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Carbon and the Anthropocene

Michael R Raupach and Josep G Canadell

Life on earth has created vast stores of detrital carbon — the remnants of carbon-based organisms after they have died. These carbon stores range from dead leaves and wood to the fossil carbon in coal, oil and gas. They contain large amounts of usable chemical energy. When the ancestors of modern humans learned to access this energy by mastering fire, they discovered a 'new trick' which led to massive evolutionary advantages for the human species. In the technological explosion of the last two centuries, industrial-scale use of energy flows from fossil carbon has not only transformed human societies and ecosystems, but also caused exponentially increasing accumulation of the released carbon in atmospheric, land and ocean carbon reservoirs. These changes have altered the carbon cycle and other cycles of matter and energy in the earth system, leading to the term 'Anthropocene' for the current epoch. In this epoch humankind is encountering finite-planet vulnerabilities for the first time, as a consequence of the dominance of its home planet bequeathed by the use of energy flows from detrital carbon. Signs of these vulnerabilities can be seen in the contemporary carbon cycle and emerging carbon–climate feedbacks. Interactions between humans, climate, the carbon cycle and other natural cycles are certain to become more profound over the next century and beyond.

Address
Global Carbon Project, Earth System Science Partnership, Centre for Atmospheric, Weather and Climate Research, CSIRO, Canberra, Australia

Corresponding authors: Raupach, Michael R (Michael.Raupach@csiro.au) and

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The Anthropocene and the carbon cycle

In a moment of geological time, human activities have transformed the earth system.[a] Both the magnitude and rate of change are so great that the epoch since the start of the industrial revolution is often called the 'Anthropocene' to distinguish it from the preceding Holocene (starting about 12 000 BP). In the Anthropocene, human activities are significantly modifying the great natural cycles of carbon, water and nutrients, together with climate, biodiversity, land cover and other properties of the state and function of the earth system [1–3].

Anthropocene trends are evident in the carbon cycle and its connection with climate. CO_2 emissions from fossil fuel combustion, other industrial processes and deforestation have increased atmospheric CO_2 concentrations, the largest single contributor to present anthropogenic radiative forcing[b] and thus to current and likely future climate change [4••,5••,6]. Significant global political efforts to reduce anthropogenic CO_2 emissions [7,8] have ensued. Indeed, the CO_2-climate connection is so well entrenched in public consciousness that it is often regarded as the single greatest environmental threat to the future well-being of humankind. However, there are also other profound contemporary changes in the earth system stemming from human activities. A recent survey [9•] concluded that biodiversity loss, disturbance of nutrient (nitrogen and phosphorus) cycles and climate change, in that order, are the three leading planetary systems which have already crossed boundaries defining a 'safe operating space for humanity'.

In this article we argue that the carbon cycle plays two fundamental roles in the emergence and development of the Anthropocene. The first, familiar role is associated with climate change, a major (but far from the only) vulnerability faced by humankind as a result of current changes in the earth system. The second and much deeper role is that carbon is central to the emergence of the Anthropocene as a planetary phenomenon, because the exploitation of energy from detrital carbon provided an essential evolutionary trigger for the Anthropocene. We review contemporary carbon–climate–human interactions as a fundamental outcome of this process, focussing on the budget of atmospheric CO_2, trends in anthropogenic CO_2 emissions and natural sinks, and feedbacks between the carbon cycle and climate.

[a] The earth system is the evolving complex system comprising the atmosphere, hydrosphere, lithosphere, biosphere and (since the arrival of humans) the anthroposphere. The anthroposphere is the sphere of human societies, cultures, knowledge, economies and built environments.

[b] Total radiative forcing in 2005 was +1.6 (0.6, 2.4) W m^{-2}, including contributions of $+1.7 \pm 0.2$ W m^{-2} from CO_2, $+1.0 \pm 0.3$ W m^{-2} from non-CO_2 greenhouse gases including CH_4, N_2O, CFCs and others, and -1.2 (-2.7, -0.4) W m^{-2} from non-gaseous sources, mainly aerosols. Thus the contributions from non-CO_2 gases and non-gaseous forcings nearly cancel, though the negative contribution from aerosols is highly uncertain [4••].

