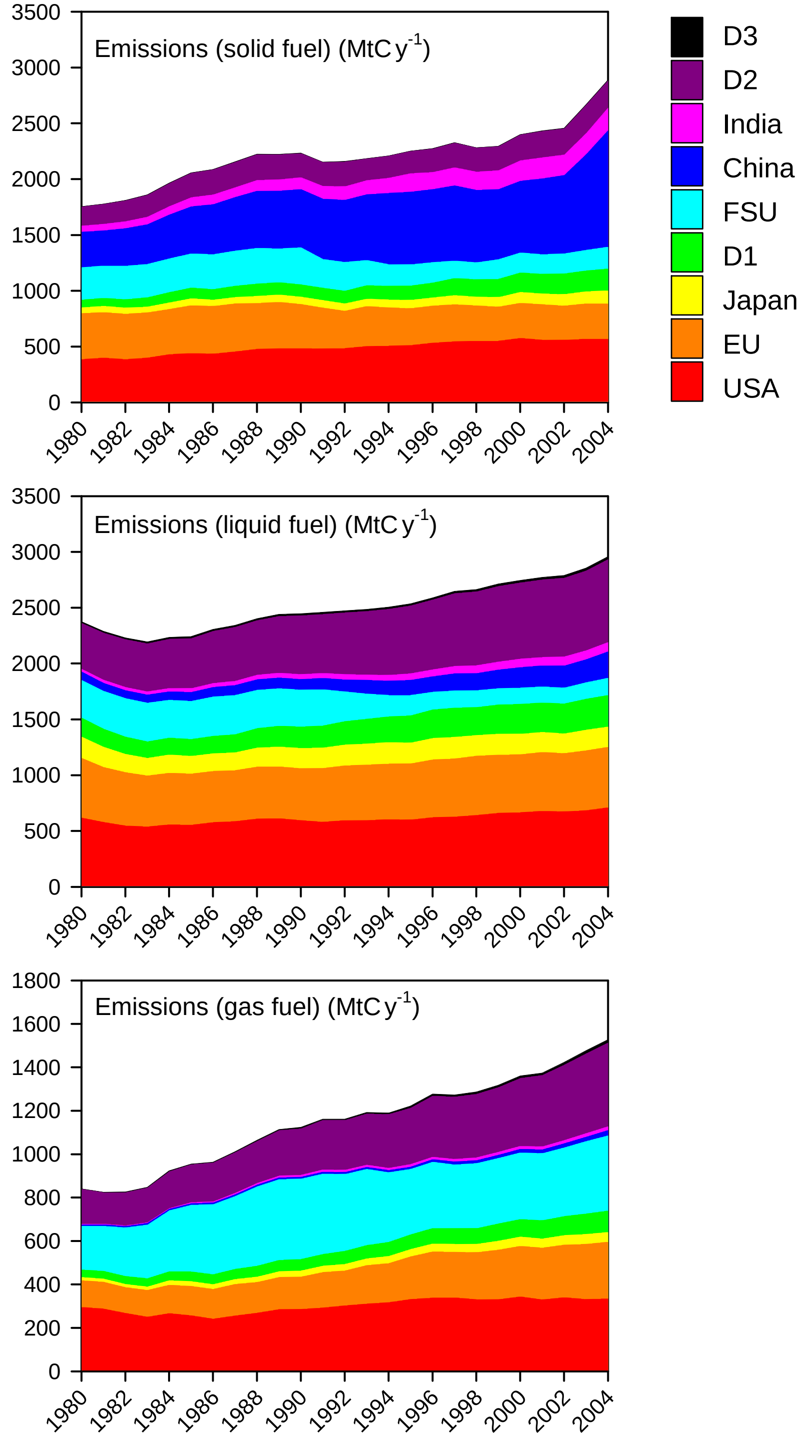
Supporting Information 1: Regional and temporal distributions of (a) fossil-fuel CO_2 emissions F_i (MtC y^{-1}); (b) commercial energy consumption E_i (EJ y^{-1}); (c) population P_i (millions); (d) GDP (MER) G_{Mi}; and (e) GDP (PPP) G_{Pi}. GDP is in G$ y^{-1} (billions of constant-price 2000 US dollars per year). Sources as in Table 1.

