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# Global and regional drivers of accelerating CO<sub>2</sub> emissions

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CO<sub>2</sub> emissions from fossil-fuel burning and industrial processes have been accelerating at a global scale, with their growth rate increasing from 1.1% y<sup>-1</sup> for 1990–1999 to >3% y<sup>-1</sup> 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<sub>2</sub> presently contributes ≈63% of the gaseous radiative forcing responsible for anthropogenic climate change (1). The mean global atmospheric CO<sub>2</sub> concentration has increased from 280 ppm in the 1700s to 380 ppm in 2005, at a progressively faster rate each decade (2, 3).<sup>‡‡</sup> This growth is governed by the global budget of atmospheric CO<sub>2</sub> (4), which includes two major anthropogenic forcing fluxes: (i) CO<sub>2</sub> emissions from fossil-fuel combustion and industrial processes and (ii) the CO<sub>2</sub> flux from land-use change, mainly land clearing. A survey of trends in the atmospheric CO<sub>2</sub> budget (3) shows these two fluxes were, respectively, 7.9 gigatonnes of carbon (GtC) y<sup>-1</sup> and 1.5 GtC y<sup>-1</sup> in 2005 with the former growing rapidly over recent years, and the latter remaining nearly steady.

This paper is focused on CO<sub>2</sub> 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<sub>2</sub> 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<sub>2</sub> 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<sup>§§</sup> (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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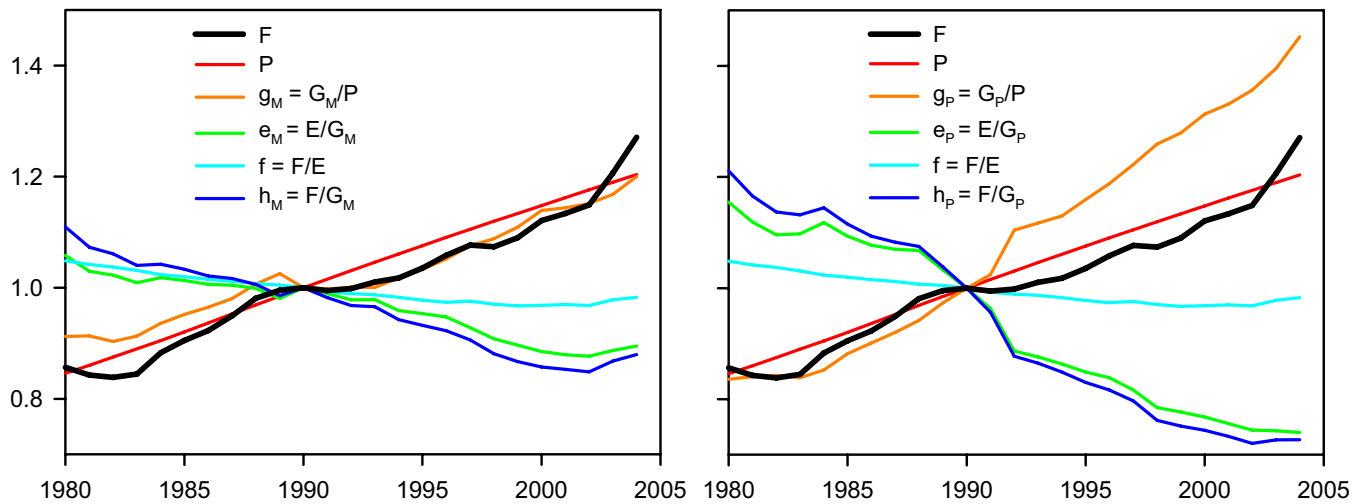
<sup>‡‡</sup>CO<sub>2</sub> data are available at [www.cmdl.noaa.gov/gmd/ccgg/trends](http://www.cmdl.noaa.gov/gmd/ccgg/trends).