Progenitors of the Anthropocene

All life on Earth, including humankind, is carbon-based. Organic carbon molecules provide the basic biochemical machinery underlying evolution and the use of environmental energy, attributes essential to life. DNA and RNA store and propagate information with nearly but not perfect pattern transcription, a property central to heredity with diversification and thence to the emergence of biotic complexity on Earth through evolution by natural selection [10]. Life also requires an energy cycle to maintain states far from thermodynamic equilibrium [11], leading to an energy flow through the biosphere for which the dominant primary energy source is solar radiation through photosynthesis by autotrophs. These carbon-based processes have led to a massive modification of the earth system by life itself, including the evolution of an atmosphere in chemical disequilibrium and the accumulation of vast stores of detrital organic carbon as living creatures die. Most detrital carbon still contains significant usable chemical energy, a fact which is critical to many life forms from heterotrophic soil microbes to fungi and scavengers. Much of the detrital carbon has always resided in fast-turnover pools on land and in the ocean which are fairly quickly recycled back to the atmosphere as CO_2, but at some times in the past (mainly in the Carboniferous period, 350–300 My BP) large quantities were also stored in fossil carbon deposits as coal, oil and gas.

Around half a million years ago, the ancestors of humankind learned a 'new trick' [12]: the use of fire to derive energy from the controlled combustion of detrital biotic carbon such as wood and peat. The ability to tap and use flows of exosomatic energy (which do not pass through the body of a life form) confers enormous evolutionary advantages. Energy no longer has to be used as it is gathered or stored within the body of the gatherer, but can be stockpiled, concentrated and used to increase the harvesting of resources and other activities beneficial to evolutionary success. Further, exosomatic energy flows can be amplified almost without limit: technologies made possible by the use of energy create the ability to generate and harness more energy. Power as energy flux unlocks power as dominance.

Fire became only one of several exosomatic energy sources harnessed by humankind, others including animal and abiotic (wind and water) power. Their collective potential was realised only gradually, and far from uniformly across different societies [13]. A critical step was the development of agriculture, leading to towns and cities and to specialisation. New economic, social and cultural modes of organisation ensued, all supported by technologies dependent on exosomatic energy flows.

A further critical transition was initiated by the discovery that energy could be derived not only from detrital biotic carbon but also from detrital fossil carbon, at first from coal. This much more concentrated energy source catalysed developments in technology, which led eventually to the technological explosion of industrial era and thence to the Anthropocene as usually defined.

In the Anthropocene, the human species has come to dominate the planet. Human numbers have swelled to billions, agriculture has transformed ecosystems, and human consumption of natural resources, including fossil fuels, has grown exponentially. Exosomatic energy was, and still is, an essential catalyst for this development, and the primary reason for its availability is that, long before the industrial era, a particular primate species learned how to tap the energy reserves stored in detrital carbon. Like life, the Anthropocene is carbon-based.

Human modification of the carbon cycle

The CO_2 budget and CO_2 airborne fraction

Strong signals of Anthropocene changes in the earth system arise in the carbon cycle itself. Measurements of atmospheric CO_2 concentrations, including the famous Mauna Loa record since 1959 [14–16], data from many other locations [17,18] and records of CO_2 and other gas concentrations in ice cores [19••,20••,21••,22], show that CO_2 in the atmosphere has increased from approximately 280 ppm at the start of the industrial revolution (and for the previous several thousand years in the Holocene) to 387 ppm in 2009 (data online[c]). The growth rate averaged 1.9 ppm year^{-1} over 2000–2008 [23••] with significant interannual variability.