Supporting Information 2: Primary Energy

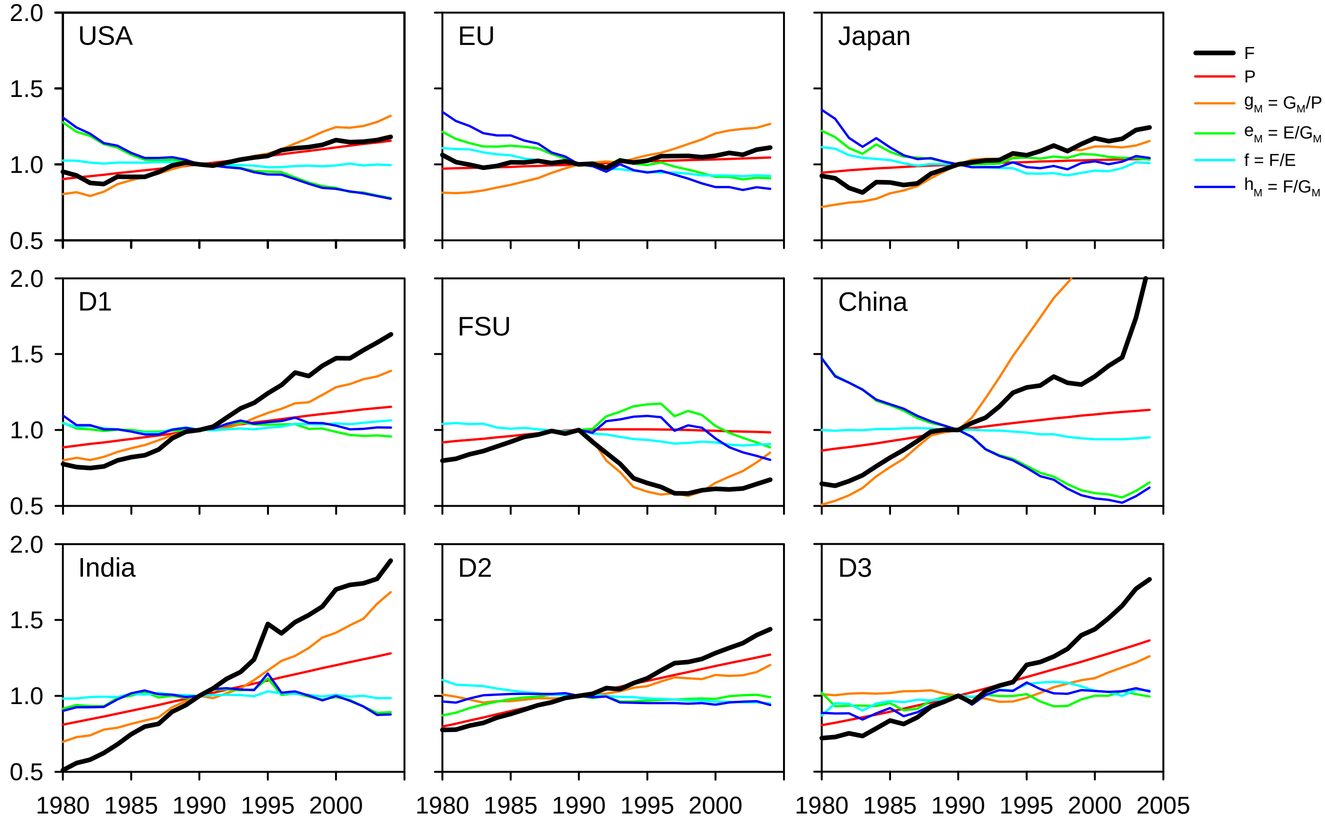
Total primary energy consumption includes (a) energy from solid, liquid and gas fossil fuels; (b) energy used in nuclear electricity generation; (c) electricity from renewables (hydroelectric, wind, solar, geothermal, biomass); and (d) non-electrical energy from renewables, mainly as heat from biomass. Commercial primary energy includes contributions (a), (b) and (c) but excludes (d). Contribution (d) can be difficult to measure, especially in developing regions. Its fractional contribution to total primary energy is often large in developing regions (> 50%), but is smaller in developed regions. Contribution (d) is included in EIA primary-energy data only for the USA, where it represented a share of total USA primary energy of 3.7% (early 1980s) declining to 2.1% (early 2000s). It is not included in the EIA data for regions other than the USA, so the non-USA energy data strictly describe commercial primary energy.

