Global and regional drivers of accelerating CO_2 emissions

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CO_2 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 CO_2 presently contributes ≈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).[‡‡] This growth is governed by the global budget of atmospheric CO_2 (4), which includes two major anthropogenic forcing fluxes: (*i*) CO_2 emissions from fossil-fuel combustion and industrial processes and (*ii*) the CO_2 flux from land-use change, mainly land clearing. A survey of trends in the atmospheric CO_2 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 CO_2 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 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 (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 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 nonfuel hydrocarbons; and fuel from "international bunkers" used for shipping and air transport (separated because it is often not included in national inventories). Hence

$$F = \underset{\approx 35\%}{F_{\text{Solid}}} + \underset{\approx 36\%}{F_{\text{Liquid}}} + \underset{\approx 20\%}{F_{\text{Gas}}} + \underset{<1\%}{F_{\text{Flare}}} + \underset{\approx 3\%}{F_{\text{Cement}}}, + \underset{<1\%}{F_{\text{NonFuelHC}}} + \underset{\approx 4\%}{F_{\text{Bunkers}}}, \quad [1]$$

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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[‡‡] CO_2 data are available at www.cmdl.noaa.gov/gmd/ccgg/trends.

[§§] Yamaji, K., Matsuhashi, R., Nagata, Y., Kaya, Y., *An Integrated System for CO_2/Energy/GNP Analysis: Case Studies on Economic Measures for CO_2 Reduction in Japan. Workshop on CO_2 Reduction and Removal: Measures for the Next Century*, March 19, 1991, International Institute for Applied Systems Analysis, Laxenburg, Austria.

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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

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

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

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

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:

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

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 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% 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% 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*).

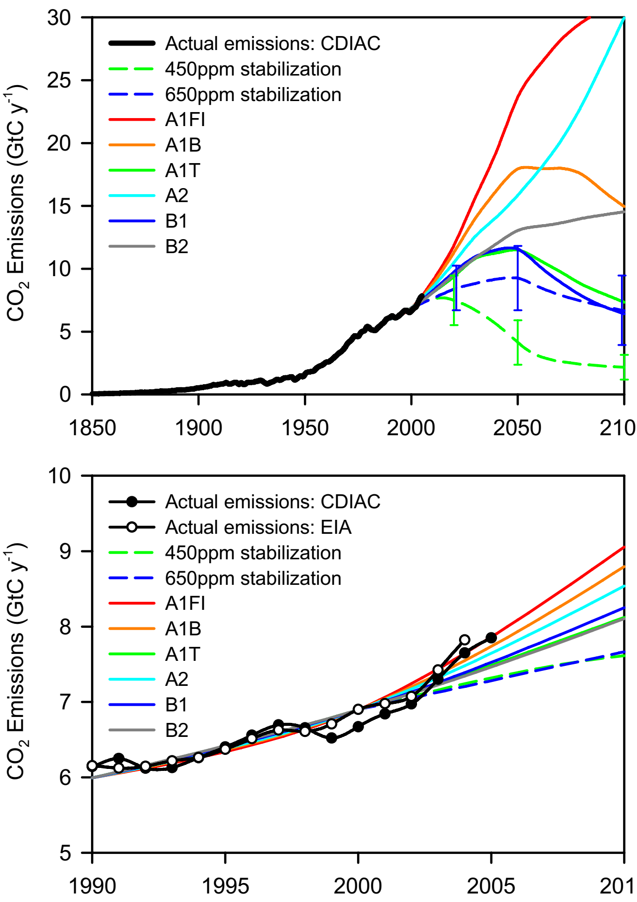

Fig. 1. Observed global CO_2 emissions including all terms in Eq. **1**, from both the EIA (1980–2004) and global CDIAC (1751–2005) data, compared with emissions scenarios (8) and stabilization trajectories (10–12). EIA emissions data are normalized to same mean as CDIAC data for 1990–1999, to account 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 CO_2 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) ≈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