<sup>§§</sup>Yamaji, K., Matsuhashi, R., Nagata, Y., Kaya, Y., *An Integrated System for CO<sub>2</sub>/Energy/ GNP Analysis: Case Studies on Economic Measures for CO<sub>2</sub> Reduction in Japan*. Workshop on CO<sub>2</sub> Reduction and Removal: Measures for the Next Century, March 19, 1991, International Institute for Applied Systems Analysis, Laxenburg, Austria.

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**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  $F = Pg_M e_M f = Pg_M h_M$  (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,  $h_M = e_M f$  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  $F = Pg_P e_P f = Pg_P h_P$ , (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).

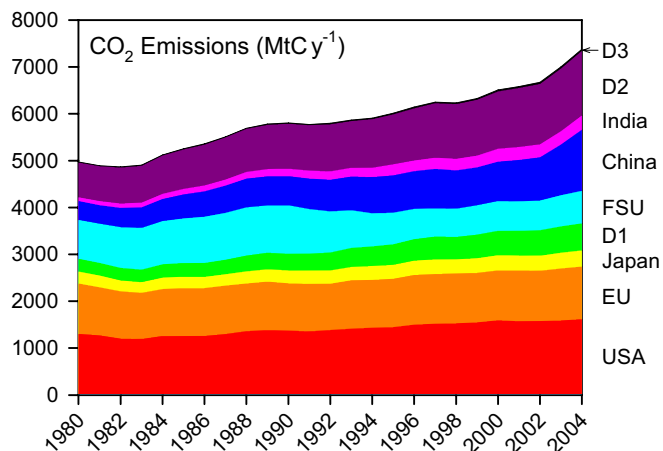
In the developed regions (U.S., Europe, Japan, and D1),  $F_i$  increased from 1980 to 2004 as a result of relatively rapid growth in mean income ( $g_i$ ) and slow growth in population ( $P_i$ ), offset in most regions by decreases in the energy intensity of GDP ( $e_i$ ). Declines in  $e_i$  indicate 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**

	$F_i$ , MtCly	$P_i$ , 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<sub>2</sub> emissions (MtC y<sup>-1</sup>), 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.

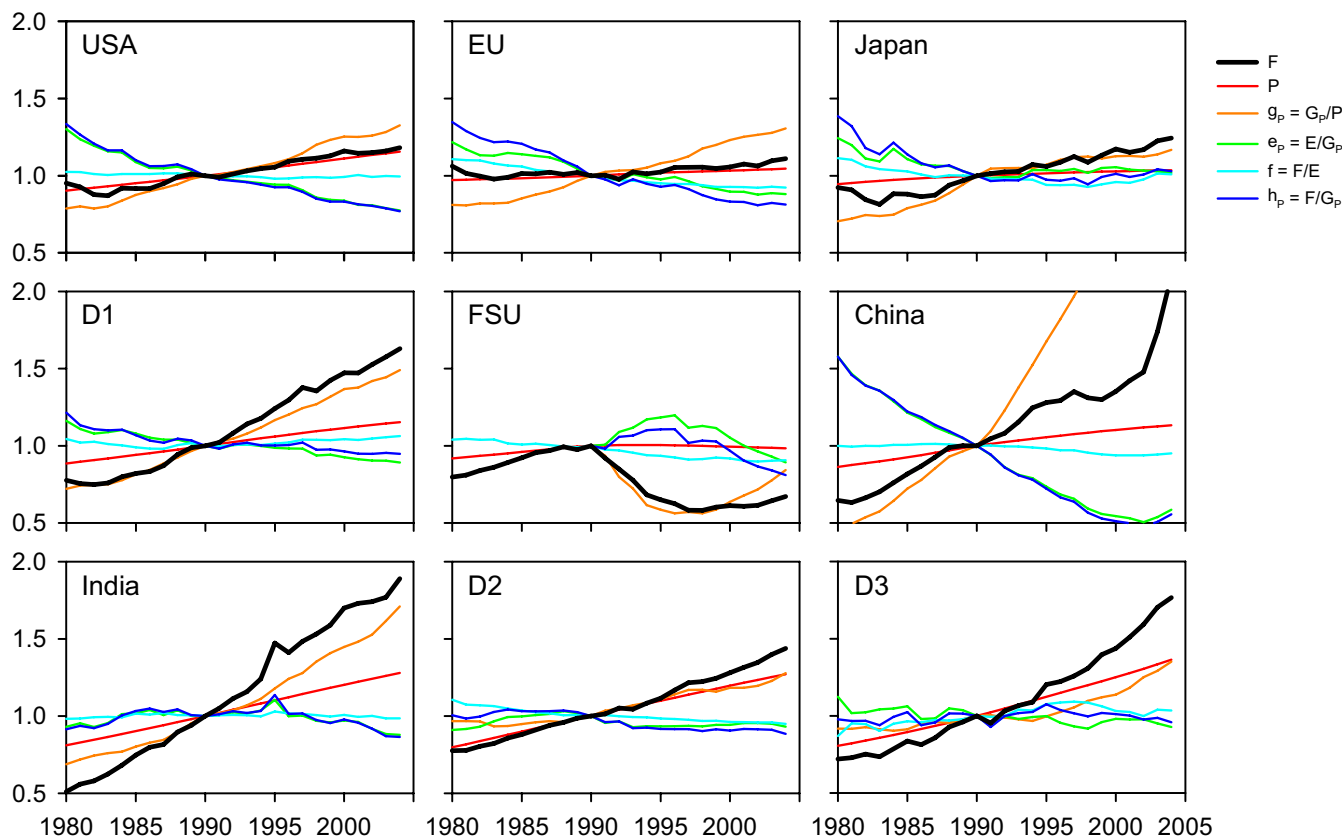
In China,  $g_i$  rose rapidly and  $P_i$  slowly over the whole period 1980–2004. Progressive decoupling of income growth from energy