Because of the nature of the energy data, the present analysis applies to commercial primary energy. The presence of contribution (d) in energy data for the USA introduces a small inconsistency amounting to an overestimate of commercial primary energy for the USA averaging about 3% (declining with time) and an equivalent overestimate of global commercial primary energy averaging about 0.7% (likewise declining with time).

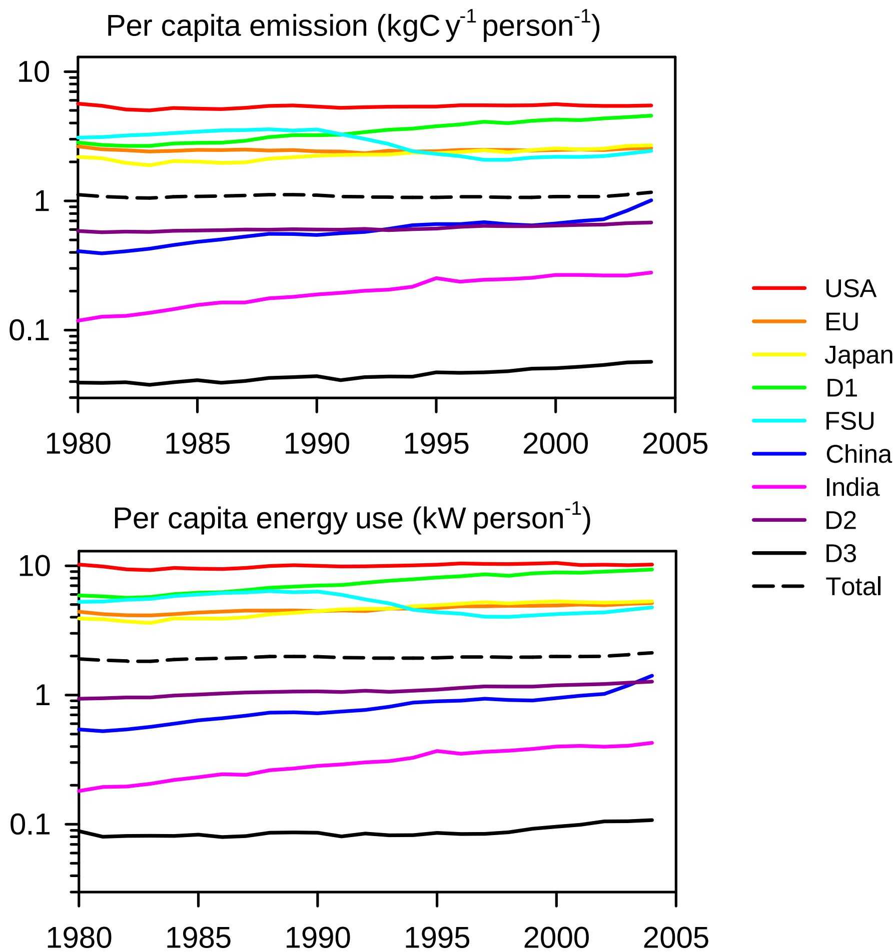
The intensities $e_i = E_i/G_i$ and $f_i = F_i/E_i$ are defined for commercial primary energy. Relative to corresponding intensities defined with total primary energy, e_i as defined here is an underestimate and f_i is an overestimate by the same factor. The carbon intensity of the economy, $h_i = F_i/G_i = e_i f_i$, is independent of the definition of primary energy.



Supporting Information 3: Regional and temporal distributions of fossil-fuel CO_2 emissions (MtC y^{-1}) from (a) solid fuels; (b) liquid fuels; (c) gas fuels. Data source: EIA.



Supporting Information 4: Factors in the Kaya identity, $F = Pgef = Pgh$, for nine regions. All quantities are normalised to 1 at 1990. Intensities are calculated with G_{Mi} (MER). Other details as for Figure 2.



Supporting Information 5: Per-capita emission F_i/P_i (upper panel) and per-capita primary commercial energy consumption E_i/P_i (lower panel). Note the vertical axes are logarithmic. Sources as in Table 1.

