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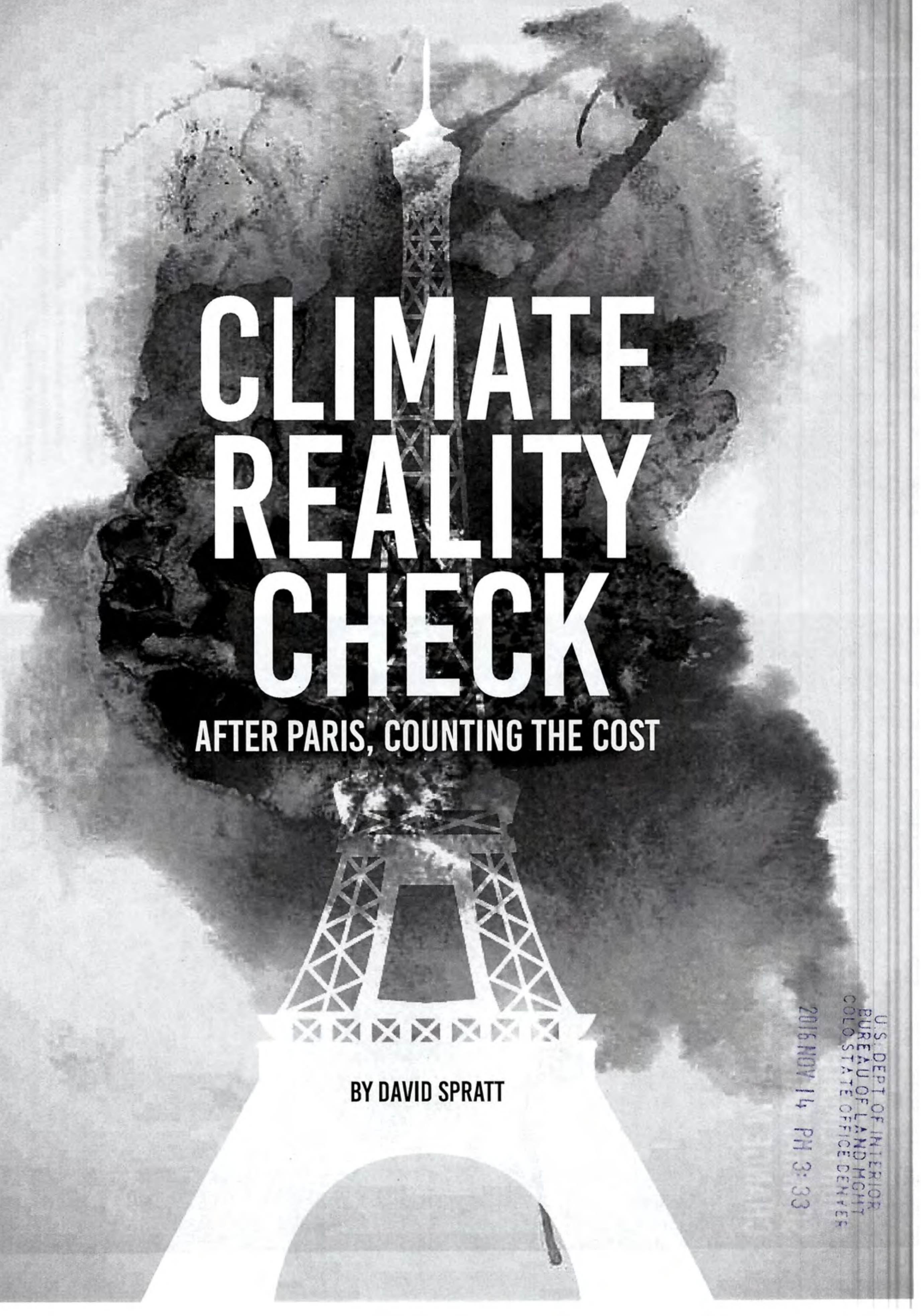
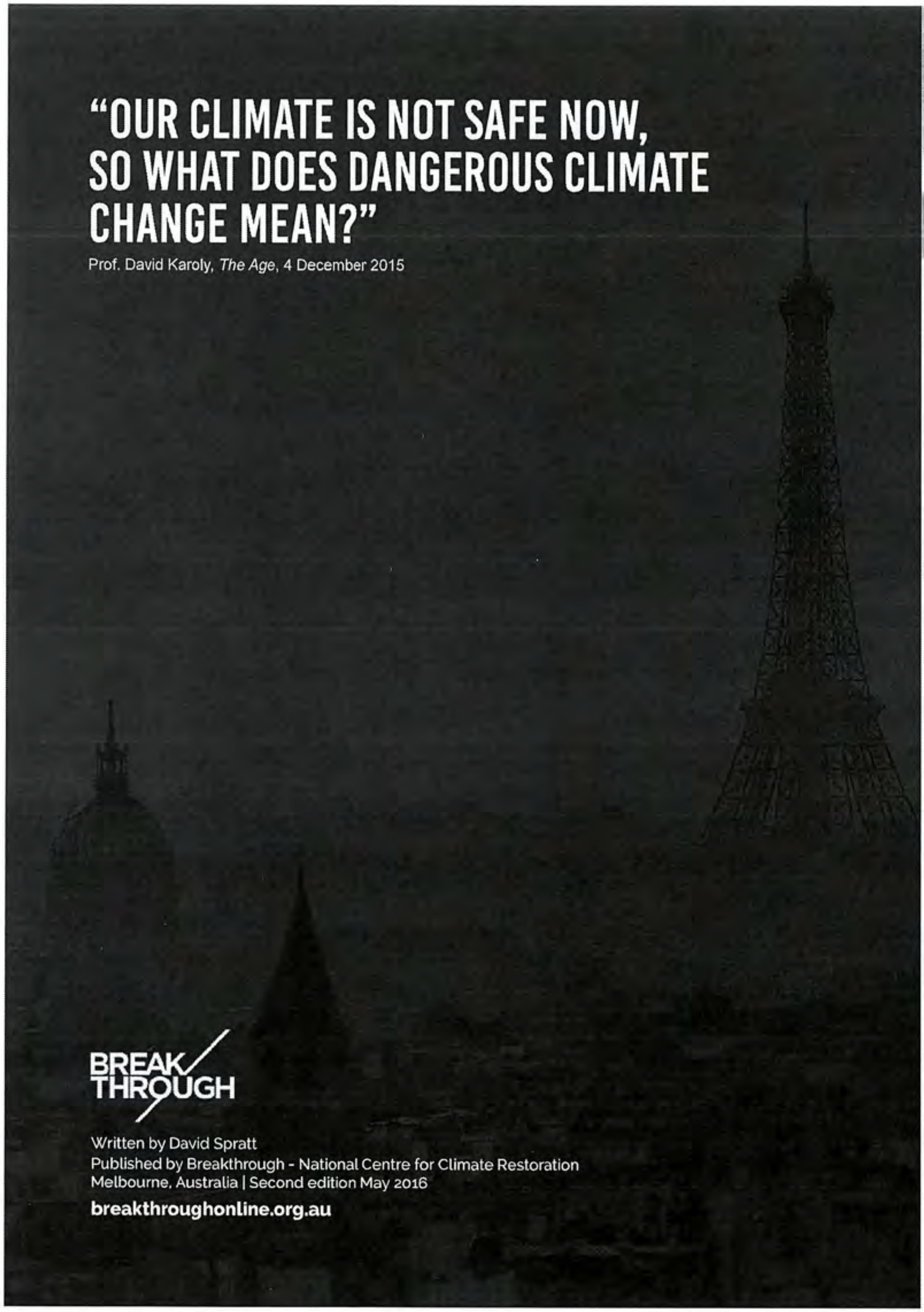


CLIMATE REALITY CHECK

AFTER PARIS, COUNTING THE COST

BY DAVID SPRATT



"OUR CLIMATE IS NOT SAFE NOW, SO WHAT DOES DANGEROUS CLIMATE CHANGE MEAN?"

Prof. David Karoly, *The Age*, 4 December 2015

BREAK THROUGH

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AFTER PARIS, COUNTING THE COST

The December 2015 Paris climate conference was a failure marketed as a success. It sets the world on course for more than 3°C of warming and all but precludes a less-than-2°C future unless radical climate interventions are applied. Commentators say "deadly flaws" in the Paris deal mean it gives the impression that global warming is now being properly addressed, when in fact the measures fall alarmingly short of what is needed to avoid escalating climate change.

Prof. Kevin Anderson of the UK Tyndall Centre for Climate Change is fond of quoting the twentieth century quantum physicist and Nobel laureate Richard P. Feynman: "For a successful technology, reality must take precedence over public relations, for Nature cannot be fooled."

We fool ourselves if we are not deeply alarmed by recent events. In 2015, atmospheric carbon dioxide (CO2) concentrations jumped by 3.05 parts per million (ppm), the largest year-to-year increase in 56 years of research data. 2015 was the fourth consecutive year that CO2 grew more than 2 ppm.[1] Methane levels also reached a new instrumental high, 254 per cent higher than the pre-industrial level.[2] And Arctic sea-ice extent hit a record winter low.

2015 was the hottest year on record by a significant margin, and the UK Met Office says 2016 will be as hot or hotter.[3] Scientists were stunned by NASA data that February 2016 was an "unprecedented" 1.65°C warmer than the beginning of the twentieth century, that is, 1.9°C higher than the pre-industrial level.[4] The current El Niño conditions have contributed around 0.2°C to the record figures[5] but, compared to previous big El Niños, we are experiencing blowout temperatures.

Prof. Michael Mann says, "We have no carbon budget left for the 1.5°C target and the opportunity for holding to 2°C is rapidly fading unless the world starts cutting emissions hard right now".[6] Other experts agree.

Prof. Stefan Rahmstorf of Germany's Potsdam University considers that we are now "in a kind of climate emergency"[7] and that at least 1.5°C is "locked in".[8] More and more scientists agree.

Like the dramatic and unexpected Arctic "big melt" in 2007, these record temperatures confront us with the terrifying reality of global warming, for Nature cannot be fooled. The recent data suggest it has taken just months for the Paris climate accord — with its escalating emissions to 2030 — to become a relic, grossly inadequate for the task the world now faces.

So what is the reality after Paris? What do recent research findings and observations teach us? And what does decisive leadership look like in the era of climate emergency?

1. CARBON EMISSIONS & TEMPERATURE

Human-caused carbon dioxide emissions increase the global average temperatures, such that the elevated temperatures remain roughly constant for many centuries.[9] One landmark research paper says that "any future anthropogenic emissions will commit the climate system to warming that is essentially irreversible on centennial timescales".[10]

In other words, we cannot, on human time scales and in the normal course of events, undo the elevated temperatures and damage done by CO_2 emissions. The only exception to this understanding would be the deployment of incoming solar radiation management or very large-scale CO_2 removal (negative-emission) technologies to cool the Earth. In the main, these technologies at present are at little more than a conceptual stage of development and not currently deployable at scale (see Section 14).[11]

2. "COMMITTED" WARMING

Accounting for inter-annual variability, global warming has now reached ~1°C above the 1880-1920 level.[12] And warming is now ~1.2°C above the 1750 pre-industrial level.[13]

If we were to cease burning fossil fuels today, the loss of aerosol cooling (see next section) would quickly add ~0.5°C or more to temperatures, taking warming to ~1.7°C above the pre-industrial level.[14] The more fossil fuels we burn, the higher this level of of "committed" warming will become in the absence of yet unproven, large-scale, negative-emission and/or solar radiation technologies.

Each decade, human activity is adding ~20 ppm of CO_2 to the atmosphere,[15] enough to cause an extra ~0.2°C of warming. So if the emissions trajectory over the next 15 years follows the Paris path — in which annual emissions would be ~10% higher in 2030 than they are today[16] — then by 2030 "committed"" warming will have risen by ~0.3°C to ~2°C.

Analyst Bill Hare of Climate Analytics says: "if the Paris meeting locks in present climate commitments for 2030, holding warming below 2°C could essentially become infeasible."[17] In this sense, Paris has locked out a less-than-2°C outcome, unless immediate and radical emission reductions occur across the high-polluting, developed economies.[18]

3. FAUSTIAN BARGAIN

A by-product of burning fossil fuels is a group of substances known as aerosols (including black-carbon soot, organic carbon, sulphates and nitrates) which have a short-term (~one week) cooling impact generally estimated to be in the range of -0.5–0.8°C. For now, these aerosols are ameliorating the warming impact of increasing levels of greenhouse gases, including carbon dioxide, methane and nitrous oxide.

Reducing the use of fossil fuels, however, will also reduce the production of aerosols, and the loss of their cooling effect will increase the global temperature. But not stopping fossil fuel use will eventually cause global warming sufficient to threaten human civilisation.

Former NASA climate science chief Prof. James Hansen keenly observed this dilemma to be our Faustian bargain, in which the "devil's payment" will be extracted from humanity via increased global warming as we end fossil fuel use:: "As long-lived CO_2 accumulates, continued balancing requires a greater and greater aerosol load. Such a solution… would be a Faustian bargain. Detrimental effects of aerosols, including acid rain and health impacts, will eventually limit the permissible atmospheric aerosol amount and thus expose latent greenhouse warming."[19]

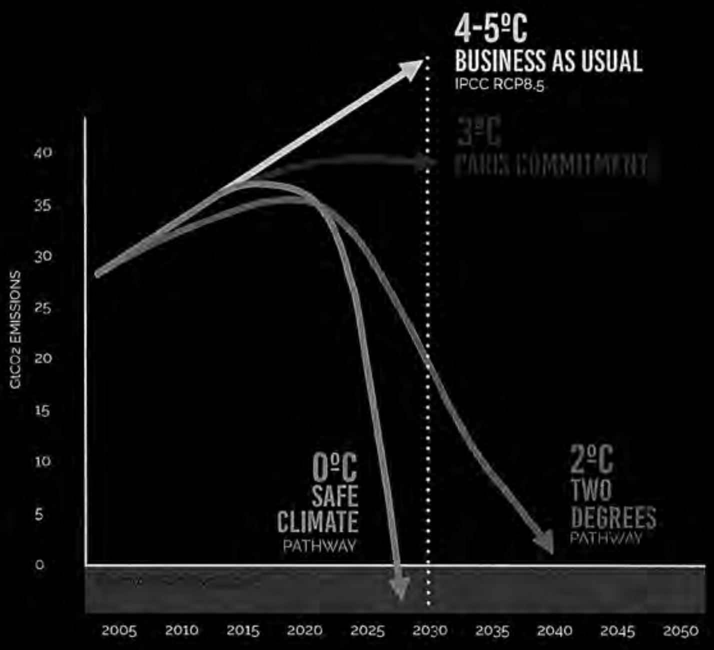
4. PARIS COMMITMENTS

Although the Paris deal gives the impression that global warming is now being properly addressed, in fact the measures fall alarmingly short of what is needed to avoid escalating climate change.[20] Amongst its "deadly flaws" is the lack of any requirement that the parties must upgrade their existing pledges before 2030.

Indeed, analysis reveals that the Paris voluntary commitments, with no further progress in the post-pledge period, would result in expected warming by 2100 of 3.5°C (uncertainty range 2.0–4.6°C).[21]

Claims that the Paris commitments represent a 2.7°C path are a misconception, based on an unjustified assumption that countries will commit in the future to keep reducing emissions after 2030 at the rate they did before 2030.[22]

PARIS COMMITMENTS COMPARED TO 2°C PATHWAY



SOURCES[7]: WBGU special report 2009, Boyd, Stern & Ward (May 2015), IPCC 2014, Climate Action Tracker, Philip Sutton

5. FEASIBILITY OF 1.5ºC GOAL

The Paris agreement's stated aims are to keep warming "well below 2°C above pre-industrial levels" and to "pursue efforts to limit the temperature increase to 1.5°C".

A goal far below 1.5°C is highly desirable, because climate change is already dangerous.

"Committed" warming today is now 1.7°C[23] and will be ~2°C by 2030 if emissions proceed along the Paris pathway. So there is no carbon budget left for 1.5°C: "And what about 1.5°C stabilisation? We're already overdrawn", says Prof. Michael E Mann, one of the world's foremost climate scientists.[24]

Researchers say there are no "model scenarios where global temperatures remain below 1.5°C throughout this century". "Overshoot" scenarios — exceeding 1.5°C of warming and returning to below 1.5°C by assuming the deployment of large-scale negative-emission technologies later in the century — impose challenging requirements, including "curtailing future energy demand... with only a slight increase over today's demand by 2100, despite rising populations and growing economies".[25]

The possibility of staying below 1.5°C of warming for the whole of this century would require geo-engineering techniques such as the deployment of sulphate aerosols to reduce the amount of incoming solar radiation (see Section 14). Such approaches are not proven or safe technology, and are opposed by the large climate action NGOs, without exception. Likewise, the large-scale negative-emission technologies necessary to get warming back under 1.5°C by 2100 in the "overshoot" scenarios are not presently deployable in an environmentally safe way and at manageable cost, and are strongly opposed by significant elements of the climate justice movement.

6. RELIANCE ON NEGATIVE EMISSIONS TECHNOLOGIES

Rather than requiring large emissions reductions in the short-to-medium term, the Paris agreement instead relies on being able to successfully suck the carbon pollution back from the atmosphere in the longer term, plumping for biomass energy with carbon capture and storage (BECCS) as the most promising negative-emissions technology.

BECCS is an unproven technology at scale and "negative-emission technologies... are currently at little more than a conceptual stage of development", yet the framing of the 2°C goal and, even more the 1.5°C one, is premised on the massive uptake of BECCS some time in the latter half of the century.[26]

Potsdam Institute head Prof. John Schellnhuber warns against "the illusion you can just extract huge amounts of carbon from the air in order to restore the atmosphere".[27]

The land-use intensity of BECCS is quite high, with values of ~1-1.7 hectares per ton of carbon per year.[28] In other words, if ALL the world's land currently devoted to cropping (~3 billion hectares) were devoted to BECCS, the drawdown would be ~3 billion tonnes of carbon per year — still only about 30% of the world's current annual emissions. Whether the storage of the compressed carbon dioxide in expired oil and gas fields and other underground geological sites would be secure and stable over the long term is another question for which there is yet no satisfactory answer.

CHANCES OF KEEPING BELOW 2ºC

Releasing a further...

2°C is the boundary between dangerous & very dangerous climate change - how much can we chance?

7. CARBON BUDGETS

Any temperature target only has practical meaning if the size of the risk of exceeding it is known, and the scale of the impacts of exceeding the target are also known. A low-impact risk target for atmospheric greenhouse gases is very much less than the current level: the IPCC reported that "to provide a 93% mid-value probability of not exceeding 2°C, the concentration (of atmospheric greenhouse gases) would need to be stabilised at or below 350 parts per million carbon dioxide equivalent (ppm CO2e)" compared to the current level of ~485 ppm CO2e.[29]

The catastrophic consequences caused by 2°C of warming demand a strong risk-management approach of having a very low probability of exceeding the target, and taking fully into account the likelihood of changes in the carbon cycle. Yet policymakers focus on "middle of the road" outcomes, and turn a collective blind eye to the bad possibilities that are much more likely to occur than is widely acknowledged (see Appendix).

While policy-makers and advocates often talk about a carbon budget of allowable fossil fuel use that would limit warming to 2°C, the evidence shows we have no such budget for a sensible risk-management, low-risk probability of exceeding that target.[30] There is no carbon budget if 2°C is considered a cap (an upper boundary not to be exceeded) as per the Copenhagen Accord, rather than a target (an aspiration which can be significantly exceeded). And there is no carbon budget for fossil fuel emissions after accounting for likely emissions resulting from future food production and deforestation.

Anderson and Bows have shown that even with a too-high goal of holding temperatures to 2°C (with only a 66% probability of success), for developed economies to play a fair role they would have to cut their emissions by 40% reduction by 2018, 70% reduction by 2024, and 90% by 2030 from 1990 levels.[31]

8. CARBON CYCLE FEEDBACKS

There is an unacceptable risk that before 2°C of warming is reached, significant "long-term" feedbacks will be triggered, in which warmer conditions make carbon sinks (stores) such as the oceans and forests less efficient at storing carbon, and polar warming triggers the large-scale release of greenhouse gases from melting terrestrial permafrost and frozen methane deposits on the ocean floor.

This escalating release of greenhouse gases generates even more warming in a cycle of reinforcing feedbacks that could make an effective human response extremely difficult.

It is conventionally considered that these feedbacks operate on millennial timescales. Yet the rate at which human activity is changing the Earth's energy balance is without precedent in the last 66 million years and about ten times faster than during the Palaeocene–Eocene Thermal Maximum, a period with one of the largest extinction events on record.[32] The rate of change in energy forcing is now so great that these "long-term" feedbacks have already begun to operate within short time frames.

A recent study makes use of projections from the most recent IPCC report to estimate that up to 200 billion tonnes of carbon could be released due to melting permafrost and cause up to 0.5°C extra warming.[33] Some carbon stores have already reached a tipping point, and are now becoming carbon emitters rather than carbon sinks.

These include Arctic tundra.[34] One research paper concluded that: "the permafrost carbon feedback will change the Arctic from a carbon sink to a source after the mid-2020s and is strong enough to cancel 42–88% of the total global land sink." [35]

In February 2013, scientists using radiometric dating techniques on Russian cave formations to measure melting rates warned that a 1.5°C global rise in temperature compared to the pre-industrial level was enough to start a general permafrost melt. [36]

In the first half of 2015, new lines of evidence were published suggesting that more elements of the system may be heading towards tipping points or experiencing qualitative change, including: the slowing of the major sea current known as the Atlantic conveyor, likely as a result of climate change; accelerating ice mass loss from Antarctic ice shelves and the vulnerability of East Antarctica glaciers; declining carbon efficiency of the Amazon forests and other sinks; rapid thinning of Arctic sea-ice; and the vulnerability of Arctic permafrost, exemplified by the proliferation of Siberian methane craters. [37]

9. CRYOSPHERE THRESHOLDS

In late 2015, a chilling report on *Thresholds and closing windows: Risks of irreversible cryosphere climate change*[38] warned that the Paris commitments will not prevent the Earth "crossing into the zone of irreversible thresholds" in polar and mountain glacier regions, and that crossing these boundaries may result in processes that cannot be halted unless temperatures were returned to below the pre-industrial level.

It warns that: "These thresholds are drawing closer… some of these changes may close during the 2020–2030 (Paris) commitment period."

The consequences would include the loss of reliable water resources from mountain glaciers for millions of people; the melting polar of ice sheets that would set the world on course to a sea-level rise of 4–10 metres or more; and the loss of fisheries and ecosystem loss from polar ocean acidification.

The report says it is not well understood outside the scientific community that cryosphere dynamics are slow to manifest but once triggered "inevitably forces the Earth's climate system into a new state, one that most scientists believe has not existed for 35–50 million years".

Observational estimates based on model simulations and the record of past climates make it appear very likely that "the loss of certain vulnerable parts of our planet's ice sheets will become unstoppable at temperatures and CO_2 concentrations at, or very close to those of today". The "best estimate" for "the threshold for Greenland melt to become irreversible" is 1.6°C, a threshold beginning near today's levels and well below the 2.7–3.5°C estimate from the Paris Accord.

10. ACCELERATING SEA-LEVEL RISE?

Climate warming causes the ocean volume to expand. It melts polar and mountain glaciers. Both raise the sea level. The questions are how far, and how fast?

Estimates of sea-level rise this century have been 0.5–2 metres, and centred around 1 metre, but this is only the tip of the iceberg. Prof. Kenneth Miller says: "The natural state of the Earth with present CO_2 levels is one with sea levels about 70 feet (21 metres) higher than now."[39] Other research scientists agree it is likely to be more than 20 metres.[40] The long-term sea-level rise associated with a 2°C warming would submerge parts of Australia on which 25-50% of the population lives.[41]

Major recent studies show a number of polar ice sheets are unstable and heading toward collapse. As to how fast the seas will rise, one answer is "several metres" this century, according to Prof. James Hansen and 17 highly-regarded co-authors, who map a potential path to the "loss of all coastal cities" and the arrival of "super storms" not previously experienced by humans.[42] Superstorm Sandy and Cyclone Haiyan may be precursors of such a future.

This research surveys evidence from the previous Eemian warm interglacial around 120,000 years ago of rapid fluctuations in sea level, and identifies a mechanism in the Earth's climate system not previously understood, but which points to a much more rapid rise in sea levels than currently anticipated. Increasing ocean stratification occurs when cooler surface layers from melting ice sheets trap warmer waters underneath, accelerating their impact on the melting of ice shelves and outlet glaciers. This in turn increases ice sheet mass loss, and generates more cool surface melt water in a positive feedback.

The consequences include the slowing or shutting down of key ocean currents including the Gulf Stream System, which would increase temperature differentials between tropical and sub-polar waters, and drive "super storms" such that "All hell will break loose in the North Atlantic and neighbouring lands."[43]

The projected cooling pattern of waters around Antarctica and the north Atlantic waters from the injection of fresh ice-melt water is already visible in the observed data and is already contributing to a circulation decline of the Gulf Stream System and cooling of some European countries.[44]

Another significant new study [45] dovetails with the Hansen study and concludes that "Antarctica has the potential to contribute more than a metre of sea-level rise by 2100 and more than 15 metres by 2500", doubling previous forecasts for total sea level rise this century to 2 metres and more. "People should not look at this as a futuristic scenario of things that may or may not happen. They should look at it as the tragic story we are following right now," says Eric Rignot, an expert on Antarctica's ice sheet and an earth sciences professor at the University of California.[46]

Retreat of Jakobshavn Glacier, Greenland.
NASA Earth Observatory images by Jesse Allen & Robert Simmon

11. ONE-DEGREE IMPACTS

Evidence suggests tipping points for events, which may be irreversible on century time scales, are being crossed already. The Arctic is warming two-to-three times as fast as the global average.[47] Even before we reached 1°C of global warming, a dynamic had been established that will lead to sea-ice-free Arctic summer conditions, with severe consequences for the future stability of permafrost and frozen methane stores, and for sea-level rises, as well as for accelerated global warming as ice sheets retreat and the Earth's albedo (reflectivity) decreases.[48]

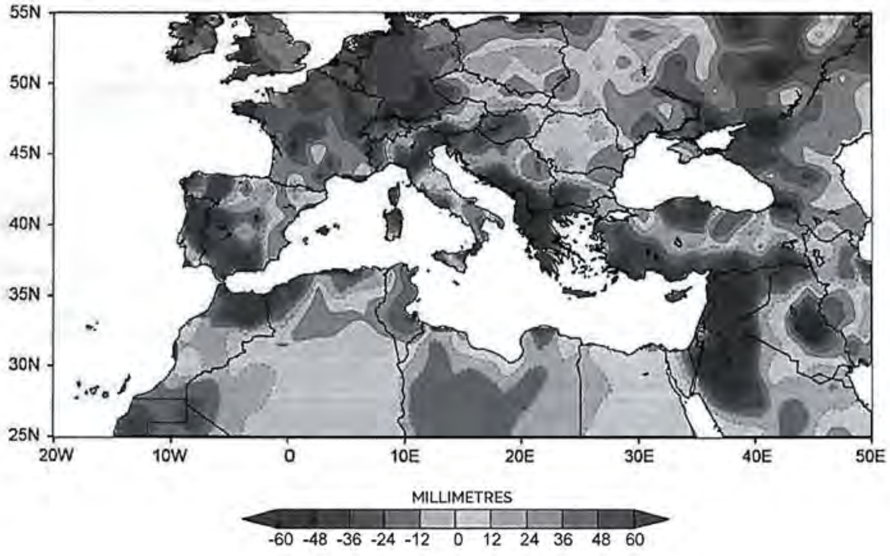
One of the most significant research findings in 2014 was that the "tipping point" has already been crossed for the Amundsen Sea sector of West Antarctica at under 1°C of warming. Scientists found that the retreat of ice was "unstoppable" (unless temperatures return to the level of the 1970s). The consequences include that: "sea levels will rise one metre worldwide… [the ice's] disappearance will likely trigger the collapse of the rest of the West Antarctic ice sheet, which comes with a sea level rise of between 3–5 metres. Such an event will displace millions of people worldwide."[49] (Note: "millions" would seem a significant understatement.)

While a one-metre sea-level rise may sound manageable, it would destroy some nations, flood some of the world's richest river-delta agricultural lands or render them unusable due to salination, and likely create climate-change-driven failed states. In Bangladesh, a one-metre sea level rise would inundate 15-17% of the land and threaten more than a million hectares of agricultural land. The Mekong River Commission warns that a one-metre sea-level rise would wipe out nearly 40% of the Mekong Delta.[50] A one-metre rise would flood one-fourth of the Nile Delta, forcing more than 10% of Egypt's population from their homes. Nearly half of Egypt's crops, including wheat, bananas and rice, are grown in the delta.[51]

Current climate trends, if not arrested and reversed rapidly, will likely lead to a substantial displacement of, and reduction in, global population, with attendant mass social conflict and migration, early signs of which are already evident in the Middle East and North Africa.