consumption (declining  $e_i$ ) was achieved up to  $\approx 2002$ , 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  $e_i$ .

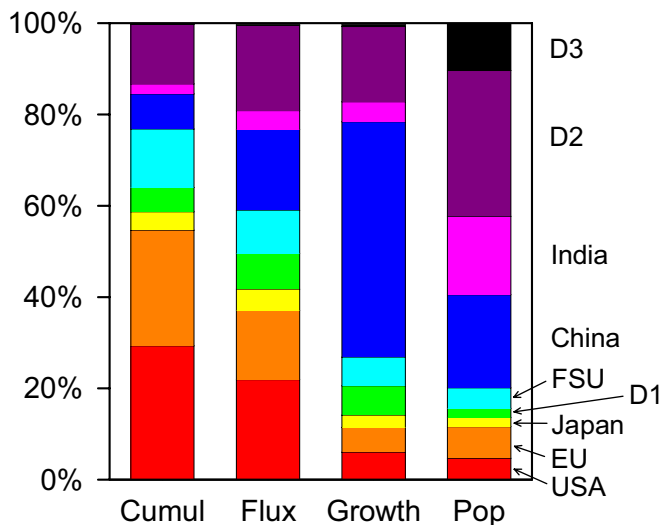
In other developing regions (India, D2, and D3), increases in  $F_i$  were driven by a combination of increases in  $P_i$  and  $g_i$ , with no strong trends in  $e_i$  or  $f_i$ . Growth in emissions ( $F_i$ ) exceeded growth in income ( $g_i$ ). Unlike China and the developed countries, strong technological 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  $\approx 2000$  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  $\approx 50$ , extends from the U.S. (for which both quantities are  $\approx 5$  times the global average) to the D3 region (for which they



**Fig. 4.** Factors in the Kaya identity,  $F = P g e f = P g h$ , 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  $\approx 1/10$  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  $\approx 1.1$  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<sub>2</sub> emissions need to be considered in the context of the whole carbon cycle. Of the total cumulative anthropogenic CO<sub>2</sub> 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<sub>2</sub> 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. Buitenhuis, *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<sub>2</sub> ( $>2$  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<sub>2</sub>. 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<sub>2</sub> emissions ( $F_i$ ), population ( $P_i$ ), GDP ( $G_{Mi}$  and  $G_{Pi}$ ), and primary energy consumption ( $E_i$ ), from four public sources<sup>11</sup>: 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-