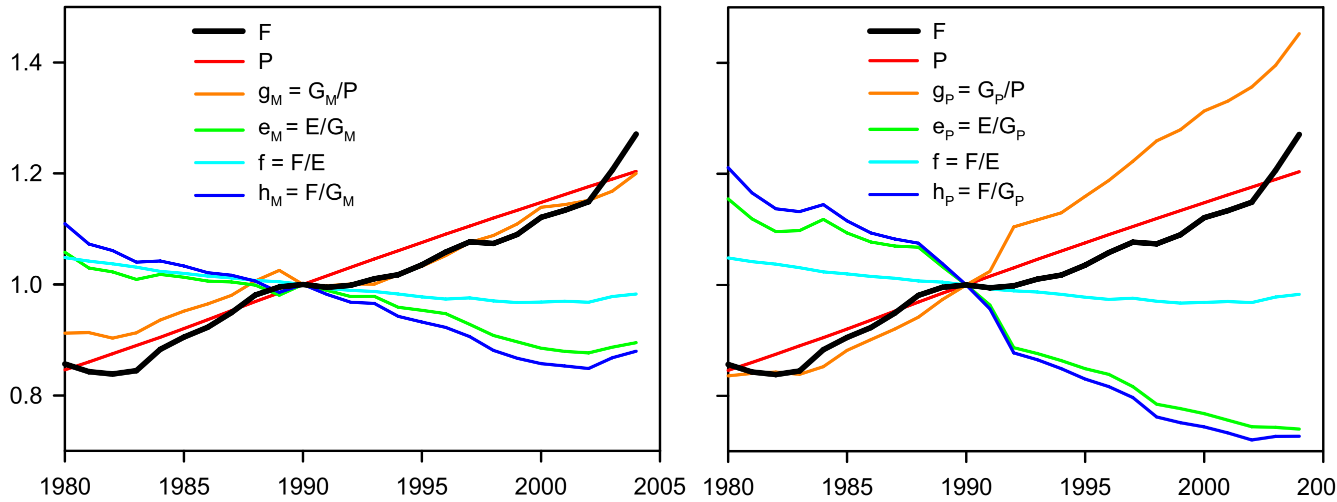

Fig. 2. Factors in the Kaya identity, $F = Pgef = Pgh$, as global averages. All quantities are normalized to 1 at 1990. Intensities are calculated by using G_M (*Left*) and G_P (*Right*). In both *Left* and *Right*, the black line (F) is the product of the red (P), orange (g), green (e), and light blue (f) lines (Eq. **2**) or equivalently of the red (P), orange (g), and dark blue (h) lines (Eq. **3**). Because $h = ef$, the dark blue line is the product of the green and light blue lines. Sources are as in Table 1.

emissions in developing regions (the sum of China, India, D2, and D3) than in developed regions (U.S., EU, Japan, and D1), and the FSU region had a much stronger reliance on gas than the world average (SI Fig. 7).

To diagnose drivers of trends in global emissions, Fig. 2 superimposes time series for 1980–2004 of the Kaya factors F, P, g, e, f, and $h = ef$ (Eqs. **2** and **3**). Fig. 2 *Left* and *Right*, respectively, use the MER and PPP forms of GDP (G_M and G_P) to calculate intensities. All quantities are normalized 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 normalization.

In Fig. 2 *Left* (MER-based), the Kaya identity is $F = Pg_Me_Mf = Pg_Mh_M$ (with $g_M = G_M/P$, $e_M = E/G_M$, and $h_M = F/G_M$). 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 Fig. 2 *Right* (PPP-based), using the Kaya identity $F = Pg_Pe_Pf = Pg_Ph_P$, (with $g_P = G_P/P$, $e_P = E/G_P$, and $h_P = F/G_P$). 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, and h_M, associated with the higher global growth rate of G_P than of G_M (SI Fig. 6). 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, Fig. 2 *Left* and *Right* both 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 (Fig. 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 Fig. 4 by plotting the normalized factors in the nine regional Kaya identities, using GDP (PPP). Equivalent plots with GDP (MER) are nearly identical (SI Fig. 8).

In the developed regions (U.S., Europe, Japan, and 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.

Table 1. Values of extensive and intensive variables in 2004

	F_i, MtC/y	P_i, million	E_i, EJ/y	G_{Mi}, G\$/y	G_{Pi}, G\$/y	$g_{Pi} = G_{Pi}/P_i$, k\$/y	$e_{Pi} = E_i/G_{Pi}$, MJ/\$	$f_i = F_i/E_i$, gC/MJ	$h_{Pi} = F_i/G_{Pi}$, gC/\$	F_i/P_i, tC/y	E_i/P_i, kW
U.S.	1,617	295	95.4	9,768	7,453	25.23	12.80	16.95	217.0	5.47	10.24
EU	1,119	437	70.8	10,479	7,623	17.45	9.29	15.81	146.8	2.56	5.14
Japan	344	128	21.4	4,036	2,412	18.85	8.89	16.05	142.7	2.69	5.31
D1	578	150	37.3	3,283	2,553	17.06	14.63	15.47	226.3	3.86	7.91
FSU	696	285	42.8	726	1,423	4.99	30.08	16.25	488.7	2.44	4.76
China	1,306	1,293	57.5	1,734	5,518	4.27	10.43	22.70	236.6	1.01	1.41
India	304	1,087	14.6	777	2,130	1.96	6.86	20.77	142.5	0.28	0.43
D2	1,375	2,020	80.9	4,280	7,044	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	7,376	6,351	423.1	35,338	36,765	5.79	11.51	17.43	200.6	1.16	2.11

All dollar amounts (\$) are in constant-price (2000) U.S. dollars. Data sources: EIA (F_i, E_i), UNSD (P_i, G_{Mi}), and WEO (G_{Pi}).