The Syrian conflict was preceded by the worst long-term drought and crop failures since civilisation began in the region, resulting in 800,000 people losing their livelihoods by 2009, and 2–3 million being driven into extreme poverty.[52] The eastern Mediterranean has experienced significant deceases in winter rainfall over the past four decades, as illustrated.[53]

Cold season (Nov-Apr) rainfall anomaly 1971-2010 compared to 1902-1970
Reds, oranges and yellows highlight lands which experienced significantly drier winters



12. DAMAGE BEFORE 2°C

The damage that will eventually be caused by the current level of warming of just 1°C is beyond adaptation for many nations and peoples, yet much higher temperatures targets have been the goal of policy-makers. Prof. James Hansen maintains that it is "well understood by the scientific community" that goals to limit human-made warming to 2°C are "prescriptions for disaster", because "we know that the prior interglacial period about 120,000 years ago was less than 2°C warmer than pre-industrial conditions and sea level was a least five to nine metres higher, so it's crazy to think that 2°C is a safe limit".[54]

The 2009 Copenhagen climate conference of governments agreed that there should be a scientific review of the 2°C cap. It was completed in 2015 for the secretariat of the UN Framework Convention on Climate Change and concluded that that 2°C is not a safe temperature cap and that a 1.5°C cap, while causing less damage than the 2°C cap, is also not safe.[55]

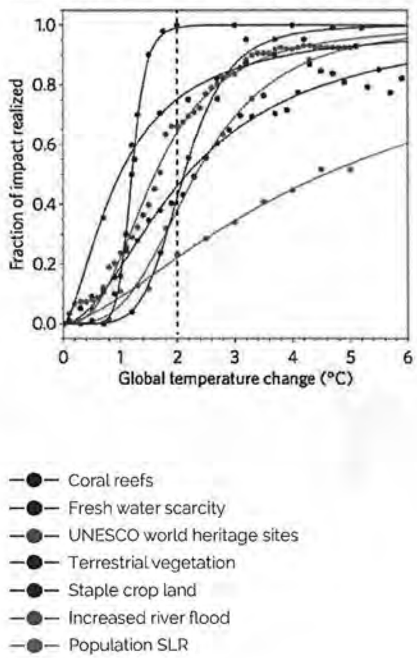
Scientists have found evidence of 41 cases of regional abrupt changes in the ocean, sea ice, snow cover, permafrost and terrestrial biospheres, many of which occur for global warming levels of less than 2°C. Although most climate models predict one or more abrupt regional shifts, any specific occurrence typically appears in only a few models.[56]

Warming of 1.5°C would set sea level rises in train sufficient to challenge significant components of human civilisation, besides reducing the world's coral ecosystems to remnant structures.[57]

Before or around +1.5°C, more significant events are likely to occur, including a decline in the efficiency of terrestrial and ocean carbon stores, and the already-documented accelerating ice-mass loss from the Greenland ice sheet and West Antarctic glaciers. New research looks at the damage to system elements — including water security, staple crops land, coral reefs, vegetation and UNESCO World Heritage sites — as the temperature increases. The findings are sobering. Almost all the damage from climate change to vulnerable categories like coral reefs, freshwater availability and plant life could happen before 2°C warming is reached, as the chart from this research results dramatically shows.[58]

Additionally, temperatures below 2°C could trigger the release of CO2 and methane from natural carbon stores (eg. permafrost, ocean-floor methane deposits, forests and peat deposits) on such a scale that human efforts to contain the level of future warming to manageable levels could be rendered ineffective.

Maximum potential climate change impacts for various sectors as determined by the sigmoidal fit



13. HOLOCENE CONDITIONS

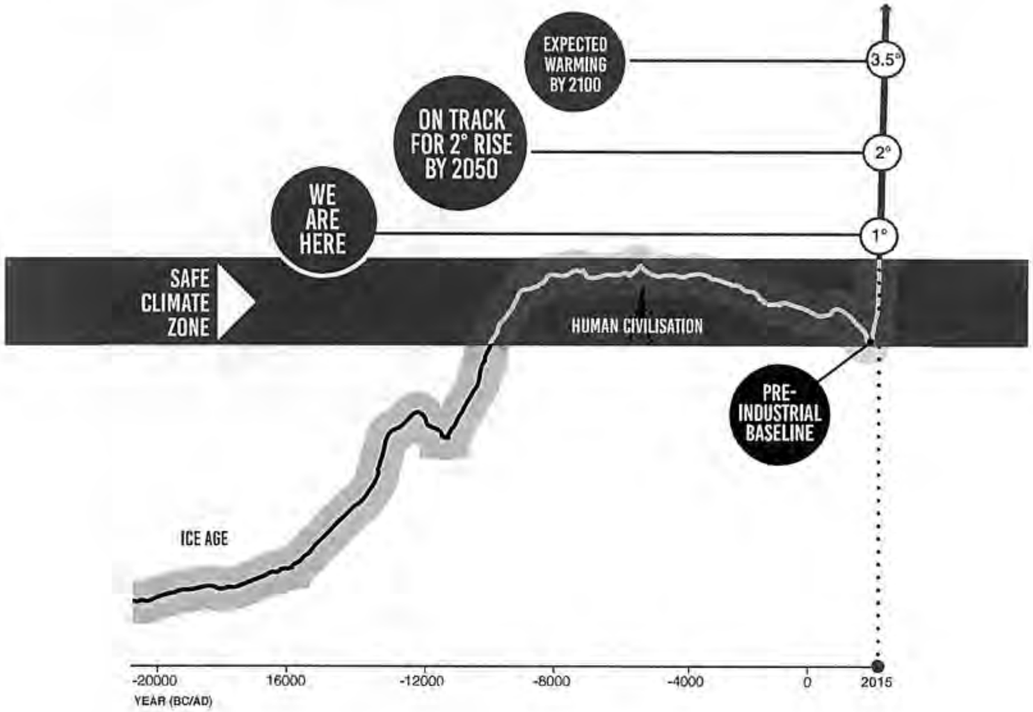
Human civilisation has flourished over the last 11,000 years under relatively stable climate conditions and sea levels in a period known as the Holocene, which provided a "safe operating space" for global societal development. [59] We have already left the Holocene temperature range, however. Reestablishing Holocene conditions of less than 325 ppm CO2e would be safe for humanity, especially given that so much of human civilisation comprises coastal settlement and delta/flood plain agriculture.

If a significant proportion of coastal settlement were to be overwhelmed by rising sea levels and forced to retreat, what then would be "safe" for humanity?

Even a small global warming above the level of the Holocene begins to generate a disproportionate warming on the Antarctic and Greenland ice sheets.[60] Even a moderate sea level rise of 1–2 metres in less than a century would produce a change in coastlines that is unprecedented for human civilisation.

Current atmospheric greenhouse gas levels (~400ppm CO2 and ~485 CO2e) are likely the highest in the last 15 million years, and never previously experienced by humans. The current conditions, if maintained over centuries to millennia (that is, until the system reaches equilibrium), would likely produce temperatures 3–6°C warmer and sea level rises of 25 metres or more, based on evidence of past climates.[61] There is a widespread view amongst scientists that "a 4°C future is incompatible with an organised global community, is likely to be beyond 'adaptation', is devastating to the majority of ecosystems and has a high probability of not being stable".[62]

Given the current state of the atmosphere, getting back to Holocene-like greenhouse gas conditions would require a rapid end to human-caused emissions, and the deployment at massive scale of efficacious biological and other carbon dioxide drawdown measures to reduce the level of atmospheric greenhouse gases for many, many decades and perhaps a century or more.



14. CLIMATE INTERVENTIONS

For thirty years, efforts to tackle climate change have focused almost entirely on emissions reduction. But the modest scale and slow pace of action, plus better scientific understanding of what constitutes dangerous climate change, have led to the realisation that what is required is not just a slowing or stabilisation of the warming, but instead a cooling of the earth to below its current temperature.

To cool the earth requires two steps. The first is an end to human emissions, to stop making warming worse. The second is removing excess CO2 from the atmosphere and/or solar radiation management, which reflects a small amount of the incoming sunlight back to space.

Solar radiation management (SRM) and carbon dioxide removal (CDR) may be termed climate interventions or engineering: "purposeful actions intended to produce a targeted change in some aspects of the climate".[63] They could only make a practical contribution if they complement dramatic emissions reduction efforts, and their net benefit depends upon their technical effectiveness, cost, risk and governance.

SRM techniques are designed to produce immediate surface cooling by employing aerosol-cooling sulphates or similar into the lower stratosphere, or boosting the earth's reflectivity in some other way. The cooling effect would be almost immediate (within months) and substantial and the cost relatively low.[64]

SRM techniques have not demonstrated clear net benefits because of as yet not-fully-understood but damaging side effects.[65] They may not be able to simultaneously restore all features of the climate (e.g., temperature and rain/snow distribution) and do not address the issue of dangerous levels of ocean acidification. There are crucial unresolved ethical, political and governance issues. SRM could actually reduce the incentive to curb anthropogenic CO2 emissions.

Some CDR techniques such as reforestation and afforestation are proven and safe, but limited in scale. Covering 3% of the world's surface with forests would be equivalent to negating just 10% of the world's current greenhouse gas emissions (a billion tonnes of carbon annually). Other CDR techniques include biochar, land management, accelerated weathering, bioenergy with carbon capture and sequestration (BECCS), direct capture and sequestration, ocean fertilization and seaweed and algal farming.

Many of these are unproven, high cost at present, slow to implement, not currently deployable at the scale needed, and have implications for land use and the maintenance of food production and traditional land ownership, farming and biodiversity protection, because of the large spatial areas required (See section 6 above).

The impact of CDR would be slow and "will not have an appreciable effect on global climate for decades" and hence does not provide an opportunity for rapid reductions of global temperature. [66]

The use of carbon capture and storage technology to store liquid CO2 either from power and industrial plants or direct capture from the atmosphere in disused oil and gas fields and other geological formations is being deployed and has substantial business-sector and policymakers' support in establishing a liquid CO2 market perhaps larger than the existing oil industry. There is concern about the ethics and efficacy of such an approach, and the safety and stability of such storage, especially in geological formations other than disused oil and gas fields and in deep ocean sediments. At the moment, most CDR options are much more expensive than emissions reduction costs, so in the first instance emissions reduction is the better option in giving more "bang for the buck", though some deployment of carbon drawdown will help drive it down the cost curve. CDR becomes important when the marginal cost is less than that of reducing emissions, only then, "with declining costs and stronger regulatory commitment, atmospheric CO2 removal could become a valuable component of the portfolio of long-term approaches to reducing CO2". [67]

The bottom line remains a question of least-worst options. The US National Academy of Sciences poses a question most of us would hope does not materialize: "If, despite mitigation and adaptation, the impacts of climate change still become intolerable (e.g., massive crop failures throughout the tropics), society would face very tough choices regarding whether and how to deploy albedo modification until such time as mitigation, carbon diox8de removal and adaptation actions could significantly reduce the impacts of climate change." It concludes that despite the moral hazard risk that albedo modification research may distract from the mitigation effort, "the potential risks from climate change appear to outweigh the potential risks from the moral hazard associated with a suitably designed and governed research program". [68]

It must be emphasized that none of these technologies is currently viable at scale in terms of technical effectiveness, cost, risk and governance.

15. DISCUSSION

Over the medium-to-long term, living with 2°C or more of warming will, in Prof. James Hansen's words, condemn "our biggest, most prosperous and populated cities to an underwater existence".[69] Climate change is already dangerous, especially for the world's most vulnerable people and species. Yet, there is no pathway to keeping warming below 1.5°C without unproven solar radiation management. In light of the Paris commitments over the next 15 years, it is also very difficult to construct pathways that do not exceed 2°C thresholds and prevent more significant tipping points being from crossed, unless large-scale climate interventions are also adopted.

Humanity faces an existential crisis. What can be done about the immediate challenges this poses?

HOW DO WE RESOLVE THESE CHALLENGES?

- **The immediate goal of any climate strategy must be to avoid passing further significant tipping points, including those related to the carbon cycle, ice sheets and sea levels.** We must seek actions that form the least-worse path for future emissions, greenhouse gas levels and temperatures.

- **No matter what we do, there will be severe and unavoidable consequences, especially for peoples and ecosystems most vulnerable to a hotter climate.** We must focus on preparing for and adapting to the changes that are now inevitable, while working to achieve negative emissions and reduce warming in a manner that causes the least damage.

- **The best path is one that includes emergency-scale action to get to zero emissions as fast as possible and by 2030.** After a natural disaster such as an earthquake or flood, we know that deploying maximum resources as quickly and efficiently as possible will produce the best result. We must respond to the climate disaster in the same way. This requires a whole-of-government effort based on conscious recognition that climate warming now represents a near-term threat to human civilisation. It requires a strong regulatory approach, because simply pushing and prodding the market within a neo-liberal framework cannot get the job done. A rescue plan must lay out the many steps to solving the problem: a plan to drive rapid emissions reductions; a plan for a just transition out of fossil fuels; a plan for the labour, skills and investment to do it; a plan for sustainable modes of work and leisure; and so on. The transition will be economically and socially disruptive because old, carbon-intensive industries must die, and current lifestyles in the high-income economies are not sustainable.

- **Innovation has astounded us.** Forty years ago when solar PV cells were ~$A100 a watt, who would have imagined that in 2015 they would be around 30 cents? We have many of the technologies we need, including battery storage rapidly falling in cost and new-generation electric vehicles that will make the petrol car obsolete. The obstacles are largely social and political, with a lack of commitment and poor regulatory systems slowing change for technologies that are already mature or rapidly sliding down the cost curve. Where technological challenges remain, we need a huge innovation and deployment effort on many fronts, including a search for efficacious climate interventions.

- **It is clear that a zero emissions strategy can't deliver, by itself, the degree of protection that would be desirable and that might be possible.** We need to set aside the reflex taboo that some people have begun to build up around CO2 drawdown or solar radiation management and openly and rigorously assess if these interventions are able to contribute in strategically important ways to a least worst, or most beneficial, climate outcome for all people and species, especially the most vulnerable.

- **Some claim that climate intervention technologies can justify continuing high fossil fuel use and are unethical.** These technologies can only be effective over the longer term if allied to a zero-emissions plan. It is suggested that climate interventions are not ethical; yet, surely not finding the path of least damage is not ethical in the face of intolerable future climate change impacts, such as massive crop failures throughout the tropics. We have a responsibility to investigate these through a large-scale research-and-development effort.

- **Radical emissions reductions can be driven more quickly by demand reduction than by replacing the energy supply system,** though of course both are essential. It is often aid that the era of fossil fuels is coming to an end,[70] but it is not coming soon enough, however: the Paris path sees emissions increasing to 2030 and new coal power stations are still being planned and built. Energy-efficiency policies can reduce energy demand at a lower cost and more quickly than building new energy supply infrastructure.[71]

- **A great social mobilization is needed to transform society.** Technological innovation in the energy sector by itself is insufficient to bring about the necessary change in energy use and production. When people are educated and motivated and act in concert, great social transformation can be achieved.

IDEAS LEADERSHIP

The reasons for failing to do what is obviously in our collective best interest have been widely canvassed, but one striking element is the lack of public ideas leadership. Only a handful of public figures in Australia have ever canvassed the main issues discussed here. Timidity and a relentless bright-siding infuse the public conversation, as if people cannot bear to hear the truth.

But what if the public is more prepared for the conversation than are our public ideas leaders?

Melanie Randle and Richard Eckersley recently investigated the perceived probability of threats to humanity and different responses to them (nihilism, fundamentalism and activism) in the US, UK, Canada and Australia. They found that:

> Overall, a majority (54%) rated the risk of our way of life ending within the next 100 years at 50% or greater, and a quarter (24%) rated the risk of humans being wiped out at 50% or greater. The responses were relatively uniform across countries, age groups, gender and education level, although statistically significant differences exist. Almost 80% agreed "we need to transform our worldview and way of life if we are to create a better future for the world" (activism). About a half agreed that "the world's future looks grim so we have to focus on looking after ourselves and those we love" (nihilism), and over a third that "we are facing a final conflict between good and evil in the world" (fundamentalism). The findings offer insight into the willingness of humanity to respond to the challenges identified by scientists and warrant increased consideration in scientific and political debate.[72]

So here is the great irony: people have a fair, intuitive sense of what might be coming, but our ideas leaders cannot talk about it.

Now is the time to press those who aspire to leadership on climate issues and action to ask the questions that prompted this discussion paper. If the propositions are contentious, we must debate them. Repressing troubling thoughts does not resolve them — they will come back to haunt us with increasingly intensity.

APPENDIX: BEWARE THE "FAT TAIL" CLIMATE

The question "How should we respond to climate change, avoid catastrophe and get back to safer conditions?" is often posed in "risk-management" terms. But what does this mean? We have tended to underestimate the rate of climate change impacts.[73] Scientists are not biased toward alarmism but rather the reverse of "erring on the side of least drama, whose causes may include adherence to the scientific norms of restraint, objectivity, skepticism, rationality, dispassion, and moderation".[74]

Too often, policy is based on least-drama, consensus scientific projections that downplay what Prof. Ross Garnaut called the "bad possibilities", that is, the relatively low-probability outcomes with very high impacts. These events may be more likely than is often assumed, as Prof. Michael E. Mann explains.

> One of the most under-appreciated aspects of the climate change problem is the so-called "fat tail" of risk. In short, the likelihood of very large impacts is greater than we would expect under typical statistical assumptions.. With additional warming comes the increased likelihood that we exceed certain "tipping points", such as the melting of large parts of the Greenland and Antarctic ice sheet and the associated massive rise in sea level that would produce.[75]

As one example of this "fat tail" risk, a greenhouse concentration may have a "most likely" outcome of ~3°C of warming, but a greater than 10% risk of warming of greater than 6°C! [76]

Prof. Garnaut suggests climate research had a conservative "systematic bias" due to "scholarly reticence".[77] Nicholas Stern wrote in similar vein about the IPCC Fifth Assessment Report: "Essentially it reported on a body of literature that had systematically and grossly underestimated the risks of unmanaged climate change".[78]

As far back as 2007, Prof. James Hansen said that scientific reticence hinders communication with the public about dangers of global warming and a potentially large sea level rise.[79] More recently Hansen wrote that: "the affliction is widespread and severe. Unless recognized, it may severely diminish our chances of averting dangerous climate change".[80]

Scientific reticence also facilitates criticism for presenting climate science that is not the middle-of-the-road version. Such charges were made against *Climate Code Red: The case for emergency action.*[81] But the evolution of climate warming since publication shows that book was not wide of the mark, because "the worst" it discussed on many key issues has already become our bitter harvest. Now the book's core proposition that we need an emergency-level response coincides with what many scientists are now saying.[82]

Two climate research scientists who reviewed the present report said it reflected most of the recent climate system insights correctly, and one said it leant toward the more "pessimistic perceptions". But that is exactly the distinction that has to be drawn between the science and the risks it implies. Waiting for catastrophe to happen before acting means that it is too late to act. It is precisely this scenario that proper risk management is designed to avoid.

As with a bushfire, a flood, a plane malfunction or any other potential disaster, it is prudent to plan for the worst that can happen, and be pleasantly surprised if it does not. To hope and plan only for "middle-of-the-road" outcomes, which characterises most climate policy-making, including in Australia, is foolish.

A prudent risk-management approach would consider the full range of real risks to which we are exposed, including those "fat tail" existential events whose consequences would be damaging beyond quantification, and which human civilization as we know it would be lucky to survive. If we focus on the "middle of the road" and ignore the worst possibilities, we may end up in a fatal crash.

"THIS IS BIGGER THAN US. THIS IS WHAT CLIMATE CHANGE LOOKS LIKE, THIS IS WHAT SCIENTISTS HAVE BEEN TELLING PEOPLE, THIS IS SYSTEM COLLAPSE."

Fire ecologist David Bowman on the January 2016 Tasmanian World Heritage bushfires [83]

Fire-killed ancient pencil pines at Lake Mackenzie,
Tasmanian Wilderness World Heritage Area.
Photographed 30 Jan 2016 © Rob Blakers.

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“SOME COASTAL CITIES WILL DROWN FOR WHAT WE HAVE DONE AND WILL DO.”

Prof. Stefan Rahmstorf, University of Melbourne forum, 22 October 2015

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Exhibit 16

PHILOSOPHICAL TRANSACTIONS OF THE ROYAL SOCIETY A

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Beyond ‘dangerous’ climate change: emission scenarios for a new world

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The Copenhagen Accord reiterates the international community's commitment to ‘hold the increase in global temperature below 2 degrees Celsius’. Yet its preferred focus on global emission peak dates and longer-term reduction targets, without recourse to cumulative emission budgets, belies seriously the scale and scope of mitigation necessary to meet such a commitment. Moreover, the pivotal importance of emissions from non-Annex 1 nations in shaping available space for Annex 1 emission pathways received, and continues to receive, little attention. Building on previous studies, this paper uses a cumulative emissions framing, broken down to Annex 1 and non-Annex 1 nations, to understand the implications of rapid emission growth in nations such as China and India, for mitigation rates elsewhere. The analysis suggests that despite high-level statements to the contrary, there is now little to no chance of maintaining the global mean surface temperature at or below 2°C. Moreover, the impacts associated with 2°C have been revised upwards, sufficiently so that 2°C now more appropriately represents the threshold between ‘dangerous’ and ‘extremely dangerous’ climate change. Ultimately, the science of climate change allied with the emission scenarios for Annex 1 and non-Annex 1 nations suggests a radically different framing of the mitigation and adaptation challenge from that accompanying many other analyses, particularly those directly informing policy.

Keywords: emission scenarios; Annex 1; non-Annex 1; cumulative emissions; climate policy; emission pathways

1. Introduction

The 2009 Copenhagen Accord [1] has received widespread criticism for not including any binding emission targets. Nevertheless, it does reiterate the international community's commitment to ‘hold the increase in global temperature below 2 degrees Celsius, and take action to meet this objective

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One contribution of 13 to a Theme Issue ‘Four degrees and beyond: the potential for a global temperature increase of four degrees and its implications’.

consistent with science and on the basis of equity' [1].[1] The Accord does not, however, quantify the degree of mitigation required to meet this commitment nor does it give an indication of whether it is still possible to do so. Moreover, and despite making reference to being guided by the 'science', the Accord makes no mention of cumulative emissions as providing the scientifically credible framing of mitigation; preferring instead to focus on the 'peaking of global and national emissions as soon as possible' and the need for 'Annex I Parties to implement ... quantified economy-wide emissions targets for 2020'. While the inclusion of nearer-term targets is certainly a welcome complement to targets for 2050, the Accord still falls short of acknowledging what the science makes absolutely clear—it is cumulative emissions that matter.

This paper takes both the Accord's commitment to 'hold the increase in global temperature below 2 degrees Celsius' along with its focus on the nearer term targets, and considers these in light of post-2000 and recession-adjusted emission trends. Building particularly on previous analyses by Anderson & Bows [2] and more recently by Macintosh [3], the paper translates earlier global assessments of cumulative emissions into emission pathways for Annex 1 and non-Annex 1 nations. The importance of the distinction between Annex 1 and non-Annex 1 is also noted in the Accord. Specifically, the Accord recognizes 'that the time frame for peaking will be longer in developing countries' and also, very significantly, that 'social and economic development and poverty eradication are the first and overriding priorities of developing countries'.

2. Analysis framing

The first decade of the new millennium has witnessed unprecedented increases in emissions reflecting ongoing high levels of energy usage for heat, electricity and transport within Annex 1 nations coupled with the very rapid industrialization of many non-Annex 1 nations, in particular China and India. Total cumulative emissions produced by nations that underwent industrialization in the nineteenth century and first half of the twentieth century will be eclipsed if the five billion people currently resident in non-Annex 1 nations remain or become locked into a fossil fuel economy. Although included in non-mitigation energy scenarios (e.g. [4,5]), this dramatic potential for emissions growth within non-Annex 1 nations is typically neglected in global and national mitigation scenarios. By considering global emission budgets alongside emission pathways for non-Annex 1 nations, this paper illustrates the increasing relevance of the latter for the mitigation policies of Annex 1 nations.

Recent years have seen the development of an increasing number of global emissions scenarios, each with a differing quantity of cumulative emission over the twenty-first century and hence with different temperature implications (e.g. [2,3,6–10]). Alongside these global analyses a growing range of ever more detailed national-level energy and emission scenarios are being developed (e.g. [11–13]). Clearly, integrating national and global analyses is a prerequisite of understanding the scale and rate of mitigation, impacts and adaptation associated with differing levels of climate change. However, as it stands, such integration is rare with

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[1] For the purpose of this paper, it is assumed that the '2 degrees Celsius' relates to the temperature rise above pre-industrial levels; though this is not made clear in the Accord.

little more than perfunctory correlation between national and global emission pathways. By disaggregating selected global emission pathways into Annex 1 and non-Annex 1 nations, this paper provides an improved and more contextual understanding of the extent of the mitigation challenge specifically and the adaptation challenge more generally.[2] Such analysis cannot substitute for detailed national-level assessments, but does offer clear guidance as to the scale and rate of mitigation necessary to avoid particular rises in temperature above pre-industrial levels.[3]

The paper comprises three principal analyses. The first derives pathways for CO_2 emissions consistent with reasonable-to-low probabilities of exceeding 2°C. The second explores the implications of incorporating all greenhouse gases within the scenario pathways for a similar chance of exceeding 2°C. The third considers how a slower uptake of mitigation measures combined with later emissions peaking impact on cumulative emissions and, hence, temperature.

(*a*) *Determining the 'appropriate' probability for 2° C*

The framing of the Copenhagen Accord around the importance of 'hold[ing] to ... below 2 degrees Celsius' reflects the clear and long-established stances of both the European Union (EU) Commission and the UK Government. The EU maintains it 'must adopt the necessary domestic measures ... to *ensure* that global average temperature increases *do not* exceed preindustrial levels by more than 2°C' [15] (emphasis added). Within the UK, the language of many Government statements suggests, if not a zero probability of exceeding 2°C, at least a very low one [16]. For example, in July 2009, the UK Government published its *UK Low Carbon Transition Plan*, in which it stated explicitly that 'to avoid the most dangerous impacts of climate change, average global temperatures *must* rise no more than 2°C' [17, p. 5] (emphasis added). The previous Secretary of State for Energy and Climate Change, Ed Miliband, subsequently reiterated this commitment, stating 'we should limit climate change to a *maximum* of two degrees' [18] (emphasis added).

Although this language is qualitatively clear, the Accord, EU and the UK do not make explicit what quantitative 'risk' of exceeding 2°C is considered 'acceptable'. Without such quantification it is not possible to derive the accompanying range of twenty-first century cumulative emissions budgets from which emission pathways can be derived. In the absence of such quantification, probabilities may be inferred based on the approach developed for the Intergovernmental Panel on Climate Change's (IPCC's) reports, whereby a correlation is made between the language of likelihood and quantified probabilities [19, p. 23]. Following this approach, the Accord's, EU's and UK Government's

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[2] Similar but less-contextual analyses also illustrate the division of global emissions between Annex 1 and non-Annex 1 nations (e.g. [14]).

[3] It is important to note that within non-Annex 1 nations there will be significant differences in peaking years and emission reduction rates between the rapidly industrializing nations (e.g. China) and regions such as sub-Saharan Africa. However, whilst China's total emissions are now higher than those from any other nation, their *per capita* emissions are around one fifth of those for the USA, and given current trends and agreements, are unlikely to succeed those in the USA in the next two to three decades (see note 17 for a discussion on cumulative *per capita* emissions).

statements all clearly imply very low probabilities of exceeding 2°C, and even a highly conservative judgement would suggest the statements represent no more than a 5–33% chance of exceeding 2°C.[4]

If government responses to climate change are to be evidence-based or at least informed significantly by science, the argument for low probabilities is reinforced still further. The characterization of 2°C[5] as the appropriate threshold between acceptable and 'dangerous' climate change is premised on an earlier assessment of the scope and scale of the accompanying impacts. However, these have since been re-evaluated with the latest assessments suggesting a significant increase in the severity of some impacts for a 2°C temperature rise (e.g. [20,21]). Consequently, it is reasonable to assume, *ceteris paribus*, that 2°C now represents a threshold, not between acceptable and dangerous climate change, but between dangerous and 'extremely dangerous' climate change; in which case the importance of low probabilities of exceeding 2°C increases substantially.

Although the language of many high-level statements on climate change supports unequivocally the importance of not exceeding 2°C, the accompanying policies or absence of policies demonstrate a pivotal disjuncture between high level aspirations and the policy reality.[6] In part this reflects the continued dominance of 'end point' targets[7] rather than scientifically credible cumulative emission budgets and their accompanying emission pathways. However, even within nations such as the UK, where the relevant policy community (and recent legislation) align themselves closely with the science of climate change, the disjuncture remains.