<sup>11</sup>EIA, [www.eia.doe.gov/emeu/international/energyconsumption.html](http://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](http://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  $F_{\text{Bunkers}}$  and  $F_{\text{NonFuelHC}}$ , and EIA country-level data omit  $F_{\text{Cement}}$  but include  $F_{\text{Bunkers}}$  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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- Hofmann DJ, Butler JH, Dlugokencky EJ, Elkins JW, Masarie K, Montzka SA, Tans P (2006) *Tellus Ser B* 58:614–619.
- Etheridge DM, Steele LP, Langenfelds RL, Francey RJ, Barnola JM, Morgan VI (1996) *J Geophys Res Atmos* 101:4115–4128.
- Raupach MR, Canadell JG (2007) in *Observing the Continental Scale Greenhouse Gas Balance of Europe*, eds Dolman H, Valentini R, Freibauer A (Springer, Berlin), in press.
- Sabine CL, Heimann M, Artaxo P, Bakker DCE, Chen C-TA, Field CB, Gruber N, Le Quéré C, Prinn RG, Richey JD, et al. (2004) in *The Global Carbon Cycle: Integrating Humans, Climate, and the Natural World*, eds Field CB, Raupach MR (Island, Washington, DC), pp 17–44.
- Hoffert MI, Caldeira K, Benford G, Criswell DR, Green C, Herzog H, Jain AK, Kheshgi HS, Lackner KS, Lewis JS, et al. (2002) *Science* 298:981–987.
- Caldeira K, Granger Morgan M, Baldocchi DD, Brewer PG, Chen C-TA, Nabuurs G-J, Nakicenovic N, Robertson GP (2004) in *The Global Carbon Cycle: Integrating Humans, Climate, and the Natural World*, eds Field CB, Raupach MR (Island, Washington, DC), pp 103–129.
- Stern N (2006) *Stern Review on the Economics of Climate Change* (Cambridge Univ Press, Cambridge, UK).
- Nakicenovic N, Alcamo J, Davis G, de Vries B, Fenhann J, Gaffin S, Gregory K, Grubler A, Jung TY, Kram T, et al. (2000) *IPCC Special Report on Emissions Scenarios* (Cambridge Univ Press, Cambridge, UK).
- Nakicenovic N (2004) in *The Global Carbon Cycle: Integrating Humans, Climate, and the Natural World*, eds Field CB, Raupach MR, (Island, Washington, DC), pp 225–239.
- Houghton JT, Ding Y, Griggs DJ, Noguer M, van der Linden PJ, Dai X, Maskell K, Johnson CA (2001) *Climate Change 2001: The Scientific Basis*, eds Houghton JT, Ding Y, Griggs DJ, Noguer M, van der Linden PJ, Dai X, Maskell K, Johnson CA (Cambridge Univ Press, Cambridge, UK).
- Wigley TML, Richels R, Edmonds JA (1996) *Nature* 379:240–243.
- Joos F, Plattner GK, Stocker TF, Marchal O, Schmittner A (1999) *Science* 284:464–467.
- Edmonds JA, Joos F, Nakicenovic N, Richels RG, Sarmiento JL (2004) in *The Global Carbon Cycle: Integrating Humans, Climate, and the Natural World*, eds Field CB, Raupach MR (Island, Washington, DC), pp 77–102.
- Rothman DS (1998) *Ecol Econ* 25:177–194.
- Marland G, Rotty RM (1984) *Tellus Ser B* 36:232–261.
- Streets DG, Jiang KJ, Hu XL, Sinton JE, Zhang XQ, Xu DY, Jacobson MZ, Hansen JE (2001) *Science* 294:1835–1837.
- Wu L, Kaneko S, Matsuoka S (2005) *Energy Pol* 33:319–335.