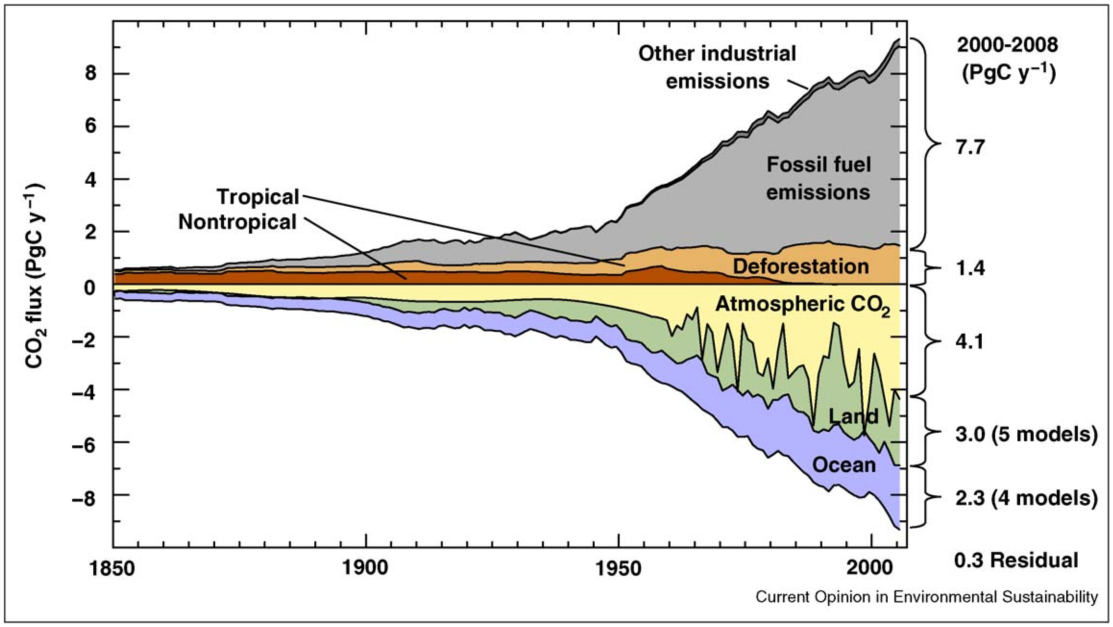
The budget governing atmospheric CO_2 concentrations is as follows:

$$\underbrace{dC_a/dt}_{\text{atmospheric accumulation}} = \underbrace{F_{\text{Foss}}}_{\text{fossil fuel and other industrial emissions}} + \underbrace{F_{\text{LUC}}}_{\text{land use change emissions}} - \underbrace{F_{\text{Land Sink}}}_{\text{land } CO_2 \text{ sink}} - \underbrace{F_{\text{Ocean Sink}}}_{\text{ocean } CO_2 \text{ sink}} \quad (1)$$

where C_a is the atmospheric CO_2 store in PgC (1 PgC = 10^{15} grams of carbon and corresponds to a CO_2 concentration of 0.47 ppm). This budget expresses the mass-balance constraint on atmospheric CO_2: the increase of CO_2 in the atmosphere is equal to total inflows minus total outflows, where all quantities have units of mass per unit time (PgC year^{-1}). In the present era the inflows of CO_2 to the atmosphere are almost entirely

[c] NOAA Earth System Research Laboratory (http://www.esrl.noaa.gov/gmd/ccgg/trends/); Scripps Institution of Oceanography (http://scrippsco2.ucsd.edu/data/atmospheric_co2.html).

Figure 1



Terms in the global CO_2 budget, Eqn (1), for the period 1850–2008 inclusive, from [23••]. Anthropogenic CO_2 emissions, shown as positive fluxes into the atmosphere, comprise contributions from fossil fuel combustion and other industrial processes (F_{Foss}), and land use change, mainly deforestation (F_{LUC}). The fate of emitted CO_2, including the accumulation of atmospheric CO_2 (dC_a/dt), the land CO_2 sink ($F_{LandSink}$) and the ocean CO_2 sink ($F_{OceanSink}$) is shown by the balancing negative fluxes. Values of average fluxes for 2000–2008 (shown at right) include a small residual because all terms were estimated independently from measurements or models, without *a priori* application of a mass-balance constraint.

because of anthropogenic emissions, comprising emissions from fossil fuels and other industrial processes including cement production (collectively denoted F_{Foss}) and emissions from net land use change (F_{LUC}). The outflows from the atmosphere are because of land and ocean CO_2 sinks ($F_{LandSink}$, $F_{OceanSink}$).

Terms in the CO_2 budget are shown in Figure 1 for the period 1850–2008, from [23••]. This CO_2 budget was based (for the first time) on independent estimates of all terms without *a priori* application of a mass-balance constraint, so the average fluxes for 2000–2008 (shown on the right in Figure 1) include a small residual term. At present, F_{LUC} is dominated by tropical deforestation. Over 2000–2008, 85% of anthropogenic emissions arose from F_{Foss}, which increased at 3.5% $year^{-1}$, and the other 15% from F_{LUC}, which was nearly steady. Over a longer period from 1850 to 2008, total ($F_{Foss} + F_{LUC}$) emissions increased nearly exponentially at 1.92% $year^{-1}$ (doubling time 36 years), with F_{LUC} being the dominant contribution before 1900 and F_{Foss} dominating after 1950.