The first report of the UK's Committee for Climate Change (CCC) [8] heralded a significant departure from a focus on end-point and typically long-term targets. Complementing the UK's 2050 emission-reduction target with short-term budgets, the report proceeds to describe an emissions pathway out to 2050, acknowledging explicitly the need to re-align policy with cumulative emissions rather than simplistic targets. Nevertheless, although the UK Government's framing of its climate change legislation is the first to detail emission pathways, it is still far removed from its and others' high-level commitments to 'limit climate change to a *maximum* of two degrees' [18]. As it stands the carbon budget and emission pathway now enshrined in legislation are underpinned by analysis assuming a 63 per cent probability of exceeding 2°C [8, p. 21];[8] a position that cannot be reconciled with the probabilities implied repeatedly by Government statements (i.e. at their highest 5–33% of exceeding 2°C).

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[4] At the 'less likely' end of the spectrum, the IPCC categorizes a 33 per cent probability of missing or exceeding something as 'unlikely', 10 per cent as 'very unlikely', 5 per cent as 'extremely unlikely' and 1 per cent as 'exceptionally unlikely'.

[5] Or at least the rate of increase associated with a 2°C rise by 2100.

[6] Although this paper explicitly steers away from issues of governance, there are clearly major implications for all tiers of government, and wider public and private decision making in both bringing about the scale of mitigation accompanying 2°C and responding to the impacts and associated adaptation of a failure to significantly mitigate.

[7] Typically 2050 but also, more recently, 2020.

[8] The 63 per cent probability of exceeding 2°C is an outcome of the CCC's modelling approach and relates to its global cumulative emissions budget. Given the UK budget is premised on the CCC's choice of regime for apportioning global emissions between nations, it is reasonable to describe the UK's budget as correlating with a 63 per cent chance of exceeding 2°C, albeit with the important caveat that other nations, at least collectively, do not exceed their apportioned emissions budgets.

While the climate specialists within the CCC are aware of the implications of their analysis and conclude explicitly that 'it is not now possible to ensure with high likelihood that a temperature rise of more than 2°C is avoided' [8, p. 16], the language of many policy statements suggests such implications are not either understood or accepted. In general there remains a common view that underperformance in relation to emissions now can be compensated with increased emission reductions in the future.[9] Although for some environmental concerns delaying action may be a legitimate policy response, in relation to climate change it suggests the scale of current emissions and their relationship to the cumulative nature of the issue is not adequately understood.

From a mitigation perspective, the gap between the scientific and policy understanding of the challenge needs urgently to be addressed. What is perhaps less evident is the implication of this gap for adaptation. As it stands and in keeping with the dominant policy discourse, the framing of much of the detailed research and practice around adaptation, if guided quantitatively at all, is informed primarily by the 2°C characterization of dangerous climate change. Yet, as the impacts of rising temperatures are unlikely to be linear and also given rising temperatures are increasingly likely to be accompanied by additional feedbacks and hence further temperature rises, adaptation must consider more extreme climate change futures than those associated with 2°C [22]. This is certainly important for the transition of Annex 1's existing built environment and infrastructures. However, it is appreciably more important for the development of new built environments, infrastructures, agricultural practices and water regimes etc. within the non-Annex 1 nations, where an opportunity still exists for societies to locate in areas geographically less vulnerable to the impacts of climate change.[10]

3. Scenario pathway assumptions

Scenario approaches are increasingly used within mitigation and adaptation research for visioning alternative futures, exploring consistency, assessing plausibility and providing policy guidance [23]. These approaches vary in terms of 'backcasting' and 'forecasting', and range from top-down and quantitative through to more bottom-up and qualitative assessments. The scenario pathways developed in this paper are explicitly 'backcasting' and quantitative. They are not vision-based, but rather are premised on a cumulative emissions framing of climate change for which richer and more qualitative scenarios could be developed in terms of mitigation, impacts and adaptation. With regard to exploring the consistency of scenarios, the relative simplicity of the analysis presented here permits the connection between temperature targets and emission reductions to be readily assessed. In that sense, the scenarios are internally consistent. This

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[9] This is particularly evident in the continued recourse to the implementation of future and innovative low-carbon technologies (e.g. carbon capture and storage, nuclear power, marine-based biofuels, etc.) as the principal route by which emissions reductions will be achieved; a position that cannot be reconciled with the rate of reductions implied in high-level statements on 2°C.

[10] Such geographical vulnerability will need to be considered alongside other cultural, institutional and economic factors if resilience to the impacts of climate change is to be embedded in development.

contrasts with most, if not all, bottom-up mitigation analyses where consistency is constrained to issues of mitigation with climate related impacts typically exogenous to the analyses.[11]

(*a*) *Cumulative emission budget*

The scenario pathways developed in this paper illustrate quantitatively the scale of mitigation implied in high-level policy statements on 2°C. Moreover, and with direct reference to Annex 1 and non-Annex 1 nations, the scenario pathways demonstrate the disjuncture between such high-level statements and the emission pathways proposed by many policy-advisers and academics. The scenario pathways are all premised on a cumulative emission budget approach, building particularly on the work of Macintosh [3] and Anderson & Bows [2,24] but also on a range of wider studies [7,25,26].

While Macintosh [3] focused on CO_2-only emissions in correlating twenty-first century budgets with global mean temperatures (denoted by the CO_2 plus regime), the budgets within Anderson & Bows' analysis were for the basket of six Kyoto gases. Given there are merits and drawbacks for each of the budgetary regimes, both are considered in this paper.

(i) *The CO_2-plus regime (C+) and twenty-first century budgets*

The budgetary regime used by Macintosh [3] separates CO_2 emissions from non-CO_2 greenhouse gases and aerosols by applying Meinshausen *et al.*'s [7] assumptions on the net radiative forcing of the non-CO_2 components. Consequently, for a given temperature and assuming other factors remain unchanged, the cumulative budget for CO_2-only is lower than would be the equivalent CO_2e greenhouse gas value. The advantage of this regime is that non-CO_2 emissions, including aerosols, are more robustly incorporated than is possible through the coarser regimes reliant on global warming potential. However, although offering significant scientific merit, the approach poorly represents the contextual framing of emission scenarios, for example, the link between aerosol emissions and assumptions about fossil fuel combustion and rates of deforestation.

The CO_2-only budgets considered in this paper are the same as the middle and lower estimates used by Macintosh [3]. Macintosh also analysed a higher budget of 2055 $GtCO_2$ (560 GtC) as an 'outer marker' of abatement necessary for avoiding a 2°C. However, given the analysis here illustrates pathways offering an 'unlikely to extremely unlikely'[4] chance of exceeding 2°C, Macintosh's high budget is excluded from the analysis.

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[11] For example, few if any energy scenarios addressing mitigation include reductions in efficiency of thermal power stations if the temperature of cooling water rises, the potential of culturally distinct migrants to embed alternative practices into established transport and housing energy use, how drought conditions may impact energy use for desalination and grey-water recycling or the impacts of changing precipitation and temperature on biomass yields. This is not a criticism of existing bottom-up analyses, but a recognition that the range of impacts associated with different levels of climate change and differential impacts on temperature and precipitation make bottom-up analysis much more challenging, if not impossible, with regard to achieving consistency.

The two remaining budgets, 1578 $GtCO_2$ (430 GtC) and 1321 $GtCO_2$ (360 GtC), are taken directly from Macintosh [3]. The first is informed by the Garnaut Climate Change Review's 450 ppm CO_2e stabilization scenario [27][12] and according to Macintosh [3] provides an approximate 50 per cent chance of not exceeding 2°C. The latter, according to Macintosh reflects the 'risk that climate-carbon cycle feedbacks respond earlier and more strongly than previously believed' and corresponds with a higher probability of not exceeding 2°C.[13]

(ii) *The basket of six regime (B6) and twenty-first century budgets*

The B6 regime, used previously by Anderson & Bows [2], assumes the correlation between global mean temperature and cumulative emissions of the basket of six Kyoto gases as adequate for informing policy-makers of the scale of mitigation necessary. In relation to aerosols it assumes they are both short-lived and sufficiently highly correlated with fossil fuel combustion and deforestation as to have little net impact on temperatures associated with twenty-first century low-emission scenario pathways [10].[14] Moreover, it assumes the 'CO_2 equivalence' of Kyoto gases reasonably captures the warming implications of non-CO_2 emissions from producing food for an increasing and more affluent population. Evidently, the CO_2e regime is not as scientifically robust as the CO_2-only regime, but it more appropriately captures the contextual implications of alternative emission scenario pathways.

The two CO_2e budgets within this paper are those used within Anderson & Bows [2] and represent the low (1376 $GtCO_2e$) and high (2202 $GtCO_2e$) ends of the IPCC AR4 cumulative emission range for stabilization at 450 ppmv CO_2e [29]. Currently Meinshausen's *et al.*'s PRIMAP tool [28] does not permit a direct calculation of the probability of exceeding 2°C for emission pathways that maintain a substantial and long-term emission burden. However, a coarse-level but nevertheless adequate estimate is possible if the long lived gases within the 'emissions floor'[15] are added to the 2000–2050 cumulative values.

(*b*) *Empirical data*

The continued and high level of current emissions is consuming the twenty-first century emission budget at a rapid rate. Consequently, it is necessary to use up-to-date and complete emissions data to construct future emission pathways. Within this paper data are aggregated for the latest year available from a number of different sources.

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[12] For more details see Macintosh [3].

[13] Probabilities based on Meinshausen *et al.*'s [7] model assumptions can be calculated using the PRIMAP tool [28] if the 2000–2049 emissions are known.

[14] 'Twenty-first century low-emission' scenarios are premised on low fossil fuel combustion and low deforestation rates. The probabilities related to 2°C in the B6 regime do however take into account the radiative forcing of the different emissions including aerosols based on assumptions embedded in Meinshausen's *et al.*'s PRIMAP tool for estimating probabilities of exceeding 2°C [28].

[15] Refers to the lowest level of annual emissions considered viable in the scenario. These emissions are typically related to agriculture and food production.

(i) *Energy and industrial process emissions*

For energy and process related CO_2 emissions from 2000 until 2008, data are taken for each Annex 1 and non-Annex 1 nation from the Global Carbon Project using the Carbon Dioxide Information Analysis Centre (CDIAC) [30] and aggregated to produce an Annex 1 and non-Annex 1 total. The nationally constructed data from this source exclude CO_2 emissions from international aviation and shipping. To include these additional emissions, data are not taken from CDIAC as their bunker fuel CO_2 emission data are not disaggregated between nations and global marine bunker emissions are based on sales records that currently underestimate significantly the global greenhouse gas emission burden [31]. Instead, international aviation CO_2 for Annex 1 nations is taken from the memo submissions to the United Nations Framework Convention on Climate Change (UNFCCC) [32]. Non-Annex 1 international aviation CO_2 data are taken from the International Energy Agency [33] as non-Annex 1 nations do not submit this information to the UNFCCC. For international marine bunkers, the data have previously been subject to high levels of uncertainty [34–36]. However, a recent study by the International Maritime Organisation [37] has produced a time series for greenhouse gas emissions associated with international shipping activity. These data provide a figure for the global aggregated CO_2 and other greenhouse gas emissions between 1990 and 2007. However, the data are not disaggregated into national statistics. To estimate the proportion of international shipping CO_2 emissions split between Annex 1 and non-Annex 1 nations, an assumption is taken that shipping activity is directly proportional to each nation's proportion of global GDP. This crude method of apportionment was used previously (e.g. [36]), and given difficulties in apportioning international shipping emissions to nations [38,39], is also used here as an adequate, though inevitably coarse-level, division of emissions between Annex 1 and non-Annex 1 nations.[16]

(ii) *Deforestation and land-use change*

For deforestation and land-use change (hereafter referred to as 'deforestation') data between 2000 and 2008 carbon emissions are again taken from the Global Carbon Project Carbon Budget Update 2009 [41]. Their figures are estimated based on deforestation statistics published by the United Nations Food and Agriculture Organization [42] and a bookkeeping method up until 2005. The 2006–2008 emissions are derived from estimates of fire emissions using satellite data from the Oak Ridge National Laboratory Distributed Active Archive Center Global Fire Emissions Database in combination with a biogeochemical model [43].

(iii) *Non-CO_2 greenhouse gas data*

The non-CO_2 greenhouse gas emission data for 2000–2005 are based on the US Environmental Protection Agency (EPA) estimates [44]. For 2006 and 2007, data are taken from an interpolation between the 2005 and 2010 EPA projections.

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[16] A hybrid approach for apportioning aviation emissions between regions may provide insights into potential apportionment regimes for shipping [40].

This dataset is identical to the one used within Anderson & Bows [2] but in this case individual national statistics are aggregated to produce the Annex 1 and non-Annex 1 totals.

(*c*) *Economic downturn*

The economic downturn of 2007–2009 had a direct impact on greenhouse gas emission growth rates, particularly those associated with energy. Although the crisis is beginning to show within 2008 emissions inventories, data were not available for either 2008–2010 bunker fuel emissions or 2009–2010 domestic fossil fuel CO_2 emissions. In the absence of such data, estimates draw on the work of Macintosh [3] and the Global Carbon Project [41]. For Annex 1 nations, fossil fuel CO_2 (excluding bunkers) is assumed to decline by 6 per cent in 2009, stabilizing at 0 per cent in 2010. Non-Annex 1 nations are assumed to exhibit 0.5 per cent decline in emissions in 2009, but given China is already reporting high levels of growth for early 2010, the 2010 growth figure is assumed to be half the recent decade's average (i.e. 2.7%). Consequently, growth in global fossil fuel CO_2 (excluding bunkers) is assumed to be -3.0 per cent in 2009 rising to 1.5 per cent in 2010. For international aviation bunkers, it is estimated Annex 1 nations' emissions declined by 2 per cent in 2008, remaining static in 2009 and 2010. Non-Annex 1 nation aviation bunkers are assumed to be stable at 2007 levels until 2009, after which they grow at 2 per cent in 2010, again half the recent decade's average. Given the international marine bunker figures are based on proportions of global GDP, the same percentage growth rates for national emission trends are applied as for Annex 1 and non-Annex 1 domestic CO_2 emissions between 2008 and 2010.

For the emissions of non-CO_2 greenhouse gases, it is assumed that their growth is also impacted by the economic downturn. However, non-CO_2 greenhouse gas emission growth rates are typically lower than those for global fossil fuel CO_2 by approximately 1–2% per year. Given the absence of recent data from the EPA, Annex 1 and non-Annex 1 non-CO_2 greenhouse gas emissions are assumed to proportionally follow the percentage change in their CO_2 counterparts. In other words, if the rate of growth halves for Annex 1 CO_2 emissions, then the rate of growth for non-CO_2 greenhouse gas emissions is also assumed to halve.

4. Scenario pathway development

Following a brief explanation of how historical and deforestation emissions are accounted for, the construction of the scenario pathways involves the following steps.

- Decide on a global cumulative CO_2 and greenhouse gas emission budget associated with a range of probabilities of exceeding 2°C.
- Construct emission pathways for the *non-Annex 1* nations with varying peak dates.
- Construct emission pathways for the *Annex 1* nations for which the cumulative emissions, when added to non-Annex 1 and deforestation emissions, do not exceed the global '2°C' cumulative budget.

- Construct emission pathways for the non-Annex 1 nations with a 2030 peak date and more 'orthodox' annual reduction rates following the peak.
- Construct emission pathways for the Annex 1 nations with a 2015 peak date and 'orthodox' annual emission-reduction rates following the peak.
- Assess the potential future climate impact of these more 'politically acceptable' and 'economic feasible' pathways.

(*a*) *Historical emissions*

In developing emission pathways for Annex 1 and non-Annex 1 regions it is necessary to make explicit which region is deemed responsible for which emissions. While the following analysis focuses specifically on the period 2000–2100, it is important to reflect briefly on the treatment of recent historical emissions. Given temperature correlates with cumulative emissions of greenhouse gases, a case could be made for considering the responsibility for twentieth century emissions in apportioning future twenty-first century emission-space between Annex 1 and non-Annex 1 regions. However, the highly constrained emission-space now remaining for a 2–3°C rise in global mean surface temperature leaves little option but to explicitly neglect the responsibility of historical emissions in developing pragmatic twenty-first century emission profiles.[17] Getting an appropriate balance of responsibilities is a matter of judgement that inevitably will not satisfy all stakeholders and certainly will be open to challenge. As it stands, the approach adopted for this paper in which historical (and deforestation) emissions are taken to be global overheads,[18] is a pragmatic decision that, if anything, errs in favour of the Annex 1 nations.[19]

(*b*) *Deforestation emissions*

To explore the constraints on emissions from Annex 1 nations of continued growth in emissions from non-Annex 1 nations, only data for fossil fuel combustion, industrial processes and agriculture are split between Annex 1 and non-Annex 1. Deforestation emissions are treated as a global overhead and thus removed from the available emission budgets prior to developing the pathways. Such an approach could be argued to unreasonably favour non-Annex 1 nations as deforestation emissions occur within their geographical boundaries. However, given most Annex 1 countries have already deforested (emitting CO_2) it could

[17] Factoring *twentieth* century emissions from Annex 1 nations into calculations of the 'fair' emission space available for Annex 1 in the *twenty-first* century would leave Annex 1 nations already in 'emission debt'. Whilst such an outcome may have some moral legitimacy, it evidently would not provide for a politically consensual framing of emission apportionment. However, the implications of including twentieth century emissions and the concept of emission debt may guide the scope and scale of climate-related financial transfers (arguably as reparation) between Annex 1 and non-Annex 1 nations.

[18] Emissions not attributable to any specific geographical location.

[19] It is worth noting that a recent paper [45] based on analysis undertaken at Tsinghua University in Beijing makes the case that 'reasonable rights and interests should be strived for, based on the equity principle, reflected through cumulative emissions *per capita*'. Building on this *cumulative emissions per capita* approach, the authors demonstrate how China's historical cumulative emissions are only one-tenth of the average in industrial countries and one-twentieth that of the USA.

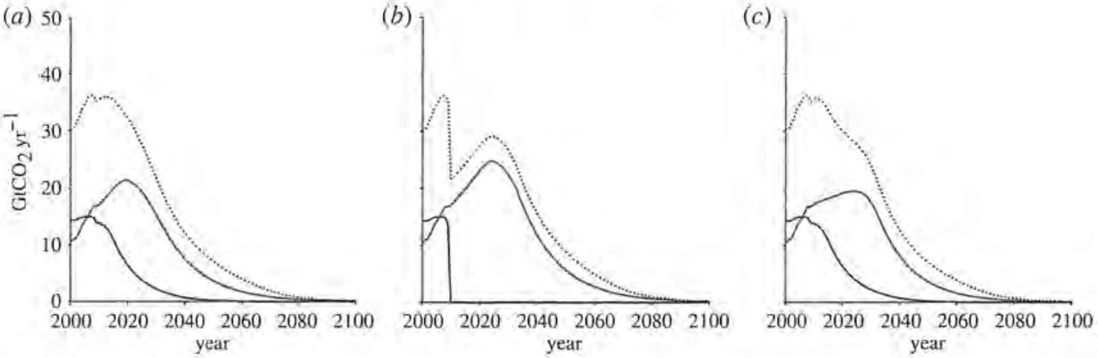

Figure 1. CO_2 scenarios for approximately 37% chance of not exceeding 2°C. All scenario pathways ((*a*) C+1, (*b*) C+2, (*c*) C+3) are for the same cumulative twenty-first century CO_2 budget of 1321 $GtCO_2$ (blue line, Annex 1; red line, non-Annex 1; dotted line, global including deforestation).

also be considered unreasonable to ascribe all of the non-Annex 1 deforestation emissions solely to non-Annex 1 nations. The global overhead approach applied here does not absolve non-Annex 1 nations of responsibility for deforestation emissions, as their available budget for energy-related emissions, along with the budget for Annex 1 nations' energy emissions, will be reduced as a consequence of the emissions from deforestation. The deforestation scenario used throughout the paper is taken as an average of the two scenarios used within Anderson & Bows [2], but updated to include the most recent emission estimates provided by the Global Carbon Project [41]. The original Anderson and Bows scenarios were optimistic compared with scenarios within the literature; the updated estimate used for this paper (266 $GtCO_2$ over the twenty-first century) continues in this optimistic vein.

(*c*) CO_2 *plus* (*C*+)

All C+ scenario pathways take the development of emissions within the non-Annex 1 nations as the starting point and then build a related Annex 1 emission pathway that holds CO_2 emissions within the chosen budget. While non-CO_2 greenhouse gases are not included in the C+ scenario pathway, CO_2 emissions associated with international bunkers and deforestation are included. The first three scenario pathways (C+ pathways 1–3 shown in figure 1) use the lowest CO_2 budget from Macintosh [3]. The second three (C+ pathways 4–6 in figure 2) use the mid-level CO_2 budget from the same paper.

C+1 assumes non-Annex 1 emission growth continues at lower than economic downturn rates from 2010 to 2015 (3% per year) and that emissions peak in 2020. For global emissions to remain within the budget, Annex 1 nations are assumed to reduce their emissions from 2011 onwards towards virtually complete decarbonization by 2050. Despite such significant reductions in Annex 1 nations (approx. 11% per year), non-Annex 1 nations' emissions still need to decline at 6 per cent per year following their peak in 2020 if global emissions are to remain within the cumulative budget. This scenario pathway results in a 56 per cent reduction from 1990 levels in emissions for Annex 1 nations by 2020, 98 per cent by 2050. Non-Annex 1 nations increase their emissions to 71 per cent higher than

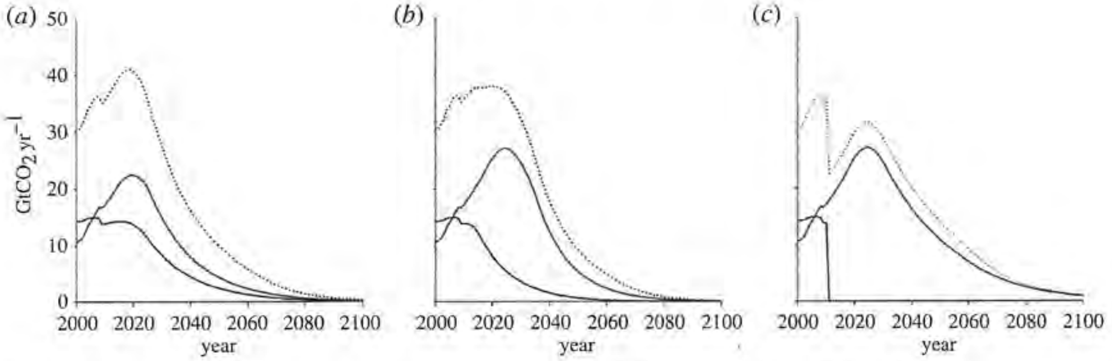

Figure 2. CO_2 scenarios for approximately 50% chance of not exceeding 2°C. All scenario pathways ((*a*) C+4, (*b*) C+5, (*c*) C+6) are for the same cumulative twenty-first century CO_2 budget of 1578 $GtCO_2$ (blue line, Annex 1; red line, non-Annex 1; dotted line, global including deforestation).

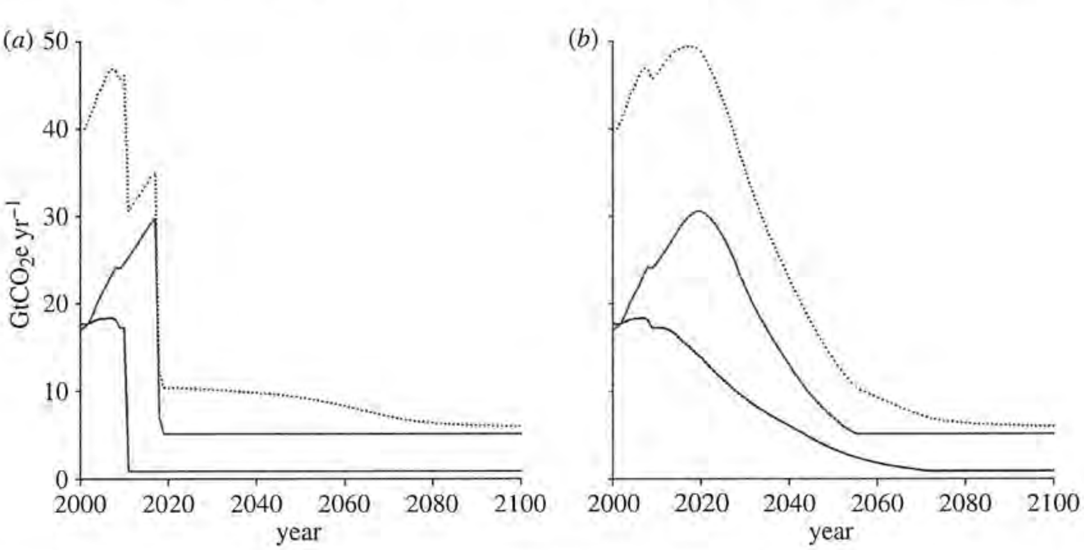

Figure 3. Kyoto gas scenarios for approximately 39–48% chance of not exceeding 2°C ((*a*) B6 1 not viable). For (*b*) B6 2, the cumulative twenty-first century CO_2e budget is 2202 $GtCO_2e$ (blue line, Annex 1; red line, non-Annex 1; dotted line, total including deforestation).

1990 levels by 2020 and then reduce them to 76 per cent below 1990 levels by 2050. Using the PRIMAP tool developed by Meinshausen *et al.* [7,28] this scenario pathway is estimated to have a 36 per cent[20] probability of exceeding 2°C.

Following the same approach, C+2 has non-Annex 1 emissions continuing to grow at a lower than pre-economic downturn rate until 2020 (3% per year), and peak in 2025. However, if this is the case, non-Annex 1 nations use the entire carbon budget and leave no emission budget for Annex 1 nations. Thus, this scenario pathway is not compatible with the lower of the cumulative carbon budgets.[21]

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[20] PRIMAP provides a range of probabilities and a 'best estimate' using cumulative emissions between 2000 and 2049. Here, 'best estimates' are presented; probabilities may vary slightly for the same twenty-first century budget, owing to differences in the 2000–2049 emissions.

[21] Given it is not possible to have an immediate cessation of emissions from all Annex 1 nations.

To explore the potential of providing for more acceptable reduction rates while still offering a 'reasonable' chance of not exceeding 2°C, C+3 assumes non-Annex 1 nations' emissions grow at a much reduced rate (1% per year) until 2025. Given this, and if Annex 1 emissions begin to reduce immediately (as in C+1), non-Annex 1 nations' emissions must still reduce at 7–8% per year after the peak date in order for global emissions to remain within the cumulative budget. Following the dip in emissions owing to the economic downturn, and as a result of a step-change in emission growth from non-Annex 1 nations, global emissions peak in 2011 and Annex 1 nations' future emissions do not grow any higher than current levels. This plausible but highly unlikely scenario has a 37 per cent chance of exceeding 2°C according to PRIMAP [28].

The next three scenario pathways (figure 2) use the higher budget of 1578 $GtCO_2$ within Macintosh [3]. C+4 assumes non-Annex 1 nation emissions grow at 4 per cent per year until 2015 peaking in 2020. The Annex 1 nations have more room to grow in early years than in C+1, but are assumed to reach a peak by 2015. Global emissions thus peak in 2019 with Annex 1 emissions 6 per cent below 1990 by 2020 and 84 per cent by 2050. Non-Annex 1 emissions are 186 per cent above 1990 levels in 2020 and 45 per cent below them by 2050. Global emissions are 67 per cent below 1990 by 2050. Both Annex 1 and non-Annex 1 emissions are assumed to decline post-peak at 5–6% per year. This scenario pathway has an estimated 50 per cent chance of exceeding 2°C according to PRIMAP [28].

C+5 again uses the higher budget within Macintosh [3] but assumes non-Annex 1 emissions to continue to grow at 4 per cent per year rates until 2020, and peak in 2025 with a rapid decline to a maximum of 7–8% per year. To remain within budget, Annex 1's emissions peak by 2010 and decline at 7–8% per year. Within this scenario pathway, global emissions are broadly flat between 2014 and 2022, although emissions are highest in 2020. Thus the penalty for a five year delay in the non-Annex 1 peak date is an additional 2 per cent per year on top of the emission reduction rate for both Annex 1 and non-Annex nations, in addition to an immediate Annex 1 reduction. C+5 has a 52 per cent chance of exceeding 2°C. C+6 uses the same higher budget but illustrates that if reductions are lower, at 4–5% per year for non-Annex 1 nations following the peak date, no emission space is available for Annex 1 nations.