Supporting Information 6: The Global Carbon Cycle

In 2005, the cumulative global fossil-fuel emission of CO_2 was $C(t)$ = 319 GtC and the cumulative emission from the other major CO_2 source, land use change, was 156 GtC (5). Of the total cumulative emission from both sources (~480 GtC), less than half (~210 GtC) has remained in the atmosphere, the rest having been taken up by land and ocean sinks (6). For the recent period 2000-2005, emission fluxes averaged 7.2 GtC y^{-1} from fossil fuels and 1.5 GtC y^{-1} from land use change; through this period the fossil-fuel flux grew rapidly at about 3% y^{-1}, and the land use change flux remained approximately steady. A time-dependent indicator of sink effectiveness is the airborne fraction, the fraction of the total emission flux from fossil fuels and land use change that accumulates in the atmosphere each year. Recent work (5) shows that the airborne fraction has averaged 0.44 for the period 1959-2005, increasing slightly through those 47 years to an average of 0.48 for 2000-2005. This implies a slight weakening of land and ocean sinks relative to total emissions.

Supporting Information 7: Data Sources

Four public data sources were used.

1. For F_i and E_i (1980-2004): the Energy Information Administration, US Department of Energy (EIA) [http://www.eia.doe.gov/emeu/international/energyconsumption.html]

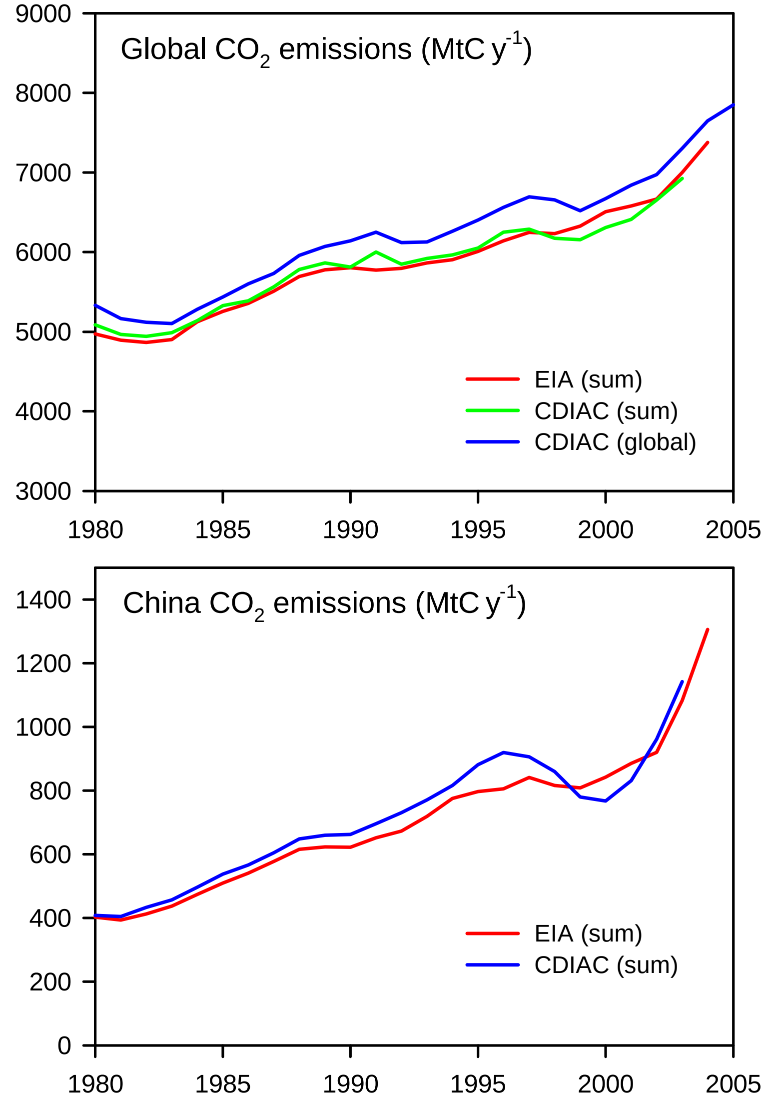
2. For F_i (1751-2005): the Carbon Dioxide Information and Analysis Center, US Department of Energy (CDIAC) (22, 23) [http://cdiac.esd.ornl.gov/trends/emis/tre_coun.htm]