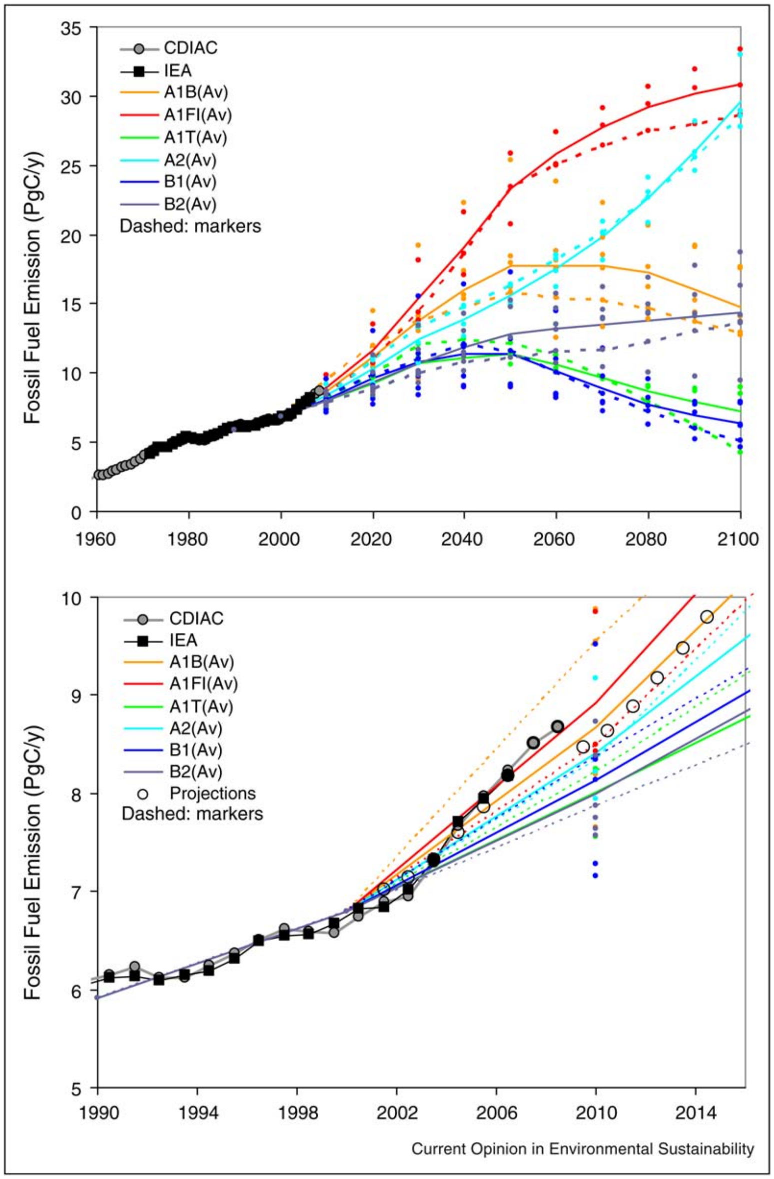
The CO_2 from total emissions accumulates in atmospheric, land and ocean reservoirs with average flux partition ratios for the period 1960–2008 of (0.45, 0.3 and 0.25) to (atmosphere, land and ocean) [24••,25•]. Thus, land and ocean CO_2 sinks respectively take up about 30% and 25% of all anthropogenic CO_2 emissions, leaving only about 45% to accumulate in the atmosphere. The continuing total CO_2 sink is a massive ecosystem service to the task of emissions mitigation.

There is substantial interannual variability in the partition ratios, mostly because of variability in the land sink [23••,24••]. Most of this interannual variability is associated with fluctuations faster than a period of 5 years [25•]. The variability correlates well with the El Niño-Southern Oscillation (ENSO) climate mode [26,27] and with volcanic activity [28], mainly because both signals modulate plant growth and soil respiration through rainfall, solar radiation and temperature.