(*d*) *Basket of six scenario pathways* (*B6*)

In a similar approach to the C+ pathways, all B6 pathways (figures 3 and 4) take the development of emissions within the non-Annex 1 nations as the starting point and then build a related Annex 1 emission scenario pathway that must, in this case, keep total greenhouse gas emissions within the chosen budget. The significant difference between the B6 and the C+ pathways is that the given emission budget is assumed to apply to the full basket of 6 greenhouse gases mirroring the approach taken in Anderson & Bows [2]. In addition to considering the effect of non-CO_2 greenhouse gases contributing to the overall budget, an essential difference is the requirement for significant emissions space post-2050 to allow for greenhouse gas emissions (specifically N_2O and CH_4) associated with food production for an approximate 9.2 billion global population (based on UN

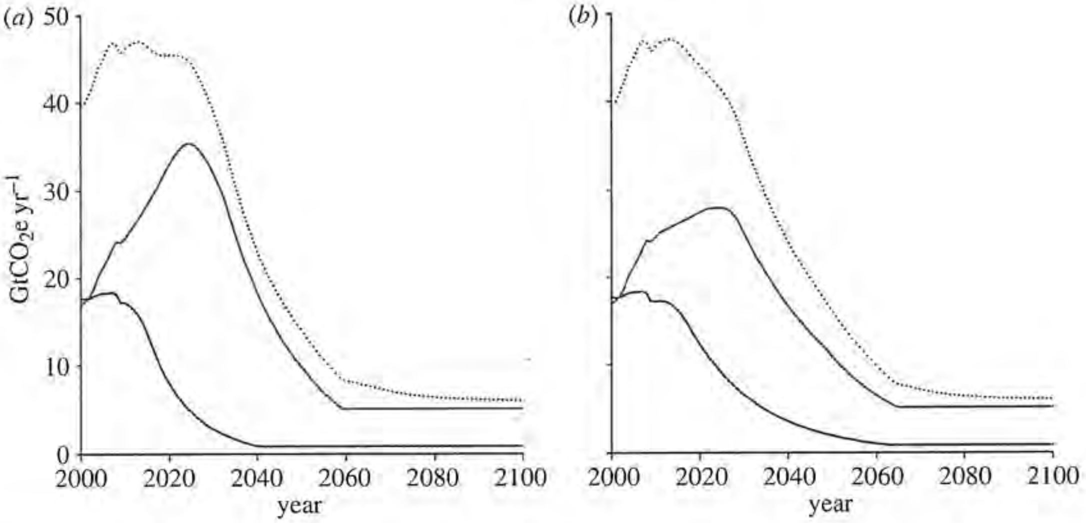

Figure 4. Kyoto gas scenarios for approximately 38–48% chance of not exceeding 2°C ((*a*) B6 3, (*b*) B6 4). The cumulative twenty-first century CO_2e budget is 2202 $GtCO_2e$. Blue line, Annex 1; red line, non-Annex 1; dotted line, total including deforestation.

median estimate for 2050 [46]). In an update to the previous Anderson & Bows [2] study, the assumed minimum level of greenhouse gas production related to food is more optimistic still at 6 $GtCO_2e$ per year as opposed to 7.5 $GtCO_2e$ per year. This is in line with the value chosen by the UK [8] and results in an estimated 0.67 tCO_2e per person from 2050 onwards for food-related non-CO_2 greenhouse gases compared with an approximate figure of 0.95 $GtCO_2e$ per person for 2010 [44,46]. Assuming by 2050 there are 7.9 billion people in non-Annex 1 nations, and 1.3 billion in Annex 1 nations [46], and assuming food consumption is more evenly balanced between Annex 1 and non-Annex 1 nations than currently, this would allow approximately 5.1 $GtCO_2e$ as a minimum annual greenhouse gas emission for non-Annex 1 nations and 0.86 $GtCO_2e$ per year for Annex 1 nations.

B6 1 uses the IPCC 'low' emission budget and assumes that between 2010 and 2015 non-Annex 1 emissions grow at slightly lower (3% per year) than pre-economic downturn rates and peak by 2020 (figure 3). Given the food-related non-CO_2 greenhouse gases post-2050, emissions from 2017 onwards for non-Annex 1 nations must tend immediately towards the emissions floor of 5.1 $GtCO_2e$. In other words, this scenario pathway is not viable.

B6 2 makes identical assumptions to B6 1 but for the 'high' IPCC emission budget (figure 3). The additional space allowed leads to a viable scenario pathway, where non-Annex 1 emissions peak in 2020, while Annex 1 nation emissions decline from 2010 onwards. Emission reductions for non-Annex 1 nations in this case are 6 per cent per year, while for Annex 1 they gradually build from around 3 per cent per year for 2015 to 2020 to 6 per cent later in the century. The PRIMAP tool to estimate the probability of exceeding the 2°C threshold assumes the vast majority of emissions are released pre-2050 (fig. 2 in [7]). Given that within the B6 scenario pathways there is a substantial cumulative emission total for the post-2050 emissions (with at least 300 $GtCO_2e$ from greenhouse gases associated with food production), inputting the 2000–2049 cumulative total for each B6 scenario into PRIMAP will result in an underestimate of the probability of exceeding 2°C. To account for this underestimate, an alternative probability is calculated assuming the following.

- The shorter-lived nature of methane compared with N_2O results in a negligible impact on post-2050 warming from methane.[22]
- N_2O and methane each account for approximately 50 per cent of the non-CO_2 greenhouse gases post-2050 (Smith, personal communication).
- The amount of non-CO_2 greenhouse gas emissions released per year possible post-2050 is 6 $GtCO_2e$ (in line with assumptions made by the UK CCC [8]) of which 3 $GtCO_2e$ per year is from N_2O.
- Thus 150 $GtCO_2e$ of cumulative emissions are added to the pre-2050 emissions to estimate an alternative probability.

If 150 $GtCO_2e$ is added to the cumulative emission total for each scenario, PRIMAP estimates an approximate ten percentage point increase in probability of exceeding 2°C (see table 1, figure is in brackets). For example, B6 2 has at least a 39 per cent chance of exceeding 2°C and is potentially as high as 48 per cent.

Both B6 3 and B6 4 take the IPCC's 'high' cumulative budget as a constraint. B6 3 assumes non-Annex 1 nation emissions peak in 2025 following a growth of 3 per cent per year between 2010 and 2020 (figure 4). With steep emission reductions for non-Annex 1 nations post-peak of 6 per cent per year, Annex 1 nations would need to reduce emissions from 2010 onwards at more than 10 per cent per year to remain within the high IPCC cumulative budget. More gradual reductions in emissions from non-Annex 1 nations would render this scenario pathway impossible. B6 3 has the same probability of exceeding 2°C as B6 2.

B6 4 mirrors the assumptions within C+3, with considerably slower growth of 1 per cent per year until a peak date in 2025 (figure 4). The emission reductions post-peak for non-Annex 1 nations are 4–5% per year, whereas for Annex 1 nations, following a levelling off of emissions until 2014, emissions decrease at 6 per cent per year. This scenario pathway has at least a 38 per cent probability of exceeding 2°C, and potentially as high as 47 per cent once post-2050 emissions are factored in.

(e) *Orthodox scenario pathways*

The final scenario pathways developed are unconstrained by a particular emission budget (figure 5). For both the C+ and B6 regimes, pathways are constructed that assume non-Annex 1 nations' emissions continue to develop along their current trajectory until 2025, peaking in 2030, then reducing at

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[22] This is an explicitly conservative assumption and results in slightly higher probabilities of not exceeding 2°C than would be the case if some allowance were to be made for post-2050 emissions of methane.

Table 1. Summary of scenario pathway characteristics.

scenario pathway	global 21st century CO_2 or greenhouse gas budget in $GtCO_2$ or [$GtCO_2e$]	Annex 1 peak date/21st century cumulative emissions in $GtCO_2$ or [$GtCO_2e$]	non-Annex 1 peak date/21st century cumulative emissions in $GtCO_2$ or [$GtCO_2e$]	global peak date	Annex 1 % reduction on 1990 levels by 2020 (2050)	non-Annex 1 % reduction on 1990 levels by 2020 (2050)	post-peak Annex 1 rate of reduction	post-peak non-Annex 1 rate of reduction	post-peak global rate of reduction (includes deforestation)	approximate % of exceeding 2°C (based on 2000–2049 emissions using PRIMAP)
C+1	1321	2007 313	2020 742	2012	56% (98%)	+1714% (54%)	10–11%	6–7%	6–7%	36%
C+2[a]	1321	2007 139	2025 916	2007	100% (100%)	+193% (27%)	—	6–7%	6–7%	
C+3	1321	2007 313	2025 742	2007	56% (98%)	+143% (54%)	10–11%	7–8%	7–8%	37%
C+4	1578	2007 532	2020 780	2019	6% (84%)	+186% (45%)	5–6%[b]	5–6%	5–6%	50%
C+5	1578	2007 363	2025 949	2020	44% (95%)	+220% (32%)	8%	7–8%	7–8%	52%
C+6[a]	1578	2007 153	2025 1159	2024	100% (100%)	+220% (+38%)	—	4–5%	4–5%	—
B6 1[a,c]	[1376]	2007 [265]	2017 [841]	2017	95% (95%)	61% (61%)	—	—	—	—
B6[c] 2	[2202]	2010 [639]	2020 [1293]	2017	25% (82%)	+135% (46%)	4–6%	5–6%	3%	39% (48%)[d]
B6[c] 3	[2202]	2007 [429]	2025 [1503]	2013–2018	57% (95%)	+154% (24%)	8–10%	6–7%	4–5%	39% (48%)[d]
B6[c] 4	[2202]	2007 [552]	2025 [1380]	2013	34% (90%)	+111% (17%)	6%	4–5%	4–5%	38% (47%)[d]
orthodox C+	2741	2015 [729]	2030 1747	2027	2% (60%)	+223% (+163%)	3%	3%	3%	88%
orthodox B6	[3662]	2015 [891]	2030 [2501]	2028	5% (62%)	+180% (128%)	3%	3%	3%	88% (92%)[d]

[a] These scenario pathways are not viable as they could not remain within the carbon budget prescribed.

[b] This is the reduction rate following the period of relatively stable emissions until 2016.

[c] All B6 scenario pathways assume an 'emission floor' of $6GtCO_2e$ for food-related emissions for an approximate 9 billion population post-2050 until 2100. If a different 'emission floor' were to be used, emission reduction rates would be altered for the same cumulative values.

[d] The figure in brackets illustrates a higher probability to take into account the ongoing emissions associated with food production as opposed to greenhouse gas emissions tending to zero.

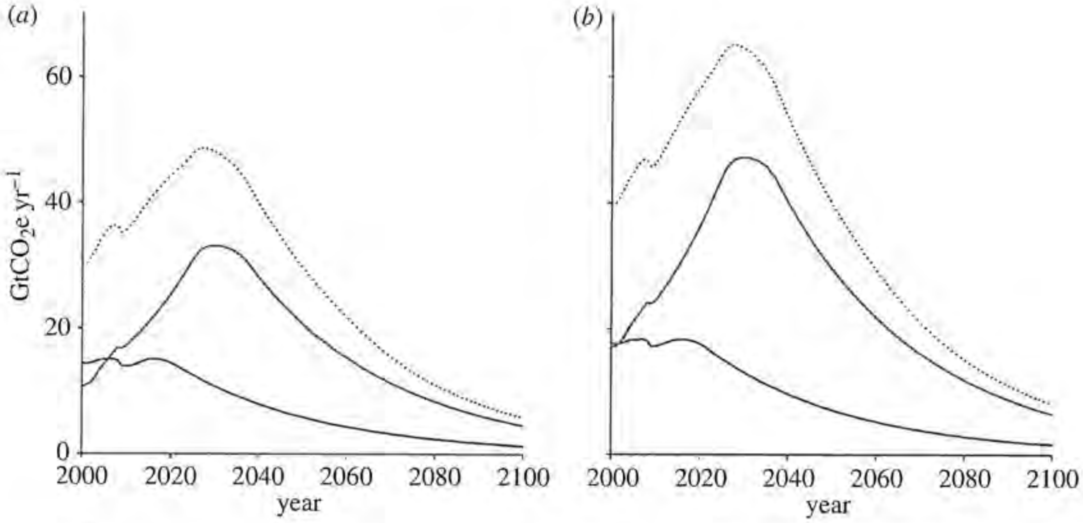

Figure 5. Emission scenarios for approximately 88–92% chance of not exceeding 2°C. Both plots illustrate 'orthodox' mitigation pathways with (*a*) C+ for CO_2 only (twenty-first century cumulative emissions: 2741 $GtCO_2$) and (*b*) B6 for Kyoto gases (twenty-first century cumulative emissions: 3662 $GtCO_2e$). Blue line, Annex 1; red line, non-Annex 1; dotted line, total including deforestation.

a rate considered politically and economically acceptable[23] (3% reduction per year). For the Annex 1 nations, emissions are assumed to be relatively stable with a peak in 2016 and subsequent emission reductions of 3 per cent per year. These scenario pathways both result in an 88 per cent chance of exceeding the 2°C threshold (potentially 92% for orthodox B6). Furthermore, their twenty-first century cumulative budgets suggest the future temperature increase compared with pre-industrial times is more likely to be of the order of 4°C rather than 2°C.

For orthodox C+, cumulative emissions of CO_2 alone are 2,741 $GtCO_2$. Cumulative emissions of approximately 2700 $GtCO_2$ are associated with stabilization of 550 ppmv CO_2. Figures in excess of 3500 $GtCO_2e$ can be assumed to be closer to the 750 ppmv range. Orthodox B6 has cumulative emissions of greenhouse gases of 3662 $GtCO_2e$, thus a reasonable probability of exceeding 4°C.

5. Discussion

(*a*) CO_2 *plus* (*C+*)

Although six C+ pathways were developed in the previous section, two were rejected for exceeding the constraints on cumulative CO_2 budgets related to the 2°C temperature threshold. One exceeded the lower of the two chosen

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[23] The pathway of the CCC's [8] most challenging scenario, '2016:4% low', has post-peak emissions reducing at 3.5 per cent per year from all sources. Stern [6] states 'there is likely to be a maximum practical rate at which global emissions can be reduced' pointing to 'examples of sustained emissions cuts of up to 1 per cent per year associated with structural change in energy systems' and that 'cuts in emissions greater than this (1%) have historically been associated only with economic recession or upheaval'. Stern concludes 'it is likely to be difficult to reduce emissions faster than around 3 per cent per year' [6, pp. 201–204]. The most stringent of the ADAM scenarios assumed emission reduction rates of approximately 3 per cent per year between a 2015 peak and 2050 [47 fig. 2, p. 32].

budgets (approx. 37% of not exceeding 2°C) owing to non-Annex 1 emissions both continuing with recent growth rates out to 2020 and peaking in 2025. The other surpassed the higher of the two cumulative budgets (approx. 50% of not exceeding 2°C) because, in addition to the emissions growth and peak years, post-peak emission reductions of 4–5% per year were insufficient to stay within the cumulative budget. Those pathways remaining within the lower budget required an immediate and rapid decline in Annex 1 emissions and an early peak in non-Annex 1 emissions, unless the latter's emission growth was constrained to rates much lower than historical trends (i.e. to 1%, compared with current growth of 3–4% per year [48]). In all cases, Annex 1 emissions continue to decline following the current economic downturn at rates in excess of 5 per cent per year. Given these pathways explicitly exclude non-CO_2 greenhouse gas emissions, the rates of reduction for CO_2 presented in table 1 illustrate the change necessary within the energy system primarily. Furthermore, figures 1 and 2 illustrate the need for complete decarbonization of the Annex 1 energy system by around 2050. For the higher (approx. 50%) chance of not exceeding 2°C, figure 2 and table 1 illustrate that a 5 year delay in the peak year for non-Annex 1 nations (from 2020 to 2025) forces a 2 per cent increase in reduction rates globally in addition to an immediate emission reduction for Annex 1 nations.

(*b*) *Basket of six* (*B6*)

When developing the B6 pathways (figures 3 and 4), it became apparent immediately that the 'low' IPCC cumulative emission value was not viable if non-Annex 1 emissions peak as late as 2020. Consequently, the minimum probability of not exceeding the 2°C threshold achievable in this scenario pathway set is 38 per cent. Moreover, given a significant portion of emissions are attributable to food production post-2050, this probability is likely to be a significant underestimate, with a more probable figure closer to 48 per cent. This result is in line with the scenario pathway analysis within Anderson & Bows [2]. For the IPCC's 'high' end of the range, emission reductions of 6 per cent per year for both Annex 1 and non-Annex 1 nations are necessary if non-Annex 1 emissions continue at recent growth rates and peak in 2020. However, if these rates are sustained for a further five years (i.e. to 2025), and non-Annex 1 post-peak reductions are 6 per cent per year or less, no emissions space remains for Annex 1 nations. Even if non-Annex 1 emissions grow at much slower rates to a 2025 peak, post-peak emission reductions of 4–5 per cent per year are still needed from the aggregate of all nations. Therefore, under the IPCC's higher budget, all viable scenario pathways exhibit emission reduction rates well in excess of those typically considered to be politically and economically feasible.

(*c*) *Orthodox*

In light of the recent Copenhagen negotiations, there continues to be an absence of any meaningful global action to mitigate emissions or set binding targets. Even if Annex 1 nations agree on the scale of necessary emission reductions, it is more probable that non-Annex 1 nations will set targets based on levels of carbon or energy intensity improvements. Although these will go some way towards addressing future high-carbon lock-in, it is unlikely that emission growth rates will be significantly moderated during the coming decade. To explore the implications of this, the two orthodox scenario pathways paint a picture of ongoing non-Annex 1 emission growth, slow action to mitigate emissions on the part of Annex 1 nations, and then sustained emission reductions at rates considered politically and economically feasible. Resulting cumulative emissions, while still within the bounds of possibility of not exceeding the 2°C threshold (8–12% chance), are more closely aligned with much higher climate change futures associated with at least 3–4°C of warming.

(*d*) *Simple and complex scenarios*

The scenarios developed in this paper are relatively contextual[24] and as such complement the wealth of scenarios from more non-contextual integrated assessment models.[25] However, while it may be argued that the latter approach benefits from greater internal consistency and more theoretically coherent parameters, the outputs are typically removed from the political and empirical reality within which responses to climate change are developed. For example, recent overviews of scenarios generated by a range of different international integrated assessment modelling communities [10,14] illustrate the non-contextual framing that typifies much of this form of analysis. Of the principal 450 ppmv scenarios reviewed, the majority had a global emissions peak in 2010, this despite irrefutable evidence to the contrary [48].[26] Over a third factored in negative emissions through the inclusion of geo-engineering in the form of 'biomass with carbon capture and storage' (CCS) technologies. These bio-CCS scenarios all included wider CCS facilities, yet were without detailed analysis of potentially significant constraints on storage capacity.[27] At least half of the scenarios relied on significant levels of 'overshoot' (between 500 and 590 ppmv CO_2e)[28] and

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[24] Though constrained explicitly to consider top-down emissions only with coarse high-level divisions between food, deforestation, energy and industrial processes.

[25] Bottom-up and built on typically idealized inputs with only limited regard for 'real-world' constraints.

[26] While Köne & Büke's [48] paper was published after many of the scenarios referred to, the overarching data and trend lines underpinning Köne and Büke's analysis were available at the time many of the scenarios were developed.

[27] The inclusion of bio-CCS also demonstrates a degree of non-contextual engagement with technology. Aside from the considerable bio-energy debate surrounding the sustainability of biofuels, no CCS power plants have yet being built and consequently large-scale CCS remains a theoretical possibility with no operating experience of capture rates (though many of the component processes have undergone testing). Given the many unknowns around bio-CCS, it is perhaps surprising they are central to so many scenarios. This non-contextual approach to technology extends to nuclear power, included as a 'key energy supply technology' in all but one of the 450ppmv scenarios reviewed. Whilst sufficient uranium exists for moderate increases in conventionally fuelled reactors, significant ramping up of nuclear capacity is likely to require fast breeder reactors with major challenges associated with their widespread introduction; here too the integrated assessment modelling approach typically treats these wider concerns as exogenous and resolvable.

several assumed fossil fuel CO_2 emissions from non-Annex 1 nations would exceed those from Annex 1 as late as 2013–2025 [14], despite the actual date being around 2006.[29]

The non-contextual framing of many complex modelling approaches (including integrated assessment modelling), allied with their inevitable opaqueness and often abstract and implicit assumptions, leaves space for the simpler, more transparent and contextual approach to scenarios presented in this paper. Making explicit the implications of particular assumptions (such as peak emission dates or very low probabilities of exceeding 2°C) provides insights that not only are intelligible to wider stakeholders and decision-makers, but can also provide 'contextual' parameters and constraints to more complex modelling approaches.

(e) *Development on the authors' 2008 paper*

Two years on from earlier analysis by Anderson & Bows [2], only the global economic slump has had any significant impact in reversing the trend of rising emissions. However, with Annex 1 and non-Annex 1 nations returning rapidly to their earlier economic and emissions trajectories and with the failure of Copenhagen to achieve a binding agreement to reduce emissions in line with 2°C, the prospects for avoiding dangerous climate change, if they exist at all, are increasingly slim. Furthermore, disaggregating global into Annex 1 and non-Annex 1 emission pathways only serves to exacerbate the scale of this disjuncture between the rhetoric and reality of mitigation. In both these regards and with the continued high-level reluctance to face the real scale and urgency of the mitigation challenge, the conclusions arising from this paper are significantly bleaker than those of the authors' 2008 paper.

6. Conclusions

Over the past five years a wealth of analyses have described very different responses to what, at first sight, appears to be the same question: *what emission-reduction profiles are compatible with avoiding 'dangerous' climate change?* However, on closer investigation, the difference in responses is related less to different interpretations of the science underpinning climate change and much more to differing assumptions related to five fundamental and contextual issues.

(1) What delineates dangerous from acceptable climate change?
(2) What risk of entering dangerous climate change is acceptable?
(3) When is it reasonable to assume global emissions will peak?
(4) What reduction rates in post-peak emissions is it reasonable to consider?
(5) Can the primacy of economic growth be questioned in attempts to avoid dangerous climate change?

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[28] Overshoot scenarios remain characterized by considerable uncertainty and are the subject of substantive ongoing research (e.g. [49,50]).

[29] Within the integrated assessment modelling scenarios referred to, the division related to Annex B regions. For all practical purposes aggregated emissions related to Annex 1 are the same as those for Annex B.

While (1) and, to a lesser extent, (2) are issues for international consideration,[30] the latter three have pivotal regional dimensions that, at their most crude level, can be understood in relation to Annex 1 and non-Annex 1 emission profiles.

In relation to the first two issues, the Copenhagen Accord and many other high-level policy statements are unequivocal in both their recognition of 2°C as the appropriate delineator between acceptable and dangerous climate change and the need to remain at or below 2°C. Despite such clarity, those providing policy advice frequently take a much less categorical position, although the implications of their more nuanced analyses are rarely communicated adequately to policy makers. Moreover, given that it is a 'political' interpretation of the severity of impacts that informs where the threshold between acceptable and dangerous climate change resides, the recent reassessment of these impacts upwards suggests current analyses of mitigation significantly underestimate what is necessary to avoid dangerous climate change [20,21]. Nevertheless, and despite the evident logic for revising the 2°C threshold,[31] there is little political appetite and limited academic support for such a revision. In stark contrast, many academics and wider policy advisers undertake their analyses of mitigation with relatively high probabilities of exceeding 2°C and consequently risk entering a prolonged period of what can now reasonably be described as extremely dangerous climate change.[32] Put bluntly, while the rhetoric of policy is to reduce emissions in line with avoiding dangerous climate change, most policy advice is to accept a high probability of extremely dangerous climate change rather than propose radical and immediate emission reductions.[33]

This already demanding conclusion becomes even more challenging when assumptions about the rates of viable emission reductions are considered alongside an upgrading of the severity of impacts for 2°C. Within global emission scenarios, such as those developed by Stern [6], the CCC [8] and ADAM [47], annual rates of emission reduction beyond the peak years are constrained to levels thought to be compatible with economic growth—normally 3 per cent to 4 per cent per year. However, on closer examination these analyses suggest such reduction rates are no longer sufficient to avoid dangerous climate change. For example, in discussing arguments for and against carbon markets the CCC state 'rich developed economies need to start demonstrating that a low-carbon economy is possible and compatible with economic prosperity' [8, p. 160]. However, given the CCC acknowledge 'it is not now possible to ensure with high likelihood that a temperature rise of more than 2°C is avoided' and given the view that reductions in emissions in excess of 3–4% per year are not compatible with economic growth, the CCC are, in effect, conceding that avoiding dangerous (and even extremely dangerous) climate change is no longer compatible with economic prosperity.

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[30] Regions can evidently identify what may constitute dangerous within their geographical boundaries, but given many impacts (and the responsibility for them) extend well beyond such boundaries any regional assessment needs to be within the context of a more global perspective.

[31] If the impacts are to remain the principal determinant of what constitutes dangerous, then would it be more reasonable to characterize '1°C as the new 2°C'?

[32] Assuming the logic for the 2°C characterization of what constitutes dangerous still holds.

[33] With policies themselves lagging even further behind in terms of both actual reductions achieved or planned for.

In prioritizing such economic prosperity over avoiding extremely dangerous climate change, the CCC, Stern, ADAM and similar analyses suggest they are guided by what is *feasible*.[34] However, while in terms of emission reduction rates their analyses favour the 'challenging though still feasible' end of orthodox assessments, the approach they adopt in relation to peaking dates is very different. All premise their principal analyses and economic assessments on the 'infeasible' assumption of global emissions peaking between 2010 and 2016; a profound departure from the more 'feasible' assumptions framing the majority of such reports. The scale of this departure is further emphasized when disaggregating global emissions into Annex 1 and non-Annex 1 nations, as the scenario pathways developed within this paper demonstrate.

Only if Annex 1 nations reduce emissions immediately[35] at rates far beyond those typically countenanced and only then if non-Annex 1 emissions peak between 2020 and 2025 before reducing at unprecedented rates, do global emissions peak by 2020. Consequently, the 2010 global peak central to many integrated assessment model scenarios as well as the 2015–2016 date enshrined in the CCC, Stern and ADAM analyses, do not reflect any orthodox 'feasibility'. By contrast, the logic of such studies suggests (extremely) dangerous climate change can only be avoided if economic growth is exchanged, at least temporarily, for a period of planned austerity within Annex 1 nations[36] and a rapid transition away from fossil-fuelled development within non-Annex 1 nations.

The analysis within this paper offers a stark and unremitting assessment of the climate change challenge facing the global community. There is now little to no chance of maintaining the rise in global mean surface temperature at below 2°C, despite repeated high-level statements to the contrary. Moreover, the impacts associated with 2°C have been revised upwards (e.g. [20,21]), sufficiently so that 2°C now more appropriately represents the threshold between dangerous and extremely dangerous climate change. Consequently, and with tentative signs of global emissions returning to their earlier levels of growth, 2010 represents a political tipping point. The science of climate change allied with emission pathways for Annex 1 and non-Annex 1 nations suggests a profound departure in the scale and scope of the mitigation and adaption challenge from that detailed in many other analyses, particularly those directly informing policy.

However, this paper is not intended as a message of futility, but rather a bare and perhaps brutal assessment of where our 'rose-tinted' and well intentioned (though ultimately ineffective) approach to climate change has brought us. Real hope and opportunity, if it is to arise at all, will do so from a raw

[34] The reference to 'feasible' technologies typically extends to carbon capture and storage, which, in 2010, remains untried for a large scale power station. Moreover, it is often allied with biomass combustion to provide 'negative' emissions (§5*d*). Without such negative emissions, several of the major analyses (e.g. [9,10]) will have increased cumulative emissions and hence further increased probabilities of exceeding 2°C (see also footnote 27).

[35] With the only exception being C+4 where Annex 1 emissions are stable until 2016, reducing thereafter.

[36] In essence, a planned economic contraction to bring about the almost immediate and radical reductions necessary to avoid the 2°C characterization of dangerous climate change whilst allowing time for the almost complete penetration of all economic sectors with zero or very low carbon technologies.

and dispassionate assessment of the scale of the challenge faced by the global community. This paper is intended as a small contribution to such a vision and future of hope.

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Exhibit 17

PHILOSOPHICAL
TRANSACTIONS
OF
THE ROYAL
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Reframing the climate change challenge in light of post-2000 emission trends

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The 2007 Bali conference heard repeated calls for reductions in global greenhouse gas emissions of 50 per cent by 2050 to avoid exceeding the 2°C threshold. While such endpoint targets dominate the policy agenda, they do not, in isolation, have a scientific basis and are likely to lead to dangerously misguided policies. To be scientifically credible, policy must be informed by an understanding of cumulative emissions and associated emission pathways. This analysis considers the implications of the 2°C threshold and a range of post-peak emission reduction rates for global emission pathways and cumulative emission budgets. The paper examines whether empirical estimates of greenhouse gas emissions between 2000 and 2008, a period typically modelled within scenario studies, combined with short-term extrapolations of current emissions trends, significantly constrains the 2000–2100 emission pathways. The paper concludes that it is increasingly unlikely any global agreement will deliver the radical reversal in emission trends required for stabilization at 450 ppmv carbon dioxide equivalent (CO_2e). Similarly, the current framing of climate change cannot be reconciled with the rates of mitigation necessary to stabilize at 550 ppmv CO_2e and even an optimistic interpretation suggests stabilization much below 650 ppmv CO_2e is improbable.