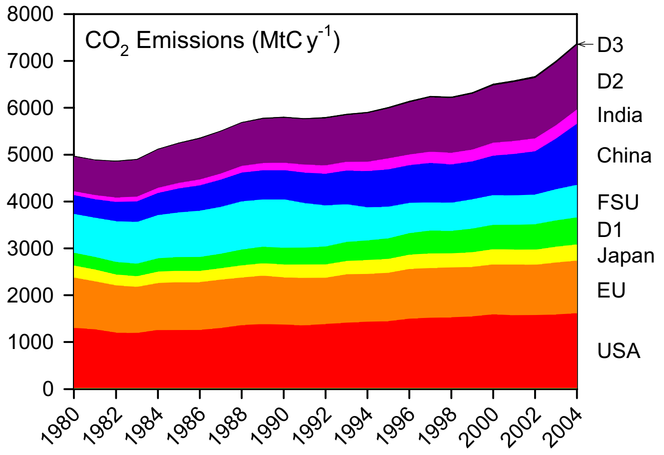

Fig. 3. Fossil-fuel CO_2 emissions (MtC y^{-1}), for nine regions. Data source is EIA.

In the FSU, emissions decreased through the 1990s because of the fall in economic activity after the collapse of the Soviet Union. Incomes (g_i) decreased in parallel with emissions (F_i), and a shift toward 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 ≈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, and 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 (although 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, although 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 grams of carbon per megajoule (gC/MJ), although for China and India it is somewhat higher, >20 gC/MJ. In time, f_i has decreased slowly from 1980 to ≈2000 as a global average (Fig. 2) and in most regions (Fig. 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 and SI Fig. 9). The interregion range, a factor of ≈50, extends from the U.S. (for which both quantities are ≈5 times the global average) to the D3 region (for which they