The partition fraction to the atmosphere is the CO_2 airborne fraction (AF)[d], which has averaged close to 0.45 for the period 1960–2008 and (with more variability) since 1900. However, there has been an increase of the AF over the period 1960–2008 at a relative growth rate of $0.24 \pm 0.2\%$ $year^{-1}$, with probability $P \sim 0.9$ of a positive trend, detectable at this level of significance by using the correlations of CO_2 growth rate with ENSO and volcanic

[d] We use the total AF, $(dC_a/dt)/(F_{Foss} + F_{LUC})$. A widely used alternative definition (e.g. [29]) is the apparent airborne fraction [30,31], $(dC_a/dt)/F_{Foss}$. The total AF is a member of a set of partition fractions summing to 1, so that $1 - AF$ is the CO_2 sink fraction, but the apparent AF does not have this property [25].

Figure 2



CO_2 emissions from fossil fuels (F_{Foss}), updated from [33••]. Observed data from two sources (http://cdiac.esd.ornl.gov/trends/emis/em_cont.htm; http://www.iea.org/co2highlights/) are shown as black and grey points. Solid coloured lines are average future emissions in 6 scenario families [34], with 28 individual scenarios shown as coloured points and marker scenarios as dashed lines, with colours corresponding to solid lines. Observations are plotted at mid-year points (1990.5, 1991.5, . . .), and scenarios at integer decades (1990.0, 2000.0, . . .). Scenarios are rescaled slightly to match actual emissions over the period 1990–2000. Upper (a) and lower (b) panels show periods 1960–2100 and 1990–2015, respectively. Open circles in (b) are estimated emissions based on GWP projections [38] and an assumed carbon intensity of the economy (F_{Foss}/GWP) scaled to 2008 and reducing at 1.2% year^{-1}, the average value for 2000–2008 inclusive.

activity to reduce noise from interannual variability [24••,25•]. A later analysis using similar principles [32] appeared to contradict this result by finding no statistically significant trend, but the AF as defined in [32] included trends in ENSO and volcanic signals and was therefore not the measured AF. With consistent definitions of the AF and its trend, all three analyses [24••,25•,32] agree.

Apart from relatively rapid interannual variability, the AF demonstrates a remarkable near constancy over a century in the face of a doubling of total (fossil fuel plus land use change) CO_2 emissions every 36 years. The AF also demonstrates a small increase over the last 50 years. A constant AF would be observed if emissions grow exponentially and there is a linear response of land and ocean CO_2 sinks to atmospheric CO_2 perturbation, idealisations which are met surprisingly well by the real carbon cycle. However, the increase over the last 50 years indicates that CO_2 sinks are ceasing to respond linearly to atmospheric CO_2 and consequently are 'losing the race' with emissions which have continued to grow exponentially. If emissions continue to grow exponentially, the result will be a further increase in the CO_2 airborne fraction.

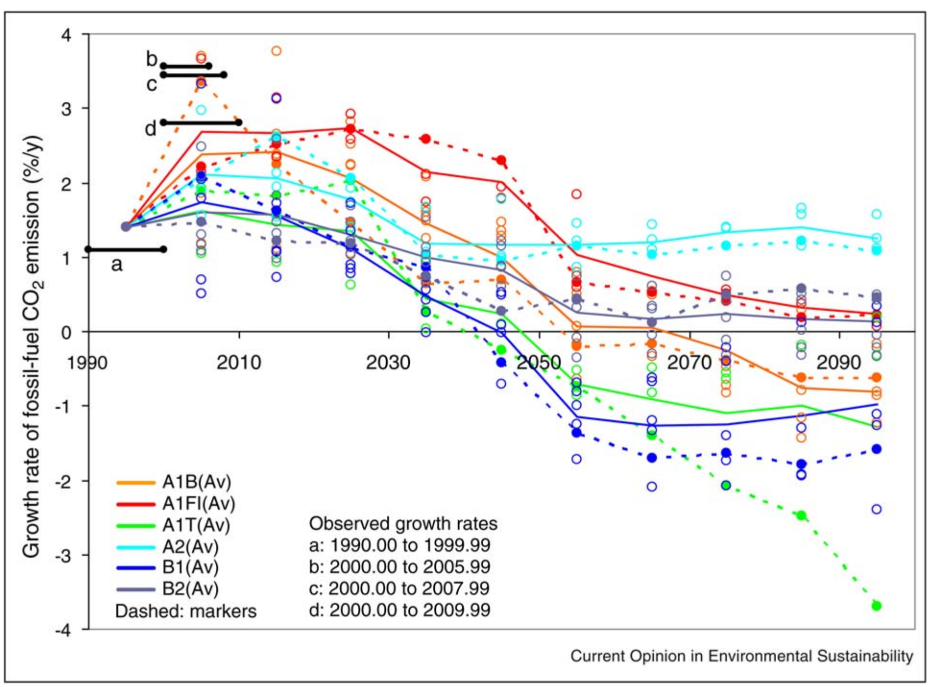
Trends in CO_2 emissions from fossil fuels