Keywords: emission scenarios; cumulative emissions; climate policy; energy; emission trends

1. Introduction

In the absence of global agreement on a metric for delineating *dangerous* from *acceptable* climate change, 2°C has, almost by default, emerged as the principal focus of international and national policy.[1] Moreover, within the scientific community, 2°C has come to provide a benchmark temperature against which to consider atmospheric concentrations of greenhouse gases and emission reduction profiles. While it is legitimate to question whether temperature is an appropriate metric for representing climate change and, if it is, whether 2°C is the appropriate temperature (Tol 2007), this is not the purpose of this paper. Instead, the paper begins by considering the implications of the 2°C threshold for global emission pathways, before proceeding to consider the implications of different emission pathways on stabilization concentrations and associated temperatures.

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[1] For example, in March 2007, European leaders reaffirmed their commitment to the 2°C threshold (European Commission 2007).

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Although the policy realm generally focuses on the emissions profiles between 2000 and 2050, the scientific community tends to consider longer periods, typically up to and beyond 2100. By using a range of cumulative carbon budgets with differing degrees of carbon-cycle feedbacks, this paper assesses whether global emissions of greenhouse gases between 2000 and 2008, combined with short-term extrapolations of emission trends, significantly impact the 2008–2100 cumulative emission budget available, and hence emission pathways.

In brief, the paper combines *current* greenhouse gas emissions data (including deforestation) with *up-to-date* emission trends and the *latest* scientific understanding of the relationships between emissions and concentrations to consider three questions.

(i) Given a small set of emissions pathways from 2000 to a date where global emissions are assumed to peak (2015, 2020 and 2025), what emission reduction rates would be necessary to remain within the 2000–2100 cumulative emission budgets associated with atmospheric stabilization of carbon dioxide equivalent (CO_2e) at 450 ppmv? The accompanying scenario set is hereafter referred to as 'Anderson Bows 1' (*AB1*).

(ii) Given the same pathways from 2000 to the 2020 emissions peak, what concentrations of CO_2e are associated with subsequent annual emission reduction rates of 3, 5 and 7 per cent? The accompanying scenario set is hereafter referred to as 'Anderson Bows 2' (*AB2*).

(iii) What are the implications of the findings from (i) and (ii) for the current framing of the climate agenda more generally, and the appropriateness of the 2°C threshold as the driver of mitigation and adaptation policy more specifically?

2. Analysis framing

(*a*) *Correlating 2°C with greenhouse gas concentration and carbon budgets*

What constitutes an acceptable temperature increase is a political rather than a scientific decision, though the former may be informed by science. By contrast, the correlation between temperature, atmospheric concentration of CO_2e and anthropogenic cumulative emission budgets emerges, primarily, from our scientific understanding of how the climate functions.

According to a recent synthesis of global climate models (Meinshausen 2006, table 28.1), the 550 ppmv CO_2e concentration, around which much policy discussion revolves, suggests an 82 per cent mid-value probability of exceeding 2°C. By contrast, to provide a 93 per cent mid-value probability of *not* exceeding 2°C, the concentration would need to be stabilized at, or below, 350 ppmv CO_2e, i.e. below current levels. While Meinshausen's analysis demonstrates the gulf between the science and the policy of approximately 2°C, the analysis within the IPCC's fourth assessment report (IPCC 2007*a*), hereafter AR4, suggests that the scale of the challenge is even more demanding. Not only has the 'best estimate' of climate sensitivity risen from 2.5°C in the 1996 report (IPCC 1996, p. 39) to 3°C in AR4, but also the inclusion of carbon-cycle feedbacks has significantly reduced the cumulative anthropogenic emissions (carbon budget) associated with particular concentrations of CO_2e (IPCC 2007*a*, topic 5, p. 6).

Understanding current emission trends in particular and the links between global temperature changes and national emission budgets more generally (sometimes referred to as the 'correlation trail'; Anderson & Bows 2007), is essential if policy is to be evidence based. Currently, national and international policies are dominated by long-term reduction targets with little regard for the cumulative carbon budget described by particular emission pathways. Within the UK, for example, while the government acknowledges the link between temperature and concentration, the principal focus of its policies is on reducing emissions by 60 per cent by 2050 (excluding international aviation and shipping; Bows & Anderson 2007). Closer examination of the UK's relatively 'mature' climate change policy reveals a further inconsistency. Within many official documents 550 ppmv CO_2e and 550 ppmv CO_2 are used interchangeably,[2] with the latter equating to approximately 615 ppmv CO_2e (extrapolated from IPCC 2007*a*, topic guide 5, table 5.1); the policy repercussions of this scale of ambiguity are substantial.

Whether considering climate change from an international, national or regional perspective, it is essential that the associated policy debate be informed by the latest science on the 'correlation trail' from temperature and atmospheric concentrations of CO_2e through to global carbon budgets and national emission pathways. Without such an informed debate, the scientific and policy uncertainties that unavoidably arise are exacerbated unnecessarily and significantly.

(*b*) *Recent emissions data and science: impact on carbon budgets*

(i) *Carbon-cycle feedbacks*

The atmospheric concentration of CO_2 depends not only on the quantity of emissions emitted into the atmosphere (natural and anthropogenic), but also on land use changes and the capacity of carbon sinks within the biosphere. As the atmospheric concentration of CO_2 increases (at least within reasonable bounds), so there is a net increase in its take-up rate from the atmosphere by vegetation and the ocean. However, changes in rainfall and temperature in response to increased atmospheric greenhouse gas concentrations affect the absorptive capacity of natural sinks (Jones *et al.* 2006; Canadell *et al.* 2007; Le Quéré *et al.* 2007). While the complex and interactive nature of these effects leads to uncertainties with regard to the size of the carbon-cycle feedbacks (Cox *et al.* 2006), all models studied agree that a global mean temperature increase will reduce the biosphere's ability to store carbon emissions over the time scales considered here (Friedlingstein *et al.* 2006). Consequently, pathways to stabilizing CO_2 concentrations that include feedbacks have lower permissible emissions than those pathways that exclude such feedbacks. According to AR4, for example, *with* feedbacks included, stabilizing at 450 ppmv CO_2e correlates with cumulative emissions some 27 per cent lower than *without* feedbacks, over a 100-year period (IPCC 2007*a*, topic guide 5, p. 6). The impact of this latest science on the link between emissions and temperature is of sufficient scale to require the emission-reduction pathways associated with particular concentrations and hence temperatures be revisited.

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[2] For example, the RCEP uses CO_2e in RCEP (2000), whereas the Energy White Paper (DTI 2006) and Climate Change Programme (DEFRA 2006) both refer to CO_2 alone.

(ii) *Latest empirical emissions data*

The current suites of emission scenarios informing the international and national climate change agenda seldom include empirical emissions data post-2000, choosing instead to model recent emissions; both the 2006 Stern Review (Stern 2006, p. 231) and the UK's 2007 draft climate change bill (DEFRA 2007) illustrate this tendency. However, recent empirical data have shown global emissions to have risen at rates well in excess of those contained within these and many other emissions scenarios (Raupach *et al.* 2007). For example, while Stern assumes a mean annual CO_2e emission growth between 2000 and 2006 of approximately 0.95 per cent, the growth rate calculated from the latest empirical data is closer to 2.4 per cent.[3] Similarly, the UK's draft climate change bill (DEFRA 2007) contains an emission pathway between 2000 and 2006 in which emissions fall, while over the same period the UK Government's emission inventory suggests, at best, that emissions have been stable.

A further and important revision to recent emissions data relates to deforestation. Within many scenarios, including Stern, emissions resulting from deforestation are estimated to be in the region of 7.3 $GtCO_2$ in 2000. However, recent data have suggested this to be an overestimate, with R. A. Houghton (2006, personal communication) having recently revised his earlier figure downward to 5.5 $GtCO_2$.[4] The impact of this reduction allied to the latest emission data reinforces the need to revisit emission pathways.

3. Scenario analysis

(*a*) *Overview*

The scenario analysis presented within this paper is for the basket of six greenhouse gases only and relies, principally, on the scientific understanding contained within AR4. The analysis does not take account of the following:

- the radiative forcing impacts of aerosols and non-CO_2 aviation emissions (e.g. emissions of NO_x in the upper troposphere, vapour trails and cirrus formation);[5]

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[3] CO_2 data from the Carbon Dioxide Information Analysis Centre (CDIAC) including recent data from G. Marland (2006, personal communication); non-CO_2 greenhouse gas data from the USA Environmental Protection Agency (EPA 2006) including the projection for 2005, and assuming deforestation emissions in 2005 to be 5.5 $GtCO_2$ (1.5 GtC), with a 0.4 per cent growth in the preceding 5 years in line with data within the Global Forest Resources Assessment (FAO 2005).

[4] FAO (2005) contains rates of tropical deforestation for the 1990s revised downward from those in the 2000 Global Forest Resources Assessment (FAO 2000; R. A. Houghton 2006, personal communication). An earlier estimate based on high-resolution satellite data over areas identified as 'hot spots' of deforestation, estimated the figure at nearer 3.7 $GtCO_2$ (1 GtC) for 2000 (Achard *et al.* 2004). It is Houghton's more recent estimate that is used in this paper.

[5] There remains considerable uncertainty as to the actual level of radiative forcing associated with aerosols, exacerbated by their relatively short residence times in the atmosphere and uncertainty as to future aerosol emission pathways (Cranmer *et al.* 2001; Andreae *et al.* 2005). Similarly, there remain significant uncertainties as to the radiative forcing impact of non-CO_2 emissions from aviation, particularly contrails and linear cirrus (e.g. Stordal *et al.* 2004; Mannstein & Schumann 2005).

- the most recent findings with respect to carbon sinks;[6]
- previously underestimated emission sources;[7] and
- the implications of early emission peaks for 'overshooting' stabilization concentrations and the attendant risks of additional feedbacks.

While aerosols are most commonly associated with net global (or at least regional) cooling, the other factors outlined above are either net positive feedbacks or, as is the case for high peak-level emissions, increase the likelihood of net positive feedbacks. Consequently, the correlations between concentration and mitigation outlined in this analysis are, in time, liable to prove conservative.

The scenarios are for CO_2e emission pathways during the twenty-first century, with empirical data used for the opening years of the century (in contrast to modelled or 'what if' data). The full scenario sets (*AB1* and *AB2*) comprise different combinations of the following: (i) emissions of CO_2 from deforestation, (ii) emissions of non-CO_2 greenhouse gases, and (iii) emissions of CO_2 from energy and industrial processes.

For *AB1*

- *Deforestation.* Two low emission scenarios for the twenty-first century.
- *Non-CO_2 greenhouse gases.* Three scenarios peaking in 2015, 2020 and 2025 and subsequently reducing to 7.5 $GtCO_2e$ per year.
- *Energy and process CO_2.* Three scenarios peaking in 2015, 2020 and 2025 and subsequently reducing to maintain the total cumulative emissions for the twenty-first century within the AR4 450 ppmv CO_2e range (with carbon-cycle feedbacks).

For *AB2*

- *Deforestation.* Two low emission scenarios for the twenty-first century.
- *Non-CO_2 greenhouse gases.* One scenario peaking in 2020 subsequently reducing to 7.5 $GtCO_2e$ per year (as per *AB1* with a 2020 peak).
- *Energy and process CO_2.* Three scenarios, each following the same pathway to a 2020 peak, but subsequently reducing at different rates to maintain total annual CO_2e reductions of 3, 5 and 7 per cent.

The following sections detail the *deforestation* and *non-CO_2 greenhouse gas* emission scenarios used to derive the post-peak *energy and process CO_2* emission scenarios and ultimately the total global CO_2e scenarios for the twenty-first century.

(*b*) *Deforestation emissions*

A significant portion of the current global annual anthropogenic CO_2 emissions are attributable to deforestation (in the region of 12–25%). However, carbon mitigation policy, particularly in OECD nations, tends to focus on those

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[6] For example, and in particular, the reduced uptake of CO_2 in the Southern Ocean (Raupach *et al.* 2007) and the potential impact of low level ozone on the uptake of CO_2 in vegetation (Cranmer *et al.* 2001).

[7] For example, significant uncertainties in the emissions estimates for international shipping (Corbett & Kohler 2003; Eyring *et al.* 2005).

Table 1. Deforestation emission scenario summary for two scenarios used to build the subsequent full CO_2e scenarios (deforestation low, D_L; deforestation high, D_H) and one for illustrative purposes only (deforestation very high, D_{VH}).

name	2000 emissions/ year (carbon stock) [$GtCO_2$]	peak date	2100 carbon stock remaining % (carbon stock) [$GtCO_2$]	emissions 2000–2100 [$GtCO_2$]
D_L (developed for this analysis)	5.5 (1060)	2015	80 (847)	213
D_H (Moutinho & Schwartzman)	5.5 (1060)	2020	70 (741)	319
D_{VH} (Moutinho & Schwartzman)	*5.5 (1060)*	*2036*	*55 (583)*	*477*

emissions from energy and industrial processes (hereafter referred to as energy and process emissions), with less direct regard for emissions arising from deforestation. While the relatively high levels of uncertainty associated with deforestation emissions make their inclusion in global mitigation scenarios problematic, the scale of emissions is such that they must be included. Within this paper two deforestation scenarios are developed; both assume climate change to be high on the political agenda and represent relatively optimistic reductions in the rate of, and hence the total emissions released from, deforestation.[8] They both have a year 2000 baseline of 5.5 $GtCO_2$, but post-2015 have different deforestation rates and hence different stocks of carbon remaining in 2100 (i.e. the amount of carbon stored in the remaining forest). The scenarios are illustrated numerically in table 1 and graphically in figure 1.

The scenarios are dependent not only on the baseline but also on estimates of the change in forestry carbon stocks between 2000 and 2100. The stock values used in the scenarios are taken from Moutinho & Schwartzman (2005) and based on their estimate of total forest carbon stock in 2000 of 1060 $GtCO_2$. According to their assumptions, the carbon stock continues to be eroded at current rates until either 2012 or 2025, following which emissions from deforestation decline to zero by either 2100 or until they equate to 15 per cent of a particular nation's forest stock (compared with 2000). They estimate two values for the carbon stocks, released as CO_2 emissions by 2100 as 319 and 477 $GtCO_2$. This implies that within their scenarios, either 70 or 55 per cent of total carbon stocks remain globally. Given that this paper and its accompanying *AB1* and *AB2* scenarios are premised on climate change being high on the international agenda, Moutinho & Schwartzman's *55 per cent of total carbon stock* value is considered too pessimistic within the context of this analysis, and although presented in figure 1, is not included in the analysis from this point onwards. Moreover, to allow for a more stringent curtailment of deforestation, the scenario developed for a 70 per cent stock-remaining estimate is complemented by one with 80 per cent remaining.

[8] While the scenarios are at least as optimistic as those underpinning, for example, the 2005 Forest Resource Assessment (FAO 2005) and the 2006 Stern report, it could be argued they are broadly in keeping with the high profile deforestation gained during the 2007 United Nations Climate Change Conference in Bali.

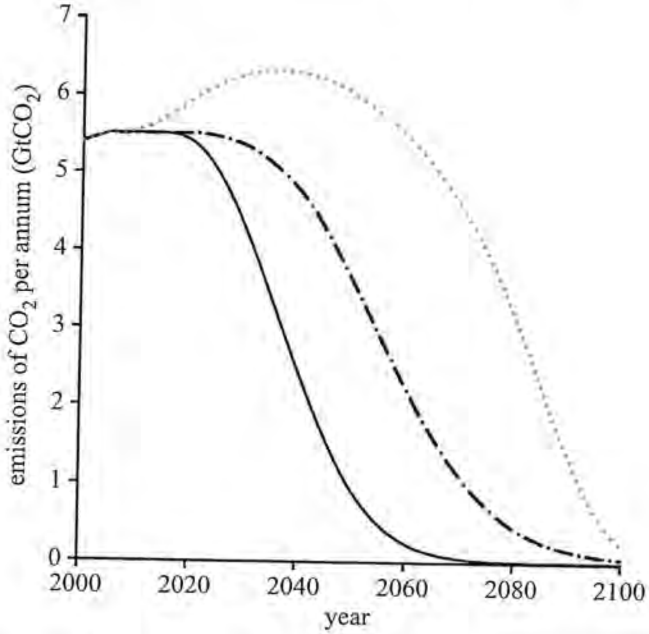

Figure 1. Deforestation emission scenarios showing three CO_2 emissions pathways based on varying levels of carbon stocks remaining in 2100. Solid curve, 80% stock remaining; dot-dashed curve, 70% stock remaining; dotted curve, 55% stock remaining.

The D_L and D_H curves both assume no increase in deforestation rates from current levels, with D_L beginning to drop from the peak level of 5.5 $GtCO_2$, 5 years prior to D_H. This, combined with the higher level of forestry, and hence carbon stock remaining in 2100, gives the D_L curve a faster rate of reduction in deforestation than is the case for the D_H curve (typically, 7.4 and 4.8% for D_L and D_H, respectively).[9]

(*c*) *Non-CO_2 greenhouse gas emissions*

To estimate the percentage reductions required from *energy and process* CO_2 emissions for both *AB1* and *AB2*, it is necessary to consider a range of future emission scenarios for the non-CO_2 greenhouse gases. Accordingly, three scenarios are developed assuming current US Environmental Protection Agency (EPA) estimates and projections of emissions from 2000 up to a range of peaking years, after which emissions are assumed to decline towards the same long-term stable level. All the scenarios represent a long-term halving in emission intensity, with the difference between them arising from the range of cumulative emissions associated with each of the peaking dates. The scenarios are illustrated numerically in table 2 and graphically in figure 2.

Anthropogenic non-CO_2 greenhouse gas emissions are dominated by methane and nitrous oxide and, along with the other non-CO_2 greenhouse gases, accounted for approximately 9.5 $GtCO_2e$ in 2000 (EPA 2006; similar figures are used within the Stern Review), equivalent to 23 per cent of global $CO_{2}e$

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[9] D_L per cent change value is the mean for the period between 2030 and 2050, and D_H is the mean value for 2040–2060.

Table 2. Non-CO_2 greenhouse gas emission scenario summary.

name	2000 emissions [$GtCO_2$]	peak year	mean growth to peak (%)	peak annual emission [$GtCO_2e$]	total 2000–2100 emissions [$GtCO_2e$]
early action	9.5	2015	1.31	11.4	858
mid-action	9.5	2020	1.51	12.2	883
late action	9.5	2025	1.53	13.3	916

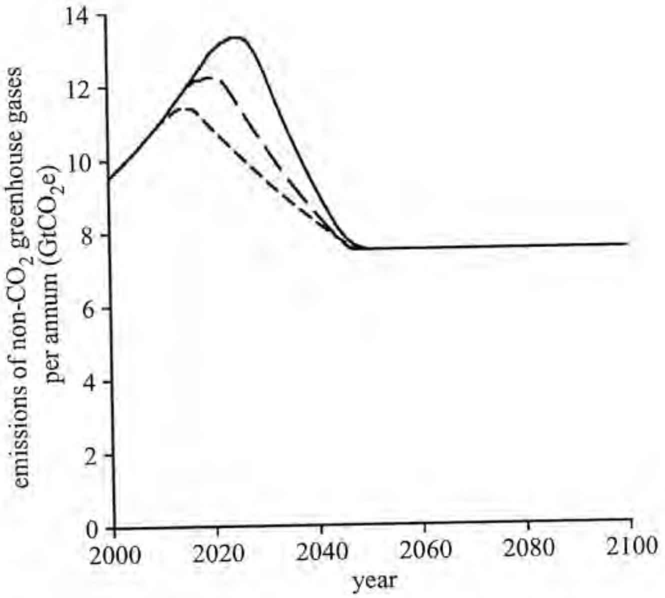

Figure 2. Three non-CO_2 greenhouse gas emission scenarios with emission pathways peaking at different years but all achieving the same residual level by 2050. Short dashed curve, early action; long dashed curve, mid-action; solid curve, late action.

emissions. Understanding how this significant portion of emissions may change in the future is key to exploring the scope for future emissions reduction from all the greenhouse gases.

The three non-CO_2 greenhouse gas scenarios presented here are broadly consistent with a global drive to alleviate climate change. The principal difference between the scenarios is the date at which emissions are assumed to peak, with the range chosen to match that for the total CO_2e emissions, namely an *early-action* scenario where emissions peak in 2015, a *mid-action* peak of 2020 and finally a *late-action* peak in 2025. All three scenarios have a growth rate from the year 2000 up until a few years prior to the peak, equivalent to that projected by the EPA (2006),[10] and broadly in keeping with recent trend data. The scenarios all contain a smooth transition through the period of peak emissions and on to a pathway leading towards a post-2050 value of 7.5 $GtCO_2e$. This value is again specifically chosen to

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[10] EPA values for global warming potential of the basket of six gases are slightly different from those used in IPCC. The difference, though noted here, does not significantly alter the analysis or results.

reflect a genuine global commitment to tackle climate change. It is approximately 25 per cent lower than the current level and consistent with a number of other 450 ppmv scenarios.[11] Given that the majority of the non-CO_2 greenhouse gas emissions are associated with food production, it is not possible, with our current understanding of the issues, to envisage how emissions could tend to zero while there remains a significant human population. The 7.5 $GtCO_2e$ figure used in this paper, assuming a global population in 2050 of 9 billion (thereafter remaining stable), is equivalent to approximately halving the emission intensity of current food production. While a reduction of this magnitude may be considered ambitious in a sector with little overall emission elasticity, such improvements are necessary if global CO_2e concentrations are to be maintained within any reasonable bounds.

The non-CO_2 greenhouse gas scenarios have similar growth rates from 2000 to their respective peak values, and ultimately all have the same post-2050 emission level (7.5 $GtCO_2e$). The rate of reduction in emissions from the respective peaks demonstrates the importance of timely action to curtail the current rise in annual emissions: the early-action scenario is required to reduce at 1.35 per cent per year, while the *mid*- and late-action scenario values are at 2 and 3 per cent, respectively. Similarly, table 2 and figure 2 demonstrate the importance for cumulative values of non-CO_2 greenhouse gas emissions not rising much higher than today and that the post-peak reduction rate achieves the long-term residual emission level as soon as is possible (7.5 $GtCO_2e$ by 2050). If the year in which emissions reach the residual level had been 2100 rather than 2050, the modest differences in cumulative emissions between the *early*-, mid- and late-action scenarios would have been substantially increased. Given that the cumulative value of non-CO_2 greenhouse gas emissions is a significant proportion of total cumulative CO_2e emissions, any delay in achieving the residual value would have significant implications for the reduction rate of energy and process CO_2 emissions necessary to meet the *AB1* and *AB2* criteria.

(*d*) *CO_2e emission scenarios for the twenty-first century*

Having developed the deforestation and non-CO_2 greenhouse gas scenarios, this section presents the complete greenhouse gas emission scenarios, *AB1* and *AB2*, for the twenty-first century. The emissions released from the year 2000 until the peak dates are discussed here in relation to both *AB1* and *AB2*, before the post-peak scenarios for each of the scenario sets are presented.

(i) *AB1 and AB2: emissions from 2000 to the peak years*

By combining the deforestation and non-CO_2 greenhouse gas scenarios with assumptions about energy and process CO_2, scenarios for all greenhouse gas emissions up until the three peaking dates are developed. Energy and process CO_2 emissions for the years 2000–2005 are taken from the Carbon Dioxide Information Analysis Centre (CDIAC), with estimates for 2006–2007 based on BP inventories (BP 2007). From 2007 to the three peaking dates of 2015 (early action), 2020 (mid-action) and 2025 (late-action) emissions of energy and process CO_2 grow at 3 per cent per year until 5 years prior to peaking. Beyond this point, emission growth gradually slows to zero at the peak year before reversing

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[11] For example, in Stern (2006, p. 233), for both his 450 ppmv CO_2e and 500–450 ppmv overshoot curve.

Table 3. Summary of the core components of scenario set *AB1*.

characteristic	2015–2100	2020–2100	2025–2100
deforestation[a]	D_H and D_L	D_H and D_L	D_H and D_L
non-CO_2 greenhouse gases[a]	early action	mid-action	late action
approximate peaking value [$GtCO_2e$]	54	60	64
cumulative emissions [$GtCO_2e$] IPCC AR4	low: 1376 medium: 1798 high: 2202	low: 1376 medium: 1798 high: 2202	low: 1376 medium: 1798 high: 2202
2100 residual emissions [$GtCO_2e$]	7.5	7.5	7.5

[a] Deforestation and non-CO_2 greenhouse gas scenarios as in tables 1 and 2.

thereafter. The 3 per cent emission growth rate chosen for CO_2 is broadly consistent with recent historical trends. Between 2000 and 2005, CDIAC data show a mean annual growth in energy and process CO_2 emissions of 3.2 per cent; this includes the slow growth years following the events of 11 September 2001.

(ii) *AB1: emissions from peak years to 2100*

From the peak years onwards, *AB1* (summarized in table 3) takes the approach that to remain within the bounds of a 450 ppmv CO_2e stabilization target, the cumulative emissions between 2000 and 2100 must not exceed the range presented within the latest IPCC report in which carbon-cycle feedbacks are included (IPCC 2007*b*).

(iii) *AB1 final scenarios*

The emission pathways for the full greenhouse gas *AB1* scenarios from 2000 to 2100 are presented in figure 3. The plots comprise the earlier deforestation and non-CO_2 greenhouse gas scenarios with growing energy and process CO_2 emissions up to the peaking year, and all have total twenty-first century cumulative values of CO_2e matching the 450 ppmv figures within AR4.

It is evident from the data underpinning figure 3 that 10 of the 18 proposed pathways cannot be quantitatively reconciled with the cumulative CO_2e emissions budgets for 450 ppmv provided within AR4. Table 4 identifies the 'impossible' scenarios (including three with prolonged annual reduction rates greater than 15%) and illustrates the post-peak level of sustained emission reduction necessary to remain within budget.

(iv) *AB1: implications for energy and process CO_2*

The constraints on the greenhouse gas emission pathways of achieving 450 ppmv CO_2e render most of the *AB1* scenarios impossible to achieve. Having established which scenarios are at least quantitatively possible and subtracting the respective non-CO_2 greenhouse gas and deforestation emissions, the energy and process emissions associated with each of the scenarios that remain feasible (figure 4) can be derived.