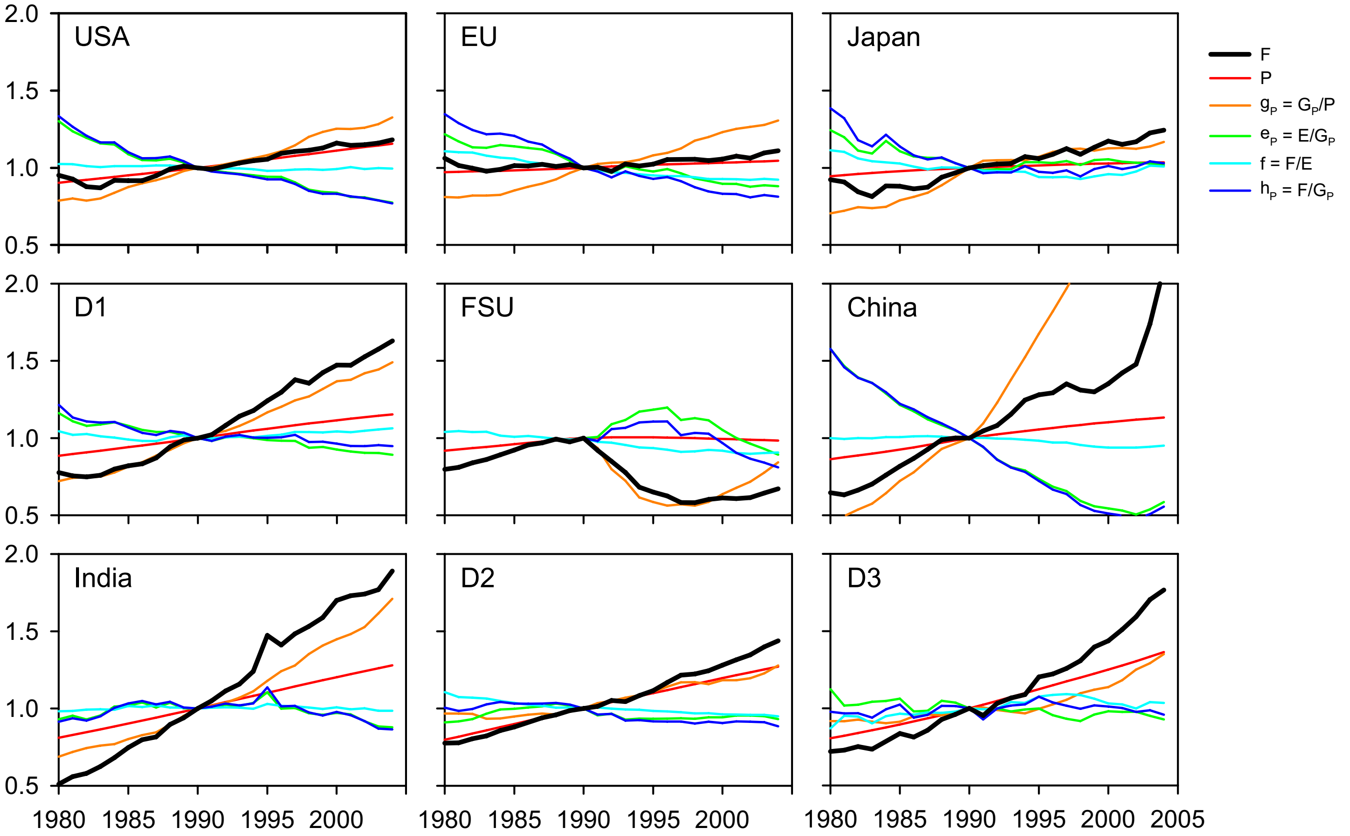

Fig. 4. Factors in the Kaya identity, $F = Pgef = Pgh$, for nine regions. All quantities are normalized to 1 at 1990. Intensities are calculated with G_{Pi} (PPP). For FSU, normalizing G_{Pi} in 1990 was back-extrapolated. Other details are as for Fig. 2.

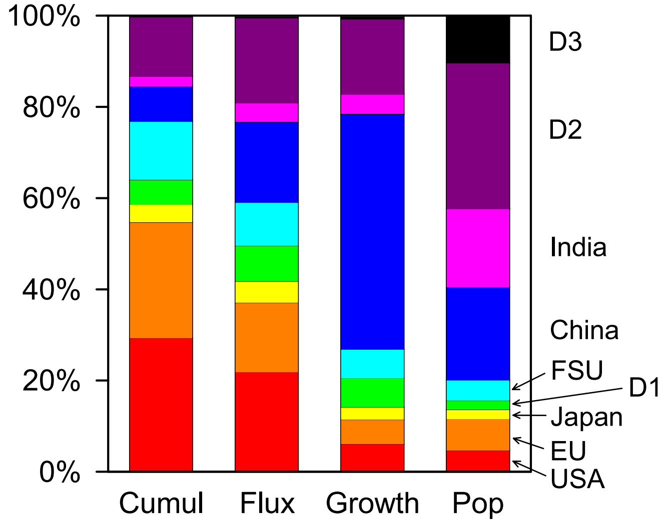

Fig. 5. Relative contributions of nine regions to cumulative global emissions (1751–2004), current global emission flux (2004), global emissions growth rate (5 year smoothed for 2000–2004), and global population (2004). Data sources as in Table 1, with pre-1980 cumulative emissions from CDIAC.

are ≈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 ≈1.1 tC/y per person and 2 kW per person, respectively, but F/P rose by 8% and E/P by 7% over the 5 years 2000–2004.

Temporal Perspectives. In the period 2000–2004, developing countries had a greater share of emissions growth than of emissions themselves (Fig. 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 gigatonnes of carbon) 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.

Fig. 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 $r(F)$ (Eq. **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 (ref. 4; *SI Text, The Global Carbon Cycle*). 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 (J. G. Canadell, C.L.Q., M.R.R., C.B.F., E. T. Buitenhaus, *et al.*, unpublished data), implying a slight weakening of sinks relative to emissions. However, the dominant factor accounting for the recent rapid growth in atmospheric CO_2 (>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 decarbonizing 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 (8), 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 (13). 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, whereas 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 (14) with increasing globalization of the economy.

Finally, we note (Fig. 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 (multidecadal) perspective on emissions is essential because of the long atmospheric residence time of CO_2. Therefore, Fig. 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 a 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[¶¶]: the EIA for F_i and E_i, the CDIAC for historic F_i from 1751 (15), the United Nations Statistics Division for P_i and G_{Mi}, and the World Economic Outlook of the International Monetary Fund 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 U.S. dollars, taking $G_M = G_P$ in 2000.

We analyzed nine noncontiguous regions (U.S., EU, Japan, D1, FSU, China, India, D2, and D3; see Introduction and *SI Text, Definition of Regions*). 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, and Lithua-

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[¶¶] EIA, www.eia.doe.gov/emeu/international/energyconsumption.html; CDIAC, http://cdiac.esd.ornl.gov/trends/emis/tre_coun.htm; United Nations Statistics Division, http://unstats.un.org/unsd/snaama/selectionbasicFast.asp; and World Economic Outlook of the International Monetary Fund, www.imf.org/external/pubs/ft/weo/2006/02/data/download.aspx.

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 $F_{\mathrm{NonFuelHC}}$, 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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