The question of the future evolution of fossil fuel emissions (F_{Foss}) is critical. Figure 2 updates a well-known figure [33••] superimposing observed historic data for F_{Foss} and projections from the Special Report on Emissions Scenarios (SRES) [34] of the Intergovernmental Panel on Climate Change (IPCC). The SRES projections are shown as 28 individual scenarios which can be assigned unambiguously to one of 6 scenario families (points), the averages of scenarios within these 6 families (solid coloured lines), and the 'marker scenarios' used for IPCC climate projections (dashed coloured lines). From 2000 to 2007 (inclusive) the growth rate of observed emissions was 3.5% year^{-1}, exceeding all scenario averages and almost all individual scenarios, with a few apparent exceptions including one marker scenario (A1B). The high emissions growth rate is expected to continue [35–37], driven by global economic growth centred in China and other rapidly developing economies, unless the carbon intensity of the global economy decreases much more rapidly than it has over recent decades [33••].

The global financial crisis of 2008–2009 has caused only a temporary slowdown in F_{Foss}. Figure 2b shows projections for F_{Foss} to 2014 based on Gross World Product (GWP) projections [38] and an assumed carbon intensity of the economy. The projections suggest that the financial crisis will cause emissions to fall by 2.8% in 2009 [23••]. In the absence of another financial crisis or immediate reductions in the carbon intensity of the global economy brought about by significant worldwide mitigation efforts, emissions growth will return within a few years to above 3% year^{-1}. Under these projections, the overall 'saving' in F_{Foss} from the financial crisis will be about three years of growth increments in F_{Foss}, or the cumulative F_{Foss} over about six weeks.

A difficulty with plots like Figure 2 is that there is some arbitrariness in the relative positions of the points for observations and scenarios, because of small uncertainties arising from reconciliation of past observations and scenarios (scenarios are rescaled slightly in Figure 2 to match observations over 1990–2000). This problem disappears if we compare proportional growth rates in emissions (Figure 3) rather than emissions themselves (Figure 2). Figure 3 demonstrates that observed growth rates for 2000–2007 (based on linear regressions) were

Figure 3



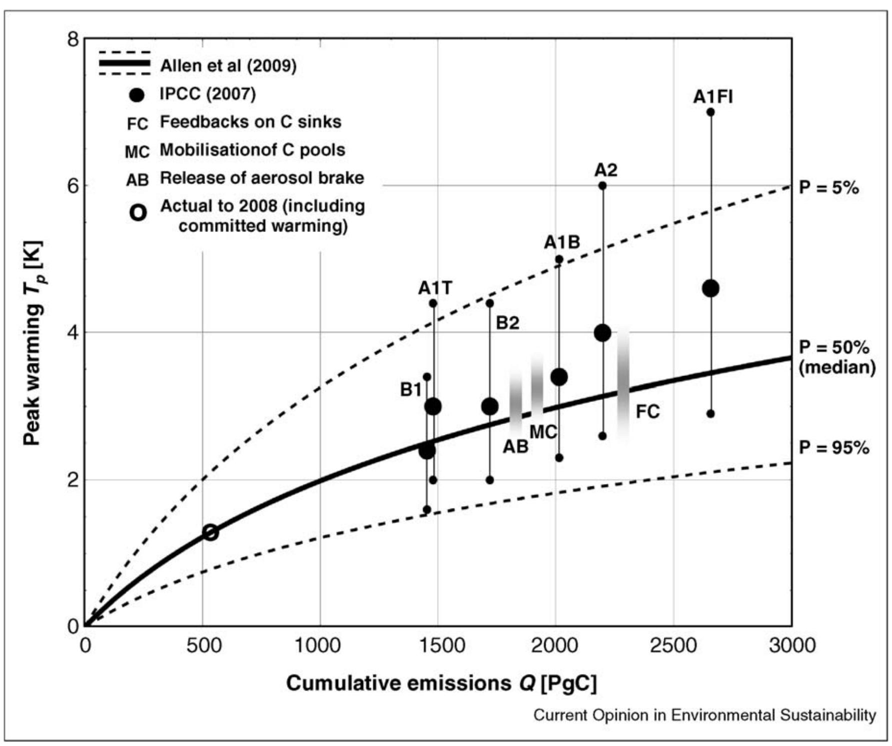
Proportional growth rates in CO_2 emissions from fossil fuels ($F_{\text{Foss}}^{-1} dF_{\text{Foss}}/dt$). Solid black bars show growth rates calculated by least-squares regressions to observed data for time intervals **(a)** 1990–1999, **(b)** 2000–2005, **(c)** 2000–2007, **(d)** 2000–2009 (all periods inclusive of end years), using CDIAC data and projections from Figure 2. Solid coloured lines show average future emissions growth rates in six scenario families [34], calculated from decadal first differences. Growth rates for individual scenarios shown as coloured points and for marker scenarios as dashed lines. Colours correspond with Figure 2.