Figure 4 illustrates that complete decarbonization of the energy and process system is necessary by between 2027 and 2063, if the total greenhouse gas emissions are to remain within the IPCC's 450 ppmv CO_2e budgets. Moreover, in combination with table 5, it is evident that the only meaningful opportunity for

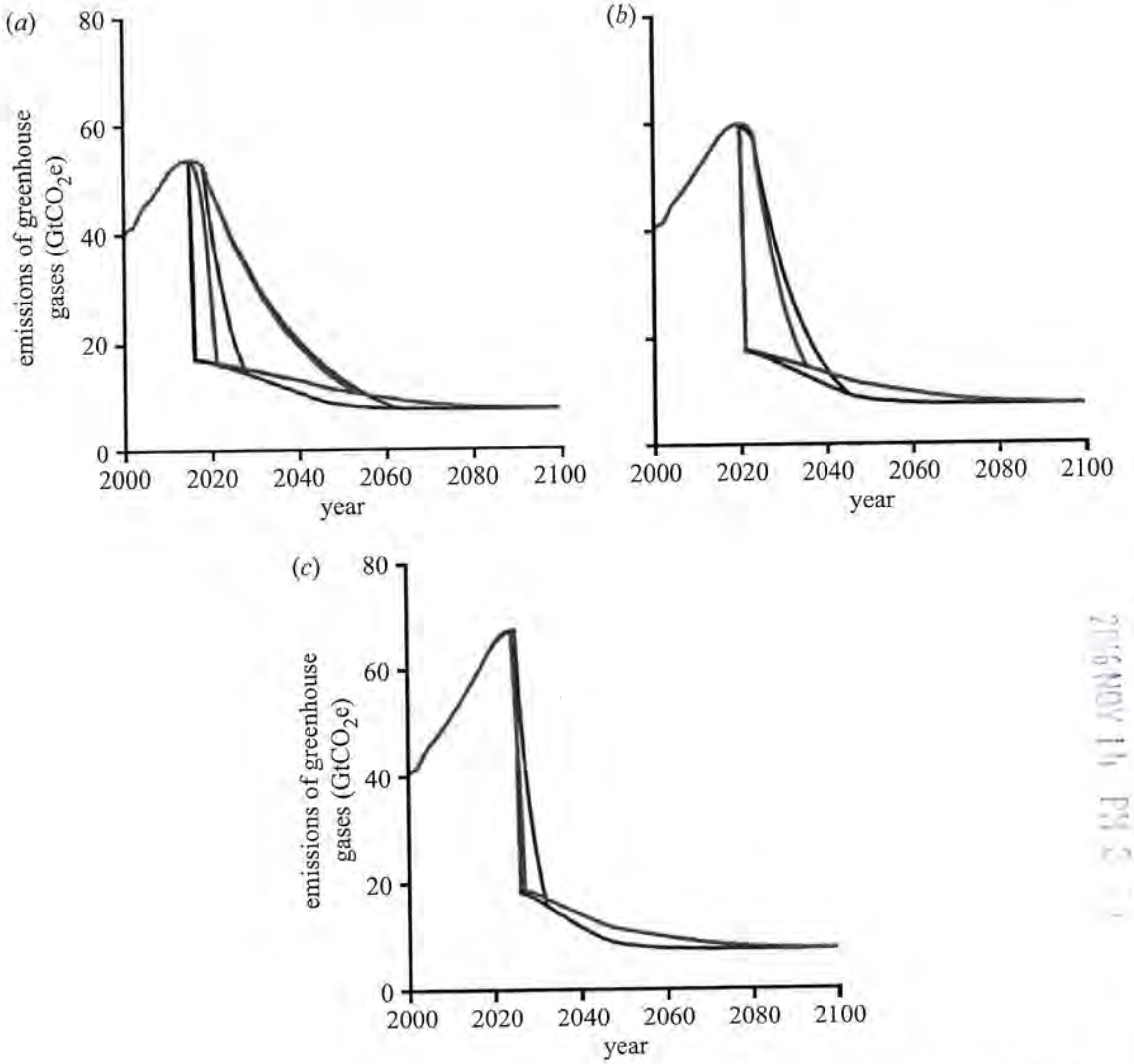

Figure 3. Greenhouse gas emission scenarios for *AB1* with emissions peaking in (*a*) 2015, (*b*) 2020 and (*c*) 2025. Dark purple curve, low D_L; black curve, low D_H; blue curve, medium D_L; red curve, medium D_H; light purple curve, high D_L; green curve, high D_H.

Table 4. Scenarios assessed in relation to their practical feasibility. (X denotes a scenario rejected on the basis of being quantitatively impossible or with prolonged percentage annual reduction rates greater than 15%. The percentage reductions given illustrate typical sustained annual emission reductions required to remain within budget.)

	deforestation D_L			deforestation D_H		
peak date	low	medium	high	low	medium	high
2015	X	13%	4%	X	X	4%
2020	X	X	8%	X	X	11%
2025	X	X	X	X	X	X

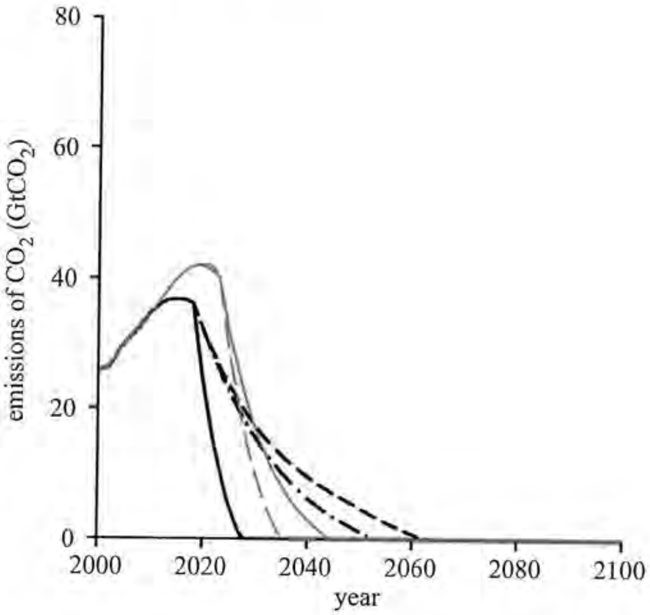

Figure 4. Energy and process CO_2 emissions derived by subtracting the non-CO_2 emissions and deforestation emissions from the total greenhouse gas emissions over the period of 2000–2100, for the *AB1* scenarios. Black solid curve, 2015 peak medium D_L; black dashed curve, 2015 peak high D_L; dot-dashed curve, 2015 peak high D_H; grey solid curve, 2020 peak high D_L; grey dashed curve, 2020 peak high D_H.

Table 5. Twenty-year sustained post-peak per cent reductions in energy and process CO_2 emissions (from 5 years following the peak year). (X denotes a scenario rejected on the basis of being quantitatively impossible, with prolonged per cent annual reduction rates greater than 15% or scenarios where full decarbonization is necessary within 20 years.)

	deforestation D_L			deforestation D_H		
peak date	low	medium	high	low	medium	high
2015	X	X	~6%	X	X	~8%
2020	X	X	X	X	X	X
2025	X	X	X	X	X	X

stabilizing at 450 ppmv CO_2e occurs if the highest of the IPCC's cumulative emissions range is used and if emissions peak by 2015.

(v) *AB2: emissions from 2020 (peak year) to 2100*

The *AB2* scenario set complements the *AB1* scenario set by exploring the implications for CO_2e budgets of three post-peak annual emission reduction rates (3, 5 and 7%). Only one peaking year is considered within this analysis with 2020 chosen as arguably the most 'realistic' of the three dates in terms of both the 'practicality' of being achieved and of the respective scope for remaining within 'reasonable' bounds of CO_2e concentrations. Table 6 summarizes the data underpinning figure 5.

Table 6. Summary of the core components of the *AB2* scenarios.

characteristic	2020–2100
deforestation[a]	D_H and D_L
non-CO_2 greenhouse gases[a]	mid-action
approximate peaking value [$GtCO_2e$]	60
post-2020 CO_2e reductions (%)	3, 5 and 7
2100 residual emissions [$GtCO_2e$]	7.5

[a] Deforestation and non-CO_2 greenhouse gas scenarios as in tables 1 and 2.

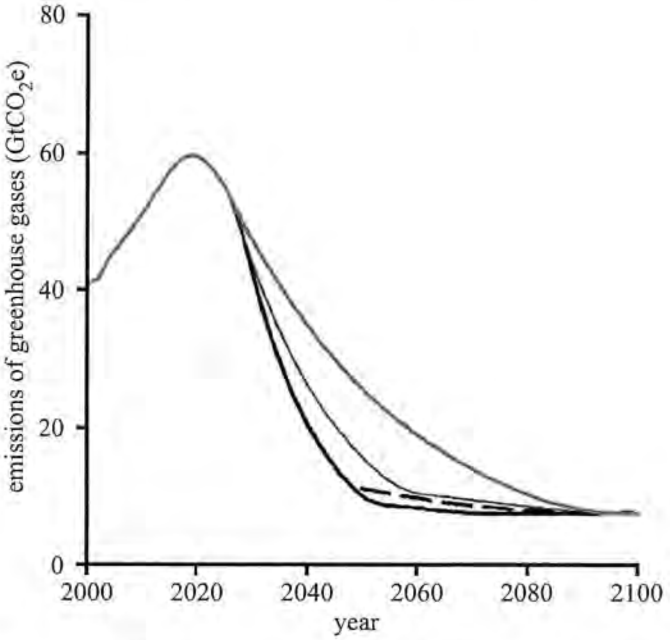

Figure 5. Greenhouse gas emission scenarios peaking in 2020, with sustained percentage emission reductions of 3, 5 and 7%. The 3 and 5% D_H scenarios are so similar to the 3 and 5% D_L that they are hidden behind those profiles. Black solid curve, 7% reduction D_L; black dashed curve, 7% reduction D_H; thin grey solid curve, 5% reduction D_L; thin grey dashed curve (hidden), 5% reduction D_H; thick grey solid curve, 3% reduction D_L; thick grey dashed curve (hidden), 3% reduction D_H.

The pathways within figure 5 equate to a range in cumulative CO_2e emissions for 2000–2100 of 2.4 $TtCO_2e$, 2.6 $TtCO_2e$ and 3 $TtCO_2e$ for 7, 5 and 3 per cent reductions, respectively. According to the cumulative emissions data contained within the Stern Review (Stern 2006: figure 8.1, p. 222), the first two values approximate to a CO_2e concentration of approximately 550 ppmv with the latter being closer to 650 ppmv.

(vi) *AB2: implications for energy and process CO_2*

Having developed the total CO_2e pathways for *AB2*, and given the deforestation and non-CO_2 greenhouse gas emission scenarios outlined earlier, the associated energy and process CO_2 scenarios can be derived (figure 6). Table 7 indicates typical post-peak annual reduction rates in energy and process CO_2 emissions for the families of 3, 5 and 7 per cent CO_2e scenarios.

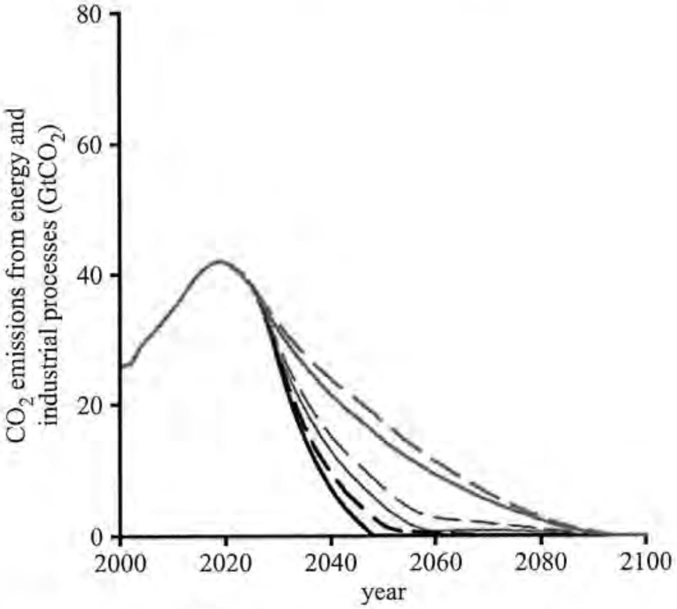

Figure 6. CO_2 emissions derived by removing the non-CO_2 greenhouse gas emissions and deforestation emissions from the total greenhouse gas emissions over the period of 2000–2100 for the *AB2* scenarios. Black dashed curve, 7% reduction D_L; black solid curve, 7% reduction D_H; thin grey dashed curve, 5% reduction D_L; thin grey solid curve, 5% reduction D_H; thick grey dashed curve, 3% reduction D_L; thick grey solid curve, 3% reduction D_H.

Table 7. Post-peak (2020) per cent reduction in energy and process CO_2 emissions.

annual reduction	deforestation D_L (%)			deforestation D_H (%)		
total CO_2e	3	5	7	3	5	7
energy and process CO_2	3	6	9	4	7	12

According to these results, the 3, 5 and 7 per cent CO_2e annual reduction rates comprising the *AB2* scenarios correspond with energy and process decarbonization rates of 3–4, 6–7 and 9–12 per cent, respectively. While the latter two ranges correlate broadly with stabilization at 550 ppmv CO_2e, the former, although arguably offering less unacceptable rates of reduction, correlates with stabilization nearer 650 ppmv CO_2e.

4. Discussion

(*a*) *AB1 scenarios*

The *AB1* scenarios presented here focus on 450 ppmv CO_2e and can be broadly separated into three categories.

(i) Scenarios that quantitatively exceed the IPCC's 450 ppmv CO_2e budget range: this equates to 10 of the 18 scenarios. Scenarios in this category are quantitatively impossible.

Table 8. Summary of the core components of the 450 ppmv scenario considered theoretically possible within the constraints of the analysis and assuming the IPCC's most 'optimistic' 450 ppmv CO_2e cumulative value.

characteristics	quantity
IPCC 450 ppmv upper limit cumulative value for 2000–2100 ($GtCO_2e$)	858
peak in CO_2e emissions	2015
post-peak annual CO_2e decarbonization rate	~4%
total decarbonization date (including forestry and excluding non-CO_2e greenhouse gas residual)	~2060–2075
post-peak sustained annual energy and process decarbonization rate	~6–8%
total energy and process decarbonization date	~2050–2060

(ii) Scenarios with current emission growth continuing until 2015, emissions peaking by 2020 and thereafter undergoing dramatic annual reductions of between 8 and 33 per cent. Scenarios in this category are, for the purpose of this paper, considered politically unacceptable.

(iii) Scenarios that, as early as 2010, break with current trends in emissions growth, with emissions subsequently peaking by 2015 and declining rapidly thereafter (approx. 4% per year). Scenarios in this category are discussed below.

For scenarios within category (iii) to be viable, it is necessary that the IPCC's upper value for 450 ppmv cumulative emissions between 2000 and 2100 be correct. If, on the other hand, the IPCC's mid- or low value turns out be more appropriate, category (iii) scenarios will either be politically unacceptable (i.e. above 8% per annum reduction) or quantitatively impossible.

However, even should the IPCC's high level ('optimistic') value be correct, the accompanying 4 per cent per year reductions in CO_2e emissions beginning in under a decade from today (i.e. by 2018) are unlikely to be politically acceptable without a sea change in the economic orthodoxy. The scale of this challenge is brought into sharp focus in relation to energy and process emissions. According to the analysis conducted in this paper, stabilizing at 450 ppmv requires, at least, global energy related emissions to peak by 2015, rapidly decline at 6–8 per cent per year between 2020 and 2040, and for full decarbonization sometime soon after 2050.

The characteristics of the resulting 450 ppmv scenario are summarized in table 8. This assumes that the most optimistic of the IPCC's range of cumulative emission values is broadly correct. While this analysis suggests stabilizing at 450 ppmv is theoretically possible, in the absence of an unprecedented step change in the global economic model and the rapid deployment of successful CO_2 scrubbing technologies, 450 ppmv is no longer a viable stabilization concentration. The implications of this for climate change policy, particularly adaptation, are profound. The framing of climate change policy is typically informed by the 2°C threshold; however, even stabilizing at 450 ppmv CO_2e offers only a 46 per cent chance of not exceeding 2°C (Meinshausen 2006). As a consequence, any further delay in global society beginning down a pathway towards 450 ppmv leaves 2°C as an inappropriate and dangerously misleading mitigation and adaptation target.

(*b*) *AB2 scenarios*

From the analysis underpinning the *AB2* scenarios, it is evident that the rates of emission reduction informing much of the climate change debate, particularly in relation to energy, correlate with higher stabilization concentrations than is generally recognized. The principal reason for this divergence arises, in the first instance, from the difference between empirical and modelled emissions data for post-2000. For example, in describing '[T]he Scale of the Challenge' Stern's 'stabilization trajectories' assume a mean annual emissions growth almost 1.5 per cent lower than was evident from the empirical data between 2000 and 2006. While the subsequent impact on cumulative emissions for this period is, in itself, significant, the substantive difference arises from short-term extrapolations of current trends. Stern's range of peak emissions for 2015 are some 10 $GtCO_2e$ lower than would be the case if present trends continued out to 2010, with growth subsequently reducing to give a peak in emissions by 2015.[12] This substantial divergence in emissions is exacerbated significantly as the peak date goes beyond 2015. If emissions were to peak by 2020 (as was assumed for the *AB2* scenarios), and again following a slowing in growth during the 5 years prior to the peaking date, emissions would, by 2020, be between 14 and 16 $GtCO_2e$ higher than Stern's 2020 range. This difference alone equates to over a third of current global annual emissions, with knock-on implications for short- to medium-term cumulative emissions seriously constraining the viable range of long-term stabilization targets.

While climate change is claimed to be a central issue within many policy dialogues, rarely are absolute annual carbon mitigation rates greater than 3 per cent considered viable. In addition, where mitigation polices are more developed, seldom do they include emissions from international shipping and aviation (Bows & Anderson 2007). Stern (2006, pp. 231) drew attention to historical precedents of reductions in carbon emissions, concluding that annual reductions of greater than 1 per cent have 'been associated only with economic recession or upheaval'. For example, the collapse of the former Soviet Union's economy brought about annual emission reductions of over 5 per cent for a decade. By contrast, France's 40-fold increase in nuclear capacity in just 25 years and the UK's 'dash for gas' in the 1990s both corresponded, respectively, with annual CO_2 and greenhouse gas emission reductions of only 1 per cent (not including increasing emissions from international shipping and aviation). Set against this historical experience, the reduction rates contained within the *AB2* scenarios are without a structurally managed precedent.

In all but one of the *AB2* scenarios, the challenge faced with regard to total CO_2e reductions is increased substantially when considered in relation to decarbonizing the energy and process systems. Despite the optimistic deforestation and non-CO_2 greenhouse gas emission scenarios developed for this paper, the repercussions for energy and process emissions are extremely severe. Stabilization at 550 ppmv CO_2e, around which much of Stern's analysis

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[12] Comparing values outlined in Stern (2006, p. 233) with those in *AB1* and *AB2* for 2015. In addition, Stern envisages a global CO_2e emissions increase of approximately 5 $GtCO_2e$ between 2000 and 2015 compared with provisional estimates for China alone of between 4.2 and 5.5 $GtCO_2e$, extending up to 12.2 $GtCO_2e$ (T. Wang & J. Watson of the Sussex Energy Group (SEG) 2008, personal communication). If the lower SEG estimate for China is correct, Stern's analysis implicitly assumes that global emissions (excluding China) remain virtually unchanged between 2000 and 2015.

revolved, requires global energy and process emissions to peak by 2020 before beginning an annual decline of between 6 and 12 per cent; rates well in excess of those accompanying the economic collapse of the Soviet Union. Even for the 3 per cent CO_2e reduction scenario (i.e. stabilization at 600–650 ppmv CO_2e), the current rapid growth in energy and process CO_2 emissions would need to cease by 2020 and begin reducing at between 3 and 4 per cent annually soon after.

It is important to note that for both *AB1* and *AB2* scenarios, there is a risk of a transient overshoot of the 'desired' atmospheric concentration of greenhouse gases as a consequence of the rate of change in the emission pathway. Given that overshoot scenarios remain characterized by considerable uncertainty and are the subject of substantive ongoing research (e.g. Schneider & Mastrandrea 2005; Nusbaumer & Matsumoto 2008), they have not been addressed within either *AB1* or *AB2*.

5. Conclusions

Given the assumptions outlined within this paper and accepting that it considers the basket of six gases only, incorporating both carbon-cycle feedbacks and the latest empirical emissions data into the analysis raises serious questions about the current framing of climate change policy. In the absence of the widespread deployment and successful application of geoengineering technologies (sometimes referred to as macro-engineering technologies) that remove and store atmospheric CO_2, several headline conclusions arise from this analysis.

- If emissions peak in 2015, stabilization at *450 ppmv* CO_2e requires subsequent annual reductions of 4 per cent in CO_2e and 6.5 per cent in energy and process emissions.
- If emissions peak in 2020, stabilization at *550 ppmv* CO_2e requires subsequent annual reductions of 6 per cent in CO_2e and 9 per cent in energy and process emissions.
- If emissions peak in 2020, stabilization at *650 ppmv* CO_2e requires subsequent annual reductions of 3 per cent in CO_2e and 3.5 per cent in energy and process emissions.

These headlines are based on the range of cumulative emissions within IPCC AR4 (for 450 ppmv) and the Stern report (for 550 and 650 ppmv),[13] with the accompanying rates of reduction representing the mid-values of the ranges discussed earlier. While for both the 550 and 650 ppmv pathways peak dates beyond 2020 would be possible, these would be at the expense of a significant increase in the already very high post-peak emission reduction rates.

These conclusions have stark repercussions for mitigation and adaptation policies. By association, they raise serious questions as to whether the current global economic orthodoxy is sufficiently resilient to absorb the scale of the challenge faced.

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[13] The 450 ppmv figure is from AR4 (IPCC 2007*a*), while the 550 and 650 ppmv figures are from Jones *et al.* (2006) and include carbon-cycle feedbacks (used in Stern's analysis). Although the Jones *et al.* figures are above the mid-estimates of the impact of feedbacks, there is growing evidence that some carbon-cycle feedbacks are occurring earlier than was thought would be the case, e.g. the reduced uptake of CO_2 by the Southern Ocean (Raupach *et al.* 2007).

It is increasingly unlikely that an early and explicit global climate change agreement or collective ad hoc national mitigation policies will deliver the urgent and dramatic reversal in emission trends necessary for stabilization at 450 ppmv CO_2e. Similarly, the mainstream climate change agenda is far removed from the rates of mitigation necessary to stabilize at 550 ppmv CO_2e. Given the reluctance, at virtually all levels, to openly engage with the unprecedented scale of both current emissions and their associated growth rates, even an optimistic interpretation of the current framing of climate change implies that stabilization much below 650 ppmv CO_2e is improbable.

The analysis presented within this paper suggests that the rhetoric of 2°C is subverting a meaningful, open and empirically informed dialogue on climate change. While it may be argued that 2°C provides a reasonable guide to the appropriate scale of mitigation, it is a dangerously misleading basis for informing the adaptation agenda. In the absence of an almost immediate step change in mitigation (away from the current trend of 3% annual emission growth), adaptation would be much better guided by stabilization at 650 ppmv CO_2e (i.e. approx. 4°C).[14] However, even this level of stabilization assumes rapid success in curtailing deforestation, an early reversal of current trends in non-CO_2 greenhouse gas emissions and urgent decarbonization of the global energy system.

Finally, the quantitative conclusions developed here are based on a global analysis. If, during the next two decades, transition economies, such as China, India and Brazil, and newly industrializing nations across Africa and elsewhere are not to have their economic growth stifled, their emissions of CO_2e will inevitably rise. Given any meaningful global emission caps, the implications of this for the industrialized nations are bleak. Even atmospheric stabilization at 650 ppmv CO_2e demands the majority of OECD nations begin to make draconian emission reductions within a decade. Such a situation is unprecedented for economically prosperous nations. Unless economic growth can be reconciled with unprecedented rates of decarbonization (in excess of 6% per year[15]), it is difficult to envisage anything other than a planned economic recession being compatible with stabilization at or below 650 ppmv CO_2e.

Ultimately, the latest scientific understanding of climate change allied with current emission trends and a commitment to 'limiting average global temperature increases to below 4°C above pre-industrial levels', demands a radical reframing[16] of both the climate change agenda, and the economic characterization of contemporary society.

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[14] Meinshausen (2006) estimates the mid-range probability of exceeding 4°C at approximately 34 per cent for 600 ppmv and 40 per cent for 650 ppmv. Given this analysis has not factored in a range of other issues with likely net positive impacts, adapting for estimated impacts of *at least* 4°C appears wise.

[15] At 650 ppmv the range of global decarbonization rate is 3–4 per cent per year (table 7, columns 1 and 4). As OECD nations represent approximately 50 per cent of global emissions, and assuming continued CO_2 emission growth from non-OECD nations for the forthcoming two decades, the OECD nations will need to compensate with considerably higher rates of emission reductions.

[16] This is not assumed desirable or otherwise, but is a conclusion of (i) the quantitative analysis developed within the paper, (ii) the premise that stabilization in excess of 600–650 ppmv CO_2e should be avoided and (iii) Stern's assertion that annual reductions of greater than 1 per cent have 'been associated only with economic recession or upheaval' (Stern 2006, p. 231).

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Exhibit 18

nature
climate change

LETTERS

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Assessment of the climate commitments and additional mitigation policies of the United States

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Current intended nationally determined contributions (INDCs) are insufficient[1] to meet the Paris Agreement goal of limiting temperature change to between 1.5 and 2.0 °C above pre-industrial levels[2], so the effectiveness of existing INDCs will be crucial to further progress. Here we assess the likely range of US greenhouse gas (GHG) emissions in 2025 and whether the US's INDC can be met, on the basis of updated historical and projected estimates. We group US INDC policies into three categories reflecting potential future policies, and model 17 policies across these categories. With all modelled policies included, the upper end of the uncertainty range overlaps with the 2025 INDC target, but the required reductions are not achieved using reference values. Even if all modelled policies are implemented, additional GHG reduction is probably required; we discuss several potential policies.

On 12 December 2015, representatives from 196 countries to the United Nations Framework Convention on Climate Change (UNFCCC)'s 21st Conference of Parties (COP-21) in Paris reached a landmark climate agreement[2] limiting global temperature increase, which will require balancing GHG emissions and sinks after mid-century.

In addition to setting a specific GHG emissions reduction target for 2025 (26–28% below the 2005 level[3]), the US INDC outlined specific steps for achieving these reductions, including existing and planned policies addressing light- and heavy-duty vehicles, appliance and equipment standards, building codes, electricity generation, hydrofluorocarbon (HFC) emissions, methane (CH_4) emissions and federal government operations.

A number of independent entities have examined the US INDC goal and policies to determine their likelihood of success. All conclude that existing federal policy will make it challenging to meet the US INDC, but opinions vary as to the likelihood of achieving the targets with additional federal actions. Eight previous studies are cited and compared with our work in the Supplementary Note.

Unlike most prior studies, our study models the final version of the Clean Power Plan (CPP) and includes a thorough accounting of other policies, including potential policies such as the Montreal Protocol amendment for HFC gases. Our study is also unique in that it estimates uncertainty ranges for historical and projected baseline GHG emissions, updates CH_4 emission estimates to reflect current scientific understanding, estimates GHG savings and uncertainty ranges for each policy, and provides a delineation of policy types spanning three categories. This detailed treatment of US climate policies will be invaluable for policymakers and other stakeholders, as US climate policy progresses toward the 2025 INDC target.

We undertake a comprehensive evaluation of historical and projected baseline US GHG emissions, focusing on key policy years 2005 and 2025. Beginning with the US Department of State's Climate Action Report (CAR)[4] and Second Biennial Report (SBR)[5], we make a number of revisions to both historical and projected emissions using consistent global warming potentials and recent updates to projected energy use, HFC emissions and land CO_2 uptake. Moreover, we make upward revisions to CH_4 emissions based on recent regional, US and global assessments. We also perform a comprehensive uncertainty analysis. See Methods for more information.

Our revised estimates produce a range in 2005 net GHG emissions from 6,323 to 7,403 $MtCO_2e$ (full uncertainty range). For 2025, net GHG emissions range from 0.6% above to 11.8% below the corresponding 2005 level. The change in net GHG emissions relative to the CAR[4] is positive in both 2005 and 2025. See Fig. 1. The largest uncertainty components are due to energy sector emissions, land sink uptake, and CH_4 emissions ($\gtrsim$400 $MtCO_2e$ each in 2005, larger in 2025).

We then estimate GHG emission impacts for a number of policies listed in Table 1, based on the US INDC. In addition, we include some policies not specified in the INDC, including commercial building codes, targets for manure and fertilizer management, and recent California legislation. Reduction estimates and uncertainty ranges are based on published reports by the federal government, independent entities or our own analysis. Some policies mentioned in the INDC, as well as existing state policies, are not modelled as they are included in the 2015 US Department of Energy's Annual Energy Outlook[6] baseline, from which our analysis proceeds.

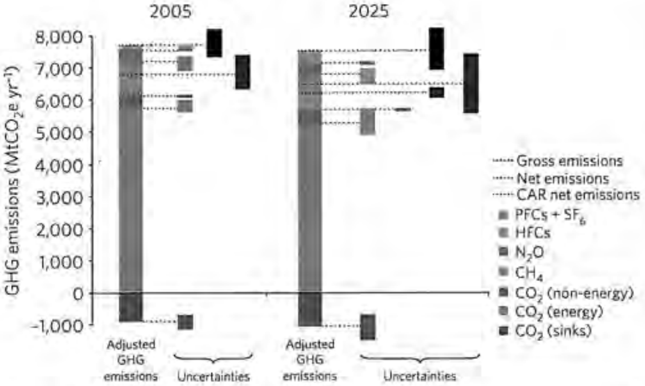

Figure 1 | Baseline 2005 and 2025 greenhouse gas (GHG) emissions with uncertainties shown for each category of emissions. Climate Action Report (CAR)[4] net GHG emissions shown for reference. CO_2, carbon dioxide; CH_4, methane; N_2O, nitrous oxide; HFCs, hydrofluorocarbons; PFCs, perfluorocarbons; SF_6, sulfur hexafluoride; $MtCO_2e$, million tonnes CO_2 equivalent.

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Table 1 | Summary of estimated greenhouse gas (GHG) emissions reduction in 2025 from policies.