3. For P_i and G_{Mi}: the United Nations Statistics Division (UNSD) [http://unstats.un.org/unsd/snaama/selectionbasicFast.asp]

4. For G_{Pi}: the World Economic Outlook of the International Monetary Fund (WEO) [http://www.imf.org/external/pubs/ft/weo/2006/02/data/download.aspx]

D1	D2	D2 (cont)	D3	EU	FSU
Andorra	Albania	Marshall Islands	Afghanistan	Austria	Armenia
Australia	Algeria	Mauritius	Angola	Belgium	Azerbaijan
Bermuda	Anguilla	Mexico	Bangladesh	Cyprus	Belarus
Canada	Antigua and Barbuda	Micronesia	Benin	Czech Republic	Estonia
Iceland	Argentina	Mongolia	Bhutan	Denmark	Georgia
Israel	Aruba	Montserrat	Burkina Faso	Finland	Kazakhstan
Liechtenstein	Bahamas	Morocco	Burundi	France	Kyrgyzstan
Monaco	Bahrain	Namibia	Cambodia	Germany	Latvia
New Zealand	Barbados	Nauru	Cape Verde	Greece	Lithuania
Norway	Belize	Netherlands Antilles	Central African Rep.	Hungary	Moldova (Republic of)
Korea (South)	Bolivia	New Caledonia	Chad	Ireland	Russian Federation
San Marino	Bosnia and Herzegovina	Nicaragua	Comoros	Italy	Tajikistan
Singapore	Botswana	Nigeria	Congo (Brazzaville)	Luxembourg	Turkmenistan
Switzerland	Brazil	Occupied Palestine	Congo (Kinshasa)	Malta	Ukraine
Taiwan	British Virgin Islands	Oman	Djibouti	Netherlands	USSR (Former)
	Brunei Darussalam	Pakistan	Equatorial Guinea	Poland	Uzbekistan
	Bulgaria	Palau	Eritrea	Portugal	
	Cameroon	Panama	Ethiopia	Slovakia	
	Cayman Islands	Papua New Guinea	Gambia	Slovenia	
	Chile	Paraguay	Guinea	Spain	
	Colombia	Peru	Guinea-Bissau	Sweden	
	Cook Islands	Philippines	Guyana	United Kingdom	
	Costa Rica	Puerto Rico	Kiribati		
	Cote d'Ivoire	Qatar	Laos		
	Croatia	Romania	Lesotho		
	Cuba	Saint Kitts-Nevis	Liberia		
	Czechoslovakia (Former)	Saint Lucia	Madagascar		
	Korea (North)	Saint Vincent and the Grenadines	Malawi		
	Dominica	Saudi Arabia	Maldives		
	Dominican Republic	Serbia and Montenegro	Mali		
	Ecuador	Seychelles	Mauritania		
	Egypt	Somalia	Mozambique		
	El Salvador	South Africa	Myanmar		
	Fiji	Sri Lanka	Nepal		
	French Polynesia	Sudan	Niger		
	Gabon	Suriname	Rwanda		
	Ghana	Swaziland	Samoa		
	Grenada	Syria	Sao Tome and Principe		
	Guatemala	Macedonia (TFYR)	Senegal		
	Haiti	Thailand	Sierra Leone		
	Honduras	Tonga	Solomon Islands		
	Indonesia	Trinidad and Tobago	Timor-Leste		
	Iran	Tunisia	Togo		
	Iraq	Turkey	Tuvalu		
	Jamaica	Turks and Caicos Islands	Uganda		
	Jordan	United Arab Emirates	Tanzania		
	Kenya	Uruguay	Vanuatu		
	Kuwait	Venezuela	Yemen		
	Lebanon	Vietnam	Zambia		
	Libyan Arab Jamahiriya	Zanzibar			
	Malaysia	Zimbabwe			

Supporting Information 8: Allocation of countries to regions D1, D2, D3, EU and FSU



Supporting Information 9: (Upper panel) Observed CO_2 emissions: from EIA data summed over all countries (red), from CDIAC data summed over all countries (green), and the global total from the CDIAC dataset (blue). (Lower panel) Emissions from China, from EIA (red) and CDIAC (blue) data.

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