indeed higher than all average and marker scenarios, including the A1B scenario, and higher than all but 2 of the 28 individual scenarios considered. Projected growth rates for 2000–2010 are lower because of the effect of the financial crisis, which will cause the average growth rate over the period 2000–2014 to be about 2.6% $year^{-1}$ with the emission projections in Figure 2b.

There has been some criticism [39] of the use of averages within the six scenario families in Figure 2 and its predecessors [33••,23••]. SRES [34] stated that no scenario, including any marker scenario, could be preferred over any other. The marker scenarios were selected to ensure that the scenarios used in IPCC climate projections were internally consistent, because nonlinearities in the integrated assessment models used to generate the scenarios would cause averages of scenarios to be internally inconsistent (for instance, different models had different population trajectories, different available energy options and the ways they interact).

This situation raises the question of what extra information is contained in the many SRES scenarios other than the markers. The entire set of SRES scenarios provides information about the evolution to 2100 of emissions and related economic and societal variables, based on the internally consistent beliefs of a large number of experts (the SRES contributors) as captured in models [40]. Any individual scenario depends on subjective choices, but these choices were constrained in SRES by defining six scenario families, each specified by a unique storyline [34]. The six ensembles formed by the scenario families provide information on plausible emissions futures as best understood at the time the SRES scenarios were developed, from expert investigators using identical subjective storylines. Therefore, we have used within-family averages of emissions as the best estimates of emissions trajectories, conditioned on the storylines. To the extent that they incorporate multiple assessments, none of which can be preferred, the averages contain more information than the marker scenarios; the full distributions (Figures 2 and 3) contain more information again. The markers differ from the averages (for instance being high for A1B and low for B1 over 1990–2010) to an extent expected when individual members are selected from scattered ensembles.

Figure 4



Peak warming from pre-industrial times (T_p) as a function of cumulative emissions (Q) from both fossil fuels and land use change, from 1750 to the far future. Solid curve is from [41••]; the 5–95% uncertainty range (dashed curves) shows probability of exceeding warming T_p at given Q, and corresponds approximately with effect of uncertainty in the climate sensitivity. Solid points show IPCC scenarios for 2100 (5), with uncertainty bars giving *likely* ranges in IPCC terminology (probability 2/3 of an outcome within this range). Grey bars show ranges of possible effects from (FC) coupled carbon–climate feedbacks on C sinks, from C^4MIP [47•]; (MC) mobilisation of previously immobile C pools; (AB) release of aerosol brake. All ranges are indicative only and include high uncertainty. Open circle shows cumulative emissions Q to 2008, with peak warming T_p including 0.7 K of warming observed to date plus 0.5 K of committed warming with radiative forcing stabilised at 2008 levels [5••].

Carbon and climate

The response of climate to human modification of the carbon cycle can be assessed through the relationship between peak warming above pre-industrial temperatures (T_p) and cumulative anthropogenic CO_2 emissions (Q) from fossil fuel combustion and net land use change since the start of the industrial revolution. Recent papers [41••,42••,43] have shown that the relationship $T_p(Q)$ is robust, within quantifiable uncertainty bands. To have a 50% chance of keeping T_p to less than 2 K, Q must be kept to less than 1000 PgC. Cumulative emissions to the end of 2008 were about 530 PgC, rising at nearly 10 PgC year^{-1} [23••], so more than half of the 1000 PgC quota has been used already. In this sense the world has passed 'peak CO_2' [44].