Category	GHG	Policy description	Value range			Full uncertainty[†]	
			Reference	Min.	Max.	Min.	Max.
					($MtCO_2e$)		
A	CO_2	CPP (final rule)	241	226	255	221	267
		Electricity and buildings (California SB350)[‡,§]	13	13	13	13	14
	N_2O	Fertilizer management (policies in SBR)[‡]	10	10	10	9	13
	HFCs	Phase-out (Final EPA SNAP rule)	59	54	64	54	72
B	All	California 2030 GHG target (Executive Order)[‡,*]	65	65	65	64	68
	CO_2	Appliance standards (2015-2016)	27	27	27	27	29
		Building codes (residential, 2015-2025)[‖]	23	23	23	23	24
		Federal government operations (Executive Order)	26	26	26	25	27
		Heavy-duty vehicles (proposed)[*]	41	36	46	36	48
	CH_4	Oil and gas (proposed)[*]	13	12	14	8	16
		Landfills (proposed)[*]	18	18	18	13	21
C	CO_2	Enhanced CPP (proposed rule)[¶]	407	393	435	384	455
		Appliance standards (2017-2025)	29	29	29	28	30
		Building codes (commercial, 2015-2025)[‡,‖]	29	29	29	29	31
	CH_4	Oil and gas (aspirational target)	121	116	125	85	146
		Manure management (voluntary roadmap)[‡]	21	3	40	2	46
	HFCs	Phase-out (Montreal Protocol amendment)	67	55	79	55	88
Subtotals	All	Category A	323	303	342	306	356
		Category B	214	208	220	196	234
		Category C	674	625	737	596	784
		All	1,211	1,136	1,299	1,099	1,373

Abbreviations: Carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O), hydrofluorocarbons (HFCs), Clean Power Plan (CPP), Senate Bill (SB), Second Biennial Report (SBR), US Environmental Protection Agency (EPA), Significant New Alternatives Policy (SNAP), million tonnes CO_2 equivalent ($MtCO_2e$), minimum (min.), maximum (max.), intended nationally determined contribution (INDC). [†] Parameter uncertainties across GHG categories are added in quadrature, except for CH_4, which was not considered to be a Gaussian distribution, but a simple range. As a result, sums of quantities in these columns do not necessarily equal the indicated subtotals. [‡] Not included in INDC. [§] SB350 (50% renewable electricity and doubled rate of building energy efficiency savings by 2030)[14]. [‖] Only residential building codes were specified in the US INDC. Because such codes cannot be mandated federally and are adopted to varying degrees at the state level, we have categorized future residential building codes as a Category B action. For commercial building codes, we have categorized future actions as Category C since no federal targets have been specified. [¶] Reductions shown are incremental to the CPP final rule. [*] See 'Note added in proof'.

Policies are divided into three categories depending on current status:

- Category A: Passed legislation or final rule (finalized by late 2015).
- Category B: Proposed legislation, proposed rule, or executive order.
- Category C: Announced target, potential policy or voluntary measure.

The rationale for categorizing different types of policy is discussed in Supplementary Methods, 'Modelled policies.' Implied in this categorization is a decreasing likelihood of policy impact in 2025 in moving from Category A to C.

Combining all of our 2025 estimates together, including uncertainties arising both from the inherent range of impacts as well as parameter uncertainty, results in GHG emission reduction ranges shown in Table 1 and Fig. 2.

The CPP contributes the most to GHG emissions reductions. Two versions are modelled: the final rule, and an enhanced version based on the proposed rule. The final rule, published in October 2015[7], is included in Category A, with estimated reductions from 221 to 267 $MtCO_2e$ in 2025. These estimates do not include some additional reductions that may have been assumed to take place elsewhere in the energy system. However, the earlier proposed rule is much more ambitious[8], with total savings that are more than twice as large; therefore, this policy is included in Category C as something that the US might later pursue.

Five other policies—CH_4 oil and gas aspirational target[9], California's 2030 GHG target[10], two HFC policies (the US Environmental Protection Agency (EPA)'s Significant New Alternatives Policy (SNAP)[11] and Montreal Protocol amendment[12]), and the heavy-duty vehicle efficiency proposed rule[13]—each have impacts of between 36 and 146 $MtCO_2e$, or 3.2 to 10.7% of total reductions. Of these, only SNAP is a Category A policy. We estimate that the remaining 10 policies, which span Categories A, B and C, collectively reduce emissions between 177 and 251 $MtCO_2e$ (16.1 to 18.3% of total reductions).

The US INDC pledges a 26 to 28% reduction below the 2005 GHG emission level in 2025. Considering the uncertainties discussed above, this produces a 2025 target ranging from 4,553 to 5,478 $MtCO_2e$. The difference between this target and the estimated 2025 emissions without INDC policies results in an 'emissions gap' ranging from 896 to 2,121 $MtCO_2e$, with a reference value of 1,510 $MtCO_2e$ corresponding to a 4.8% reduction below the 2005 level.

Including policies that the US has actively adopted (Category A) results in remaining emissions between 5,230 and 7,135 $MtCO_2e$. While it would appear that there is some overlap with the target emissions range, as the high end of the 2025 target is higher than the low end of remaining emissions, this is not the case. Because of the way these ranges are correlated with common assumptions about energy-related CO_2 emissions, land sinks, and CH_4 emissions, the estimated emissions gap after including Category A reductions is 551 to 1,805 $MtCO_2e$, or 8.7 to 24.4% of the 2005 level. See Fig. 3.

Including Category B policies results in an emissions gap of 340 to 1,586 $MtCO_2e$, while including Category C policies as well lowers the gap to between −356 and 924 $MtCO_2e$. While the low end of this latter range is indeed negative, indicating emissions 5.6% lower than the maximum 2025 target (26% below the 2005 level), it corresponds to favourable assumptions for all parameters, and implementation of all policies. The upper end, corresponding to less favourable parameter assumptions, is 12.5% above the minimum 2025 target (28% below the 2005 level), indicating that further reductions will be necessary to close this gap with confidence. We briefly discuss policy options below; for more information, see Supplementary Discussion.

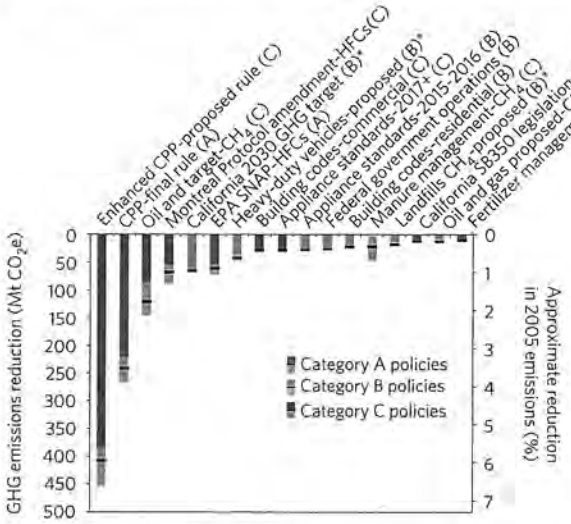

Figure 2 | Rank-ordered greenhouse gas (GHG) reduction estimates in 2025 by policy. Lighter coloured bars indicate full uncertainty ranges. Black horizontal lines denote reference values. CO_2, carbon dioxide; CH_4, methane; N_2O, nitrous oxide; HFCs, hydrofluorocarbons; $MtCO_2e$, million tonnes CO_2 equivalent; EPA, US Environmental Protection Agency; SNAP, Significant New Alternatives Policy. *See 'Note added in proof'.

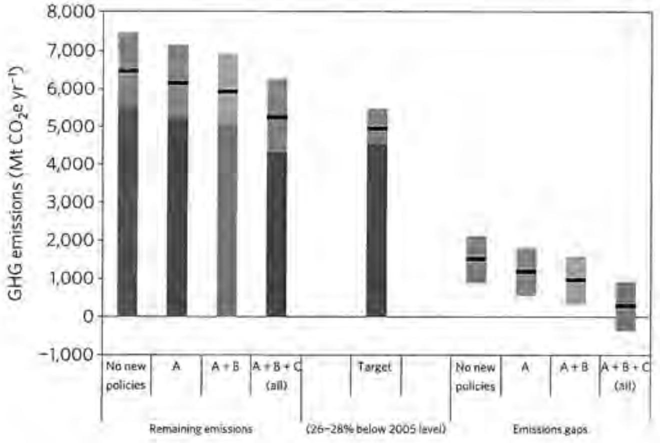

Figure 3 | Estimated remaining 2025 greenhouse gas (GHG) emissions, target and emissions gaps by policy category. Lighter coloured bars indicate full uncertainty ranges. Black horizontal lines denote reference values. Colour code: No new policies (grey); Category A (blue); Categories A + B (green); Categories A + B + C (red); Target (purple). $MtCO_2e$, million tonnes carbon dioxide equivalent.

In the electricity sector, an aggressive phase-out of coal and natural gas generation, with accompanying increases in renewables, energy efficiency and possibly nuclear generation could be enacted. As an example, California plans to meet a 33% renewable electricity target in 2020, and 50% in 2030[14], as well as phase-out coal generation by 2030[15]. Several other states[16] are also actively reducing electricity-sector GHG emissions. Together, these strategies could even exceed proposed rule CPP reductions (see Supplementary Discussion, 'Extensions of the CPP').

Vehicle electrification represents an important GHG emission reduction strategy in the transportation sector, due to the lower GHG intensity of electricity- versus petroleum-powered vehicles. California and seven other states[17] have a 2025 target of 3.3 million zero net emission vehicles; if scaled to the US, it would encompass 16 million vehicles, 6% of projected stock. Such a target could save more than 50 $MtCO_2e$ and also reduce air pollution.

Policies that shift mobility use from private vehicles to lower GHG modes (public transit, non-motorized mobility, and on-demand shared-ride vehicles), such as in California[18], could be strengthened. Moreover, vehicle automation could significantly lower GHG emissions[19], although increased usage might undermine some savings.

Current biofuels targets have been reduced from 36 billion gallons of ethanol-equivalent originally proposed for 2022[20]. However, there may be more than 1 billion tonnes of US biomass available by 2030, sufficient for 70 billion gallons[21], with significant GHG savings.

Hydrogen can be produced from many sources and could reduce GHG emissions across multiple sectors. Federal spending of ~US$100 million annually supports ambitious hydrogen production, storage and fuel cell goals, but more could be done to realize them, such as increased commercialization and infrastructure efforts[22].

Electrifying building and industrial heating can reduce emissions when electricity has a lower GHG emissions intensity than fossil sources[23]. Electric heat pumps are far more efficient than combustion, and high-temperature industrial approaches can provide higher throughput, space savings and improved quality[24].

The majority of oil and gas sector CH_4 leaks probably come from a minority of 'super-emitters' that, if identified and addressed, could reduce sector emissions 65 to 87%[25]. Moreover, landfill CH_4 emissions could be reduced by 90% in new facilities, and up to 60% in older ones[26].

The use of slow-release fertilizers has been shown to reduce N_2O emissions by 35%, without a corresponding increase in labour[27]. With the majority of the 345 $MtCO_2e$ of estimated 2025 N_2O emissions due to agriculture, such an application would result in much larger reductions than assumed under current federal policy[5].

Additional HFC reductions of ~33% or 82 $MtCO_2e\,yr^{-1}$ in 2025 could come from more aggressive Montreal Protocol amendments[28].

A variety of land management practices could enhance carbon storage, reducing 2030 CO_2 emissions by >40 $MtCO_2e\,yr^{-1}$ in California (The Nature Conservancy, unpublished data, 2015), with greater potential nationally.

Finally, GHG emissions trading now being pursued in a handful of US states[10,29] as well as internationally[30] could unlock low-cost GHG reduction strategies, lowering total emissions while saving money.

In conclusion, updated estimates of 2005 and 2025 US GHG emissions, along with estimates of the impacts of US INDC policies, indicate that additional mitigation measures will probably be required to reduce US GHG emissions to the 2025 INDC target (26–28% below the 2005 level). Promising strategies exist spanning multiple sectors and technologies. Time is short, so it is vital for the US to develop achievable plans to maintain pressure on other nations to support the Paris Agreement.

Note added in proof: The recent passage of California SB 32 on 25 August 2016 codifies the statewide GHG emissions reduction target (Executive Order B-30-15) in law[31]. Furthermore, the US Environmental Protection Agency and the US Department of Transportation's National Highway Traffic Safety Administration jointly finalized the heavy-duty vehicle standards on 16 August 2016[32], and the US Environmental Protection Agency finalized its CH_4 emissions standards for oil/gas and landfill sectors on June 3, 2016 and July 15, 2016, respectively[33,34]. All these changes elevate the corresponding policies from Category B to A. However, this Letter was resubmitted before these changes occurred, so they were not incorporated in the analysis.

Methods

Methods and any associated references are available in the online version of the paper.

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Author contributions

M.W. performed HFC policy analysis and comparison to prior studies; J.B.G. performed all other calculations and analysis. J.B.G. and M.W. wrote the manuscript and addressed reviewer concerns.

Additional information

Supplementary information is available in the online version of the paper. Reprints and permissions information is available online at www.nature.com/reprints. Correspondence and requests for materials should be addressed to J.B.G.

Competing financial interests

The authors declare no competing financial interests.

Methods

Historical US GHG emissions were obtained from the US Environmental Protection Agency (EPA)'s 2015 GHG emissions inventory[35], which provided annual historical estimates from 1990 to 2013. We also examined emissions data from EPA's 2014 GHG emissions inventory[36], which provided annual historical estimates from 1990 to 2012, for additional information about HFC and perfluorocarbon (PFC) emissions. EPA's 2016 draft inventory[37] reported emissions to 2014, and makes important revisions to prior year estimates, suggesting that historical (including 2005) net emissions were higher by >300 $\mathrm{MtCO_2e\,yr^{-1}}$. However, as the data were not finalized, we did not utilize them in our analysis.

Other data sources provided both historical and projected emissions. The US Department of State's 2014 US Climate Action Report (CAR)[4] and 2016 Second Biennial Report (SBR)[5] provided five-year estimates for all GHGs from 2000 to 2030 (plus some years between 2010 and 2015). The US Energy Information Administration's 2015 and 2016 Annual Energy Outlook (AEO) reports[6,38] provided annual energy-related CO_2 emissions to 2040, and the EPA's 2015 Significant New Alternatives Policy (SNAP) report[11] provided HFC emissions in 5-year intervals from 2010 to 2030.

The SBR was released after our initial analysis was completed, and its projected baseline GHG emissions included some, but not all, policies we modelled in our analysis. As a result, it was not possible to use the SBR projections to represent future emissions in the absence of federal actions in support of the US INDC. Therefore, we have retained the CAR projections with some important modifications.

For energy-related CO_2 emissions, we used 2015 AEO projections[6] modified to subtract bunker fuel emissions (in accordance with Intergovernmental Panel on Climate Change (IPCC) inventory reporting guidelines[1]), and included projected emissions from US territories estimated from historical EPA data[35]. We also subtracted some industrial CO_2 emissions reported by the CAR as non-energy emissions. (The 2016 AEO, which included projections with and without the CPP, was released too recently to be incorporated into this analysis. However, we did utilize a small additional GHG saving arising from outside the electricity sector as a result of the CPP that was not included in the EPA analysis[8]; see Supplementary Methods, 'Historical and projected baseline US GHG emissions' for details.)

For non-energy CO_2 emissions, we retained the CAR projections (none were separately provided in the SBR). For land use CO_2, we used SBR projections, as they reflected important recent revisions in estimated future land use practices and resulting CO_2 absorption. Emissions of non-CO_2 GHGs were expressed in CO_2 equivalent units using 100-year global warming potentials (GWPs) from either the IPCC Second Assessment Report (SAR)[39] or Fourth Assessment Report (AR4)[40]. The AR4 GWPs were used in the US INDC and all data sets except the EPA's 2014 GHG inventory and the CAR, which used SAR GWPs. For consistency, we converted non-CO_2 emissions from SAR to AR4 GWPs, as described in Supplementary Methods, 'Global warming potentials (GWPs).' We retained these adjusted CAR emission projections for N_2O, PFCs and SF_6. For HFCs, however, the EPA recently made significant upward revisions to projected baseline emissions in its 2015 SNAP report[11], so we used those projections instead.

A number of recent studies point toward important differences between CH_4 emission estimates from EPA, and those based on measurements obtained from towers, aeroplanes and satellites[41–47]. As a result, we used a correction factor of $1.50^{+0.25}_{-0.40}$ times the EPA's GHG values for historical CH_4 emissions and the CAR's AR4-adjusted projected emissions, resulting in increases in estimated CH_4 emissions of 354^{+177}_{-283} $\mathrm{MtCO_2e}$ in 2005 and 368^{+184}_{-295} $\mathrm{MtCO_2e}$ in 2025. While these upward revisions represent the latest scientific understanding, considerable uncertainty remains. More detail about these corrections can be found in Supplementary Methods, 'CH_4 adjustments.'

To characterize uncertainty in energy-related CO_2 projections, we examined the 2015 AEO reference case along with 13 side cases[6]. We found that total CO_2 emissions in 2025 varied by approximately ±4%, and used this range to characterize future uncertainty. The additional uncertainty arising from our modifications to the AEO projections were found to be negligible. See Supplementary Methods, 'Uncertainty estimates,' for details. For CH_4, as noted above, we used a correction factor with uncertainty bounds.

In addition to the above uncertainties, we used EPA's own uncertainty estimates[35] for GHG emissions in 2013 to estimate intrinsic uncertainty. We used separate 95% uncertainty interval estimates for each GHG except for CO_2, where we used separate uncertainty estimates for energy, non-energy and land sink emissions. We assumed that the relative uncertainty in each GHG category would remain the same in other years, including 2005 and 2025, and applied these estimates to all adjusted emissions estimates except CH_4 (since our own estimate of uncertainty was far larger than what EPA assumed).

EPA parameter uncertainty estimates were combined in quadrature as per standard error propagation methods. Other sources of uncertainty, which had minimum/maximum ranges but no formal confidence intervals, were linearly combined (that is, without quadrature) to obtain a maximum uncertainty range, which we refer to as 'full uncertainties.'

For each INDC policy listed in Table 1, we developed GHG reduction estimates based on federal government analyses, extrapolations from independent analyses, and synthesis from scientific literature. 'High' and 'low' bracketing uncertainty estimates were developed for most policies; others utilized single-point values. To these ranges we added intrinsic uncertainties described above to arrive at full uncertainty estimates. When subtracting GHG emissions policy reductions from baseline emissions, care was taken to include intrinsic uncertainties only afterward, to avoid overestimating the uncertainty.

More details are given in Supplementary Methods, 'Modelled policies,' but in brief, we estimated 2025 policy impacts as follows:

(1) Clean power plan. We used EPA's analysis of its final rule (Category A, despite a current legal challenge[48]) to obtain a range of GHG savings[8]. For the enhanced version of the CPP (Category C), we used EIA's analysis[49] of the proposed rule to estimate a range of GHG savings across scenario variants, and subtracted this range from estimated final rule savings.

(2) Appliance and equipment standards. We performed trend analysis on historical estimates in ref. 50 to estimate future savings in electricity and natural gas, converting to GHG emissions via data from ref. 51 and EIA[6]. Category B represented savings from standards finalized through 2016, whereas Category C included savings from potential new standards through 2025.

(3) Building codes. We based our estimates for future residential (Category B) and commercial (Category C) building code energy savings on state-by-state projections of ref. 52, converting to GHG emissions in a similar manner as for appliance and equipment standards (see above).

(4) Heavy-duty vehicles. We used estimates from EPA and US Department of Transportation of their proposed rule[13] (Category B; see 'Note added in proof') policy for medium- and heavy-duty vehicles spanning multiple scenarios and calculation methods to provide a range of GHG savings.

(5) Federal government operations. We used the Administration's own estimate[53] of GHG savings from clean electric and thermal energy sources, reduced energy use in federal buildings and federal vehicle fleets, and similar savings from major federal suppliers for this Category B executive order.

(6) CH_4 mitigation. Using our revised higher emissions rates of CH_4 from US sources, we adjust percentage savings estimates for certain CH_4 reduction policies:

Oil and gas. We used the Administration's estimate of its proposed rule[54] (Category B; see 'Note added in proof') GHG savings range. We also used the Administration's aspirational target (Category C) of a 40 to 45% sector reduction from the 2012 level by 2025[55].

Landfills. Category B (see 'Note added in proof') savings are based on an EPA proposed rule analysis[56].

Manure management. We base savings on the Administration's voluntary biogas roadmap[57] (Category C) savings estimates.

No other federal policies exist with quantitative reduction targets for CH_4, so none were included.

(7) N_2O mitigation. We used the difference between adjusted CAR[4] and SBR[5] N_2O emissions as a proxy for current federal policy (Category A) fertilizer management N_2O savings discussed in the SBR.

(8) HFC mitigation. We used estimated reductions from EPA's 2015 SNAP[58] regulations (Category A), while larger reductions are based on compliance with a proposed Montreal Protocol amendment (Category C)[59].

(9) California policies. California has the most aggressive GHG emissions reductions policy of any state in the US[60]. We used the CALGAPS model[61] to simulate recently passed California renewable portfolio standard and building efficiency legislation (SB350, Category A) and the statewide GHG emissions reduction target (Executive Order B-30-15, Category B; see 'Note added in proof'). These policies are additional to the federal CPP, because California is expected to meet its CPP obligations with existing policies 'years ahead of schedule'[62] and projects its own GHG emissions in 2030 to be 34% below the CPP target[63], or 15 $\mathrm{MtCO_2e}$, higher than our estimated savings from SB350. The statewide GHG emissions reduction target is estimated from the difference between the 2030 target of 40% below the 1990 level[10] and expected emissions from all other existing policies[61].

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Exhibit 19

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LETTERS

Greenhouse-gas emission targets for limiting global warming to 2 °C

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More than 100 countries have adopted a global warming limit of 2 °C or below (relative to pre-industrial levels) as a guiding principle for mitigation efforts to reduce climate change risks, impacts and damages[1,2]. However, the greenhouse gas (GHG) emissions corresponding to a specified maximum warming are poorly known owing to uncertainties in the carbon cycle and the climate response. Here we provide a comprehensive probabilistic analysis aimed at quantifying GHG emission budgets for the 2000–50 period that would limit warming throughout the twenty-first century to below 2 °C, based on a combination of published distributions of climate system properties and observational constraints. We show that, for the chosen class of emission scenarios, both cumulative emissions up to 2050 and emission levels in 2050 are robust indicators of the probability that twenty-first century warming will not exceed 2 °C relative to pre-industrial temperatures. Limiting cumulative CO_2 emissions over 2000–50 to 1,000 Gt CO_2 yields a 25% probability of warming exceeding 2 °C—and a limit of 1,440 Gt CO_2 yields a 50% probability—given a representative estimate of the distribution of climate system properties. As known 2000–06 CO_2 emissions[3] were ~234 Gt CO_2, less than half the proven economically recoverable oil, gas and coal reserves[4–6] can still be emitted up to 2050 to achieve such a goal. Recent G8 Communiqués[7] envisage halved global GHG emissions by 2050, for which we estimate a 12–45% probability of exceeding 2 °C—assuming 1990 as emission base year and a range of published climate sensitivity distributions. Emissions levels in 2020 are a less robust indicator, but for the scenarios considered, the probability of exceeding 2 °C rises to 53–87% if global GHG emissions are still more than 25% above 2000 levels in 2020.

Determining probabilistic climate change for future emission scenarios is challenging, as it requires a synthesis of uncertainties along the cause–effect chain from emissions to temperatures; for example, uncertainties in the carbon cycle[8], radiative forcing and climate responses. Uncertainties in future climate projections can be quantified by constraining climate model parameters to reproduce historical observations of temperature[9], ocean heat uptake[10] and independent estimates of radiative forcing. By focusing on emission budgets (the cumulative emissions to stay below a certain warming level) and their probabilistic implications for the climate, we build on pioneering mitigation studies[11,12]. Previous probabilistic studies—while sometimes based on more complex models—either considered uncertainties only in a few forcing components[13], applied relatively simple likelihood estimators ignoring the correlation structure of the observational errors[14] or constrained only model parameters like climate sensitivity rather than allowed emissions.

Using a reduced complexity coupled carbon cycle–climate model[15,16], we constrain future climate projections, building on the Fourth IPCC Assessment Report (AR4) and more recent research. In particular, multiple uncertainties in the historical temperature observations[9] are treated separately for the first time; new ocean heat uptake estimates are incorporated[10]; a constraint on changes in effective climate sensitivity is introduced; and the most recent radiative forcing uncertainty estimates for individual forcing agents are considered[17].

The data constraints provide us with likelihood estimates for the chosen 82-dimensional space of climate response, gas-cycle and radiative forcing parameters (Supplementary Fig. 3). We chose a Bayesian approach, but also obtain 'frequentist' confidence intervals for climate sensitivity (68% interval, 2.3–4.5 °C; 90%, 2.1–7.1 °C), which is in approximate agreement with the recent AR4 estimates. Given the inherent subjectivity of Bayesian priors, we chose priors for climate sensitivity such that we obtain marginal posteriors identical to 19 published climate sensitivity distributions (Fig. 1a). These distributions are not all independent and not equally likely, and cannot be formally combined[18]. They are used here simply to represent the wide variety of modelling approaches, observational data and likelihood derivations used in previous studies, whose implications for an emission budget have not been analysed before. For illustrative purposes, we chose the climate sensitivity distribution of ref. 19 with a uniform prior in transient climate response (TCR, defined as the global-mean temperature change which occurs at the time of CO_2 doubling for the specific case of a 1% yr^{-1} increase of CO_2) as our default. This distribution closely resembles the AR4 estimate (best estimate, 3 °C; likely range, 2.0–4.5 °C) (Supplementary Information).

Maximal warming under low emission scenarios is more closely related to the TCR than to the climate sensitivity[19]. The distribution of the TCR of our climate model for the illustrative default is slightly lower than derived within another model set-up[19], but within the range of results of previous studies (Fig. 1b), and encompasses the range arising from emulations by coupled atmosphere–ocean general circulation models[16] (AOGCMs) (Fig. 1c).

Representing current knowledge on future carbon-cycle responses is difficult, and might be best encapsulated in the wide range of results from the process-based C4MIP carbon-cycle models[8]. We emulate these C4MIP models individually by calibrating 18 parameters in our carbon-cycle model[16], and combine these settings with the other gas cycles, radiative forcing and climate response parameter uncertainties gained from our historical constraining.

Additional challenges arise in estimating the maximum temperature change resulting from a certain amount of cumulative emissions. The analysis needs to be based on a multitude of emission pathways with realistic multi-gas characteristics[20,21], as well as varying

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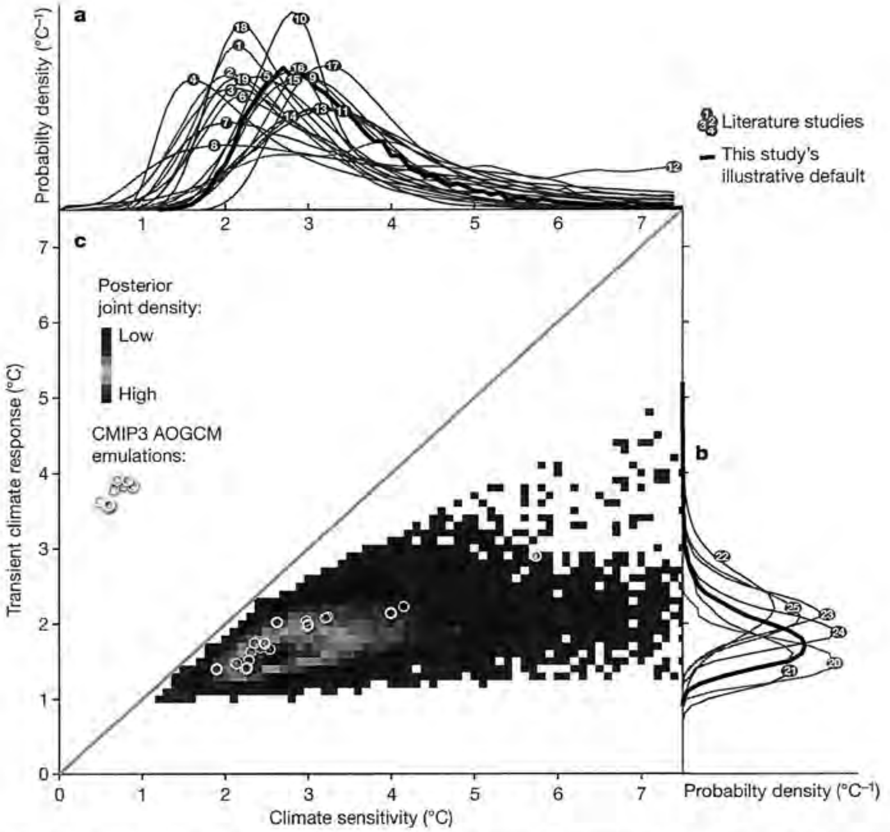

Figure 1 | Joint and marginal probability distributions of climate sensitivity and transient climate response. **a**, Marginal probability density functions (PDFs) of climate sensitivity; **b**, marginal PDFs of transient climate response (TCR); **c**, posterior joint distribution constraining model parameters to historical temperatures, ocean heat uptake and radiative forcing under our representative illustrative priors. For comparison, TCR and climate sensitivities are shown in **c** for model versions that yield a close emulation of 19 CMIP3 AOGCMs (white circles)[16]. Data sources for curves 1–25 are given in Supplementary Information.

shapes over time. AOGCM results for multi-gas mitigation scenarios were not available for assessment in the IPCC AR4 Working Group I Report[22]. Consequently, IPCC AR4 Working Group III[23] provided equilibrium warming estimates corresponding to 2100 radiative forcing levels for some multi-gas mitigation scenarios, using simplified regressions (Supplementary Fig. 6). Thus, 15 years after the first pioneering mitigation studies[11,12], there is still an important gap in the literature relating emission budgets for lower emission profiles to the probability of exceeding maximal warming levels; a gap that this study intends to fill.