Figure 4, simplified from [43], shows estimates of $T_p(Q)$ from several sources. Solid and dashed lines give the predicted warming T_p exceeded with 50% (median), 95% and 5% probabilities, from [41••]. The black points show cumulative emissions and warmings to 2100 from IPCC scenarios [5••] (with confidence intervals encompassing 2/3 of the probability mass, corresponding to *likely* ranges in IPCC terminology). Forcing is measured by how far along the horizontal (Q) axis humanity chooses to proceed before CO_2 emissions are reduced to near zero. Response is measured on the vertical (T_p) axis, with several factors contributing to its uncertainties.

1. *Uncertainty in climate sensitivity*: Probably the largest uncertainty is in the response of climate to a given radiative forcing, because of poorly known physical and biogeochemical feedbacks which are both positive (reinforcing) and negative (dampening). Reinforcing feedbacks are particularly important because they lead to skewed or 'long-tailed' probability distributions for future climate change [45,46], which imply significant risks of very serious outcomes. The uncertainty because of climate sensitivity is comparable with that estimated by [41••], shown by dashed lines in Figure 4.
2. *Carbon–climate feedbacks on land and ocean CO_2 sinks*: The influence of climate change on land and ocean CO_2 sinks occurs both through changes in atmospheric composition (particularly rising CO_2) and changes in climate (particularly the averages and distributions of temperature and precipitation). The effects have been studied in carbon–climate model intercomparisons including the Coupled Carbon Cycle Climate Model Intercomparison Project (C^4MIP) [47•]; also see [48•]. C^4MIP found that carbon–climate feedbacks engendered by coupling of climate and carbon cycle models increased warming (under an A2 emissions scenario) by 0.1–1.5 K. This range is indicated by the 'FC' bar in Figure 4, encompassing median result from [41••] which also incorporated major carbon–climate feedbacks. This bar is located near the Q value for the A2 emissions scenario used in C^4MIP, though the uncertainty increases with Q in a way similar to the uncertainty shown by the dashed lines [43].
3. *Mobilisation of carbon from disturbed pools*: Several hitherto largely immobile carbon pools can be disturbed by climate change, leading to release to the atmosphere. A major potential pool is the organic carbon in frozen soils, estimated at nearly 1700 PgC in total [49•], of which around 100 PgC may be vulnerable to release by thawing over the next century [50•]. There is also a significant pool of carbon in tropical peatland soils, mainly in the Southeast Asian archipelago, of which around 30 PgC may be vulnerable to decomposition and fire following drainage [51•]. Net releases of carbon in other forest ecosystems are also likely through fire, insect attack and ecological transitions [52,53]. The 'MC' bar in Figure 4 shows a conservative range for the overall warming consequences of these vulnerabilities; this range depends on Q [43] and is shown at just one Q value for simplicity.
4. *Release of the 'aerosol brake'*: There are significant vulnerabilities associated with anthropogenic influences on the earth system other than through carbon–climate feedbacks. One concern is additional radiative forcing from release of the 'aerosol brake' on warming, which may occur as anthropogenic aerosol loads in the atmosphere decrease through efforts to improve air quality. This would reduce the present significant (though highly uncertain) net negative contribution from aerosol radiative forcing [54]. A possible range for the resulting additional warming is shown by the 'AB' bar in Figure 4; as with other bars, this range depends on Q [43].

These vulnerabilities act mainly to increase warming. Temperature increases are highly uncertain and are not additive. In particular, temperature increases may be higher than indicated if the climate system crosses thresholds which lead to further positive feedbacks.

Conclusion

Anthropocene changes in the earth system, including changes in the carbon cycle, climate and other aspects, are a fundamental outcome of the evolutionary advantage acquired by humankind through its use of exosomatic energy flows. Detrital carbon was the initial energy source for these flows and is still a major source. Many of the resulting perturbations to the earth system are now growing exponentially [3] which clearly cannot continue indefinitely on a finite planet. In this century, the greatest challenge facing humankind is to develop resilience to these finite-planet vulnerabilities.

Acknowledgements

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