We compute time-evolving distributions of radiative forcing and surface air temperature implications for the set of 26 IPCC SRES[21] and 20 EMF-21 scenarios[20] shown in Fig. 2a and b. We complement these with 948 multi-gas equal quantile walk emission pathways[24] that share—by design—similar multi-gas characteristics (Supplementary Fig. 5) but represent a wide variety of plausible shapes, ranging from early moderate reductions to later peaking and rapidly declining emissions towards near-zero emissions (Supplementary Information). Whereas Fig. 2e shows a standard plot of global-mean temperature versus time for two sample scenarios, Fig. 2f highlights the strong correlation between maximum warming and cumulative emissions. The fraction of climate model runs above 2 °C (dashed line in Fig. 2f) is then our estimate for the probability of exceeding 2 °C for an individual scenario (as indicated by the dots in Fig. 3a). We focus here on 2 °C relative to pre-industrial levels, as such a warming limit has gained increasing prominence in science and policy circles as a goal to prevent dangerous climate change[25]. We recognize that 2 °C cannot be regarded as a 'safe level', and that (for example) small island states and least developed countries are calling for warming to be limited to 1.5 °C (Supplementary Information). We chose the twenty-first century as our time horizon, as this time frame is sufficiently long to determine which emission scenarios will probably lead to a global surface warming below 2 °C. Under these scenarios, temperatures have stabilized or peaked by 2100, while warming continues under higher scenarios.

For our illustrative distribution of climate system properties, we find that the probability of exceeding 2 °C can be limited to below 25% (50%) by keeping 2000–49 cumulative CO_2 emissions from fossil sources and land use change to below 1,000 (1,440) Gt CO_2 (Fig. 3a and Table 1). If we resample model parameters to reproduce 18 published climate sensitivity distributions, we find a 10–42% probability of exceeding 2 °C for such a budget of 1,000 Gt CO_2. If the acceptable exceedance probability were only 20%, this would require an emission budget of 890 Gt CO_2 or lower (illustrative default). Given that around 234 Gt CO_2 were emitted between 2000 and 2006 and assuming constant rates of 36.3 Gt $CO_2\,yr^{-1}$ (ref. 3) thereafter, we would exhaust the CO_2 emission budget by 2024, 2027 or 2039, depending on the probability accepted for exceeding 2 °C (respectively 20%, 25% or 50%).

To contrast observationally constrained probabilistic projections against current AOGCM and carbon-cycle models, we ran each emission scenario with all permutations of 19 CMIP3[26] AOGCM and 10 C4MIP carbon-cycle model emulations[16]. The allowed emissions are similar to the lower part of the range spanned by the observationally constrained distributions, suggesting that the current AOGCMs do not substantially over- or underestimate future climate change compared to the values obtained using a model constrained by observations, although no probability statement can be derived from the proportion of runs exceeding 2 °C (black dashed line in Fig. 3a). Using an independent approach focusing on CO_2 alone, Allen *et al.*[27]

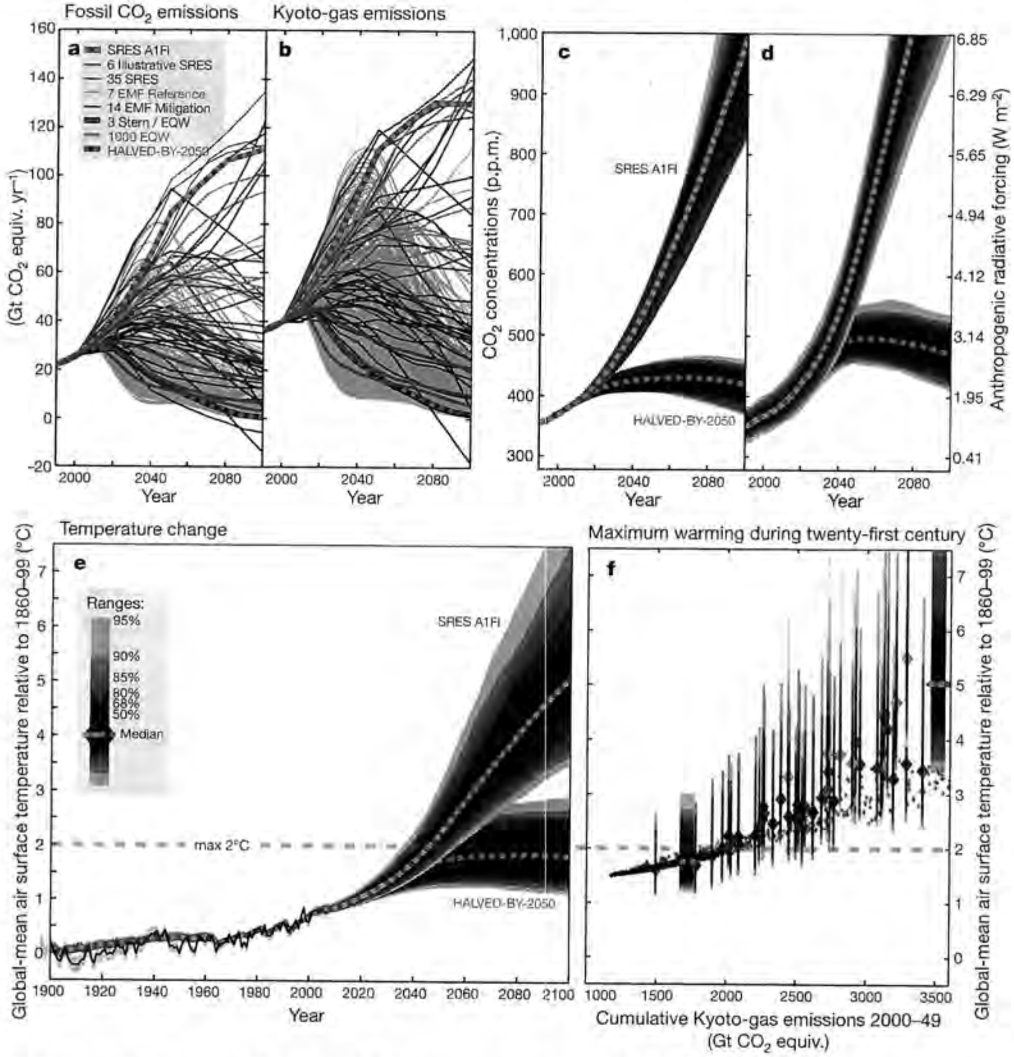

Figure 2 | Emissions, concentrations and twenty-first century global-mean temperatures. **a**, Fossil CO_2 emissions for IPCC SRES[21], EMF-21[20] scenarios and a selection of equal quantile walk[24] (EQW) pathways analysed here; **b**, GHGs, as controlled under the Kyoto Protocol; **c**, median projections and uncertainties based on our illustrative default case for atmospheric CO_2 concentrations for the high SRES A1FI[21] and the low HALVED-BY-2050[30] scenario, which halves 1990 global Kyoto-gas emissions by 2050; **d**, total anthropogenic radiative forcing; **e**, surface air global-mean temperature; **f**, maximum temperature during the twenty-first century versus cumulative Kyoto-gas emissions for 2000–49. Colour range shown in **e** also applies to **c**, **d** and **f**.

find that a range of 2,050–2,100 Gt CO_2 emissions from year 2000 onwards cause a most likely CO_2-induced warming of 2 °C: in the idealized scenarios they consider that meet this criterion, between 1,550 and 1,950 Gt CO_2 are emitted over the years 2000 to 2049.

We explored the consequences of burning all proven fossil fuel reserves (the fraction of fossil fuel resources that is economically recoverable with current technologies and prices: Fig. 3b and Methods). We derived a mid-estimate of 2,800 Gt CO_2 emissions from the literature, with an 80%-uncertainty range of 2,541 to 3,089 Gt CO_2. Emitting the carbon from all proven fossil fuel reserves would therefore vastly exceed the allowable CO_2 emission budget for staying below 2 °C.

Although the dominant anthropogenic warming contribution is from CO_2 emissions, non-CO_2 GHG emissions add to the risk of exceeding warming thresholds during the twenty-first century. We estimate that the so-called non-CO_2 'Kyoto gases' (methane, nitrous oxide, hydrofluorocarbons, perfluorocarbons and SF_6) will constitute roughly one-third of total CO_2 equivalent (CO_2 equiv.) emissions based on 100-yr global warming potentials[28] over the 2000–49 period. Under our illustrative distribution for climate system properties, and taking into account all positive and negative forcing agents as provided by Table 2.12 in AR4[17], the cumulative Kyoto-gas emission budget for 2000–50 is 1,500 (2,000) Gt CO_2 equiv., if the probability of exceeding 2 °C is to be limited to approximately 25% (50%) (Table 1).

For the lower scenarios, Kyoto-gas emissions in the year 2050 are a remarkably good indicator for probabilities of exceeding 2 °C, because for these scenarios (with emissions in 2050 below ~30 Gt CO_2 equiv.), radiative forcing peaks around 2050 and temperature soon thereafter. This is indicated by the narrow spread of individual scenarios' exceedance probabilities for similar 2050 Kyoto-gas emissions, as shown in Supplementary Fig. 1b. If emissions in 2050 are half 1990 levels, we estimate a 12–45% probability of exceeding 2 °C (Table 1) under these scenarios.

Emissions in 2020 are a less robust indicator of maximum warming (note the wide vertical spread of individual scenario dots in Supplementary Fig. 1c)—even if restricted to this class of relatively smooth emission pathways. However, the probability of exceeding 2 °C rises to 75% if 2020 emissions are not lower than 50 Gt CO_2 equiv. (25% above 2000). Given the substantial recent increase in fossil CO_2 emissions (20% between 2000 and 2006)[3], policies to reduce global emissions are needed urgently if the 'below 2 °C' target[29] is to remain achievable.

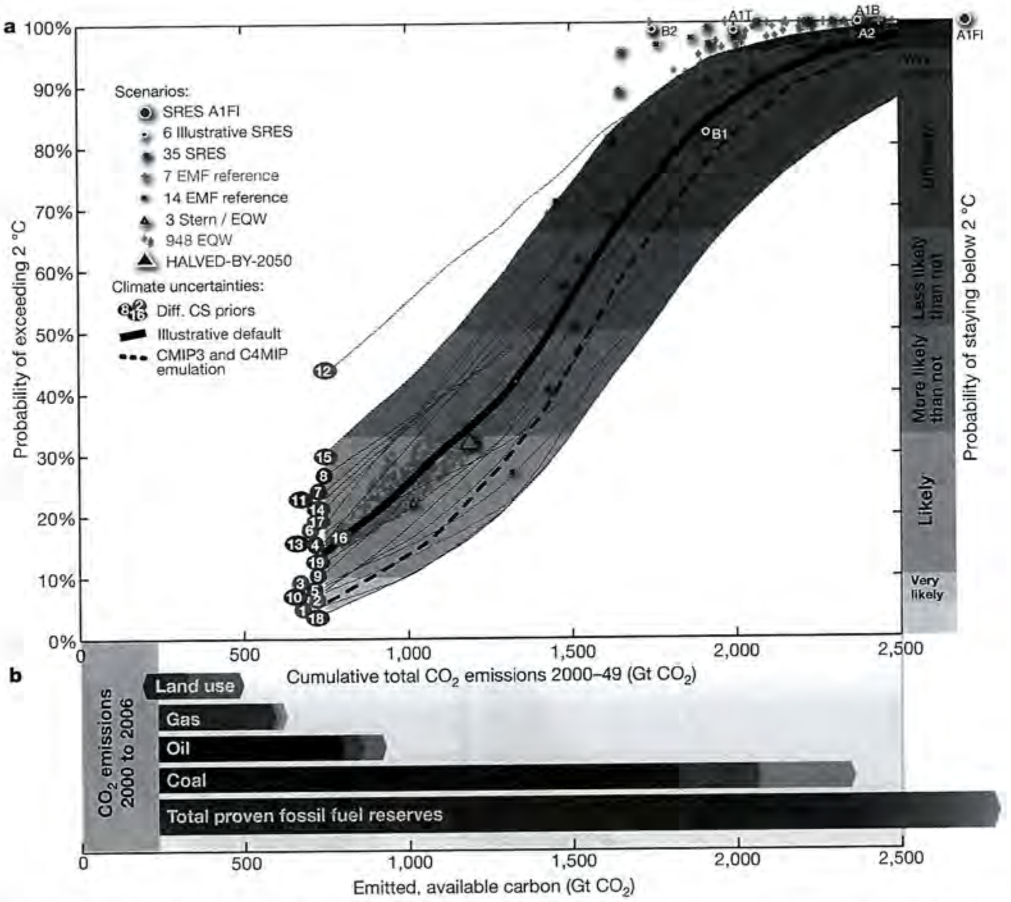

Figure 3 | The probability of exceeding 2 °C warming versus CO_2 emitted in the first half of the twenty-first century. **a**, Individual scenarios' probabilities of exceeding 2 °C for our illustrative default (dots; for example, for SRES B1, A2, Stern and other scenarios shown in Fig. 2) and smoothed (local linear regression smoother) probabilities for all climate sensitivity distributions (numbered lines, see Supplementary Information for data sources). The proportion of CMIP3 AOGCMs[26] and C4MIP carbon-cycle[8] model emulations exceeding 2 °C is shown as black dashed line. Coloured areas denote the range of probabilities (right) of staying below 2 °C in AR4 terminology, with the extreme upper distribution (12) being omitted. **b**, Total CO_2 emissions already emitted[3] between 2000 and 2006 (grey area) and those that could arise from burning available fossil fuel reserves, and from land use activities between 2006 and 2049 (median and 80% ranges, Methods).

Table 1 | Probabilities of exceeding 2 °C

Indicator	Emissions	Probability of exceeding 2 °C*	
		Range	Illustrative default case‡
Cumulative total CO_2 emission 2000–49	886 Gt CO_2	8–37%	20%
	1,000 Gt CO_2	10–42%	25%
	1,158 Gt CO_2	16–51%	33%
	1,437 Gt CO_2	29–70%	50%
Cumulative Kyoto-gas emissions 2000–49	1,356 Gt CO_2 equiv.	8–37%	20%
	1,500 Gt CO_2 equiv.	10–43%	26%
	1,678 Gt CO_2 equiv.	15–51%	33%
	2,000 Gt CO_2 equiv.	29–70%	50%
2050 Kyoto-gas emissions	10 Gt CO_2 equiv. yr^{-1}	6–32%	16%
	(Halved 1990) 18 Gt CO_2 equiv. yr^{-1}	12–45%	29%
	(Halved 2000) 20 Gt CO_2 equiv. yr^{-1}	15–49%	32%
	36 Gt CO_2 equiv. yr^{-1}	39–82%	64%
2020 Kyoto-gas emissions	30 Gt CO_2 equiv. yr^{-1}	(8–38%)†	(21%)†
	35 Gt CO_2 equiv. yr^{-1}	(13–46%)†	(29%)†
	40 Gt CO_2 equiv. yr^{-1}	(19–56%)†	(37%)†
	50 Gt CO_2 equiv. yr^{-1}	(53–87%)†	(74%)†

* Range across all priors reflecting the various climate sensitivity distributions with the exception of line 12 in Fig. 3a.

† Note that 2020 Kyoto-gas emissions are, from a physical perspective, a less robust indicator for maximal twenty-first century warming with a wide scenario-to-scenario spread (Supplementary Fig. 1c).

‡ Prior chosen to match posterior of ref. 19 with uniform priors on the TCR.

METHODS SUMMARY

To relate emissions of GHGs, tropospheric ozone precursors and aerosols to gas-cycle and climate system responses, we employ MAGICC 6.0[16], a reduced complexity coupled climate–carbon cycle model used in past IPCC assessment reports for emulating AOGCMs. Out of more than 400 parameters, we vary 9 climate response parameters (one of which is climate sensitivity), 33 gas-cycle and global radiative forcing parameters (not including 18 carbon-cycle parameters, which are calibrated separately[16] to C4MIP carbon-cycle models[8]), and 40 scaling factors determining the regional 4 box pattern of key forcings (Supplementary Table 1). Other parameters are set to default values[16].

To constrain the parameters, we use observational data of surface air temperature[9] in 4 spatial grid boxes from 1850 to 2006, the linear trend in ocean heat content changes[10] from 1961 to 2003 and year 2005 radiative forcing estimates for 18 forcing agents[17], in addition to a constraint on the twenty-first century change of effective climate sensitivity derived from AOGCM CMIP3 emulations[16]. With a Metropolis-Hastings Markov chain Monte Carlo approach, based on a large ensemble ($>3 \times 10^6$) of parameter sets using 45 parallel Markov chains with 75,000 runs each, we estimate the posterior distribution of different MAGICC parameters. Estimated likelihoods take into account observational uncertainty and climate variability from various AOGCM control runs, HadCM3 being the default.

For forward projections with the model, we combine, at random, 600 sets of the 82 historically constrained parameters with one of 10 carbon-cycle calibrations. We supplemented 26 multi-gas IPCC SRES[21] and 20 EMF-21 reference and mitigation scenarios[30] by 948 equal quantile walk multi-gas pathways[24]. The proven fossil fuel reserve estimates for natural gas, oil and coal were compiled from various sources[4,5] by combining the reserve estimates with net calorific values and emission factors (and their 95% uncertainty ranges) according to IPCC 2006 guidelines[6] (Supplementary Information).

Full Methods and any associated references are available in the online version of the paper at www.nature.com/nature.

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Author Contributions M.M. and N.M. designed the research with input from W.H., R.K. and M.A. M.M. performed the climate modelling, N.M. the statistical analysis, W.H. the compilation of fossil fuel reserve estimates; all authors contributed to writing the paper.

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METHODS

Coupled carbon cycle–climate model. We use a reduced complexity coupled carbon cycle climate model (MAGICC 6.0), requiring (hemispheric) emissions of GHGs, aerosols, and tropospheric ozone precursors as inputs for calculating atmospheric concentrations, radiative forcings, surface air temperatures, and ocean heat uptake. MAGICC is able to closely emulate both CMIP3[36] AOGCMs and C4MIP[8] carbon-cycle models, and has been used extensively in past IPCC assessment reports[16]. We use MAGICC 6.0 here both for future climate projections based on historical constraints and for emulating more complex AOGCMs or carbon-cycle models. The model contains many parameters whose values are uncertain. We looked at the impact of 82 parameters on model behaviour, which are summarized in the vector $\mathbf{\Theta}$.

Observational constraints. As one set of observational constraints, we use yearly averaged temperatures in our four grid boxes (Northern and Southern Hemisphere Land and Ocean) as provided in ref. 9 for the years 1850–2006. We arrange those measurements in a 628-dimensional vector $\mathbf{T}$. The respective space-time dependency of the errors is obtained from ref. 9. We use the full-length control runs of all AOGCMs runs available at PCMDI (http://www-pcmdi.llnl.gov/, as of mid-2007) to assess internal variability. We project the 628-dimensional vector of temperature observations into a low-dimensional subspace. We choose m so that 99.95% of the MAGICC variance is preserved and find that an eight-dimensional subspace is sufficient but findings are insensitive to this choice. We then find the $m \times 628$-dimensional matrix P_m, which corresponds to the projection of $\mathbf{T}$ into the space spanned by the first m PCA components. The likelihood is finally based on the m-dimensional vector $\mathbf{T}_m = P_m\mathbf{T}$ instead of the 628-dimensional vector $\mathbf{T}$. We now assume that the internal variability of $\mathbf{T}_m$ has a Gaussian distribution and estimate the $m \times m$-dimensional covariance matrix Σ_m from the data set as $P_m\, \Sigma\, P_m^{\,T}$, where Σ is the previously derived covariance matrix of the observations (including internal variability and measurement errors).

Ocean heat uptake is only considered via its linear trend Z_1 of $+0.3721$ (1σ: ± 0.0698) $10^{22}\,\mathrm{J\,yr^{-1}}$ for the heat content trend over 1961 to 2003 up to 700 m depth[10]. See Supplementary Fig. 2 for the match between the constrained model results and the observational data[31] as well as more recent results[10].

Radiative forcing estimates as listed in ref. 17 (Table 2.12 therein) provide an additional set of 17 constraints $Z_2,...,Z_{18}$ (Supplementary Table 2). The error of 14 of these radiative forcing estimates is assumed to have a Gaussian distribution. The remaining 3 observational constraints, however, exhibit skewness, which we model by a distribution we call here 'skewed normal' (Supplementary Information). All radiative forcing uncertainties are assumed to be independent.

Given that MAGICC 6.0 has substantially more freedom to change the effective climate sensitivity over time[16] than what is observed from AOGCM diagnostics, we introduce another constraint Z_{19}. This constraint limits the ratio of the twenty-first century change in effective climate sensitivity, expressed by the ratio of average effective climate sensitivities in the periods 2050–2100 and 1950–2000. Based on AOGCM CMIP3 model emulations[16], we derive a distribution with a median at 1.23 (with a 90% range between 1.06 to 1.51) under the SRES A1B scenario.

Likelihood estimation. To calculate the likelihood, the observations are split into the projected temperature observations $\mathbf{T}_m$ and the remaining observational constraints $Z_1,...,Z_{19}$. Let f be the density of temperature observations under a given parameter setting $\mathbf{\Theta}$, taking into account both the measurement errors and internal climate variability. Let h_k, $k = 1,\ldots,19$, be the density functions of the remaining observational constraints. Under independence of $Z_1,...,Z_{19}$ and $\mathbf{T}$, the likelihood $L(\mathbf{\Theta})$ of model parameters $\mathbf{\Theta}$ is given by:

$$L(\mathbf{\Theta}) = f(T_m|\mathbf{\Theta}) \prod_{k=1}^{19} h_k(Z_k|\mathbf{\Theta})$$

We follow mostly a Bayesian approach. A prior distribution π over the parameter vector $\mathbf{\Theta}$ is specified in various ways as discussed further below, see Supplementary Table 1 for prior assumption on key parameters. Given the a priori assumption, we are able to specify the posterior distribution $g(\mathbf{\Theta})$ of the parameters as proportional to the product of the likelihood $L(\mathbf{\Theta})$ and the prior $\pi(\mathbf{\Theta})$.

Sensitivity to the chosen prior and a comparison with frequentist inference are discussed further below. For frequentist inference, we work directly with the likelihood.

Model sampling. To draw models from the posterior distribution $g(\mathbf{\Theta})$, we use a Markov chain Monte Carlo approach and a standard Metropolis-Hastings algorithm with adaptive step sizes to attain an average acceptance rate of 60%. 45 Markov chains are run in parallel for 75,000 iterations each. Adjusting for a burn-in time of 20,000 iterations, and retaining only every 30th model, to decrease dependence between successive models, a total of 82,500 models are drawn from the posterior distribution. For probabilistic forecasts, 600 models with maximal spacing in this set of 82,500 models are retained and combined randomly with one of the 10 parameter sets used for emulating individual C4MIP carbon-cycle models[16].

Representation of climate sensitivity distributions. Apart from the frequentist likelihood confidence intervals, we represent the wide range of literature studies on Bayesian climate sensitivity distributions[19,32–41]. Specifically, we change the prior for climate sensitivity such that a match between our posterior PDF of climate sensitivity and the posterior distribution in the considered studies is achieved.

Fossil fuel reserves. Our median estimates of proven recoverable fossil fuel reserves are based on ref. 42, with the exception of the non-conventional oil reserves which are taken as the median between ref. 43 and ref. 44. Potential emissions are estimated using IPCC 2006 default net calorific values and carbon content emission factors[6] (Table 1.2 and Table 1.3 therein).

We estimate the 80% uncertainty range in these reserve estimates as being ±10% of the WEC[42] estimates or the range of estimates in the literature[4,43–46], whichever is greater, for individual classes of reserves. We combine these reserve uncertainties with the provided 95% ranges of calorific values and emission factors for each class of energy reserves[6] (Supplementary Table 3). See Supplementary Information for an expanded description of the methods.

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Exhibit 20

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Global Carbon Budget 2015

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Abstract. Accurate assessment of anthropogenic carbon dioxide (CO_2) emissions and their redistribution among the atmosphere, ocean, and terrestrial biosphere is important to better understand the global carbon cycle, support the development of climate policies, and project future climate change. Here we describe data sets and a methodology to quantify all major components of the global carbon budget, including their uncertainties, based on the combination of a range of data, algorithms, statistics, and model estimates and their interpretation by a broad scientific community. We discuss changes compared to previous estimates as well as consistency within and among components, alongside methodology and data limitations. CO_2 emissions from fossil fuels and industry (E_{FF}) are based on energy statistics and cement production data, while emissions from land-use change (E_{LUC}), mainly deforestation, are based on combined evidence from land-cover-change data, fire activity associated with deforestation, and models. The global atmospheric CO_2 concentration is measured directly and its rate of growth (G_{ATM}) is computed from the annual changes in concentration. The mean ocean CO_2 sink (S_{OCEAN}) is based on observations from the 1990s, while the annual anomalies and trends are estimated with ocean models. The variability in S_{OCEAN} is evaluated with data products based on surveys of ocean CO_2 measurements. The global residual terrestrial CO_2 sink (S_{LAND}) is estimated by the difference of the other terms of the global carbon budget and compared to results of independent dynamic global vegetation models forced by observed climate, CO_2, and land-cover change (some including nitrogen–carbon interactions). We compare the mean land and ocean fluxes and their variability to estimates from three atmospheric inverse methods for three broad latitude bands. All uncertainties are reported as $\pm 1\sigma$, reflecting the current capacity to characterise the annual estimates of each component of the global carbon budget. For the last decade available (2005–2014), E_{FF} was $9.0 \pm 0.5\,\mathrm{GtC\,yr^{-1}}$, E_{LUC} was $0.9 \pm 0.5\,\mathrm{GtC\,yr^{-1}}$, G_{ATM} was $4.4 \pm 0.1\,\mathrm{GtC\,yr^{-1}}$, S_{OCEAN} was $2.6 \pm 0.5\,\mathrm{GtC\,yr^{-1}}$, and S_{LAND} was $3.0 \pm 0.8\,\mathrm{GtC\,yr^{-1}}$. For the year 2014 alone, E_{FF} grew to $9.8 \pm 0.5\,\mathrm{GtC\,yr^{-1}}$, 0.6 % above 2013, continuing the growth trend in these emissions, albeit at a slower rate compared to the average growth of $2.2\,\%\,\mathrm{yr^{-1}}$ that took place during 2005–2014. Also, for 2014, E_{LUC} was $1.1 \pm 0.5\,\mathrm{GtC\,yr^{-1}}$, G_{ATM} was $3.9 \pm 0.2\,\mathrm{GtC\,yr^{-1}}$, S_{OCEAN} was $2.9 \pm 0.5\,\mathrm{GtC\,yr^{-1}}$, and S_{LAND} was $4.1 \pm 0.9\,\mathrm{GtC\,yr^{-1}}$. G_{ATM} was lower in 2014 compared to the past decade (2005–2014), reflecting a larger S_{LAND} for that year. The global atmospheric CO_2 concentration reached 397.15 ± 0.10 ppm averaged over 2014. For 2015, preliminary data indicate that the growth in E_{FF} will be near or slightly below zero, with a projection of -0.6 [range of -1.6 to $+0.5$] %, based on national emissions projections for China and the USA, and projections of gross domestic product corrected for recent changes in the carbon intensity of the global economy for the rest of the world. From this projection of E_{FF} and assumed constant E_{LUC} for 2015, cumulative emissions of CO_2 will reach about 555 ± 55 GtC ($2035 \pm 205\,\mathrm{GtCO_2}$) for 1870–2015, about 75 % from E_{FF} and 25 % from E_{LUC}. This living data update documents changes in the methods and data sets used in this new carbon budget compared with previous publications of this data set (Le Quéré et al., 2015, 2014, 2013). All observations presented here can be downloaded from the Carbon Dioxide Information Analysis Center (doi:10.3334/CDIAC/GCP_2015).

1 Introduction

The concentration of carbon dioxide (CO_2) in the atmosphere has increased from approximately 277 parts per million (ppm) in 1750 (Joos and Spahni, 2008), the beginning of the industrial era, to 397.15 ppm in 2014 (Dlugokencky and Tans, 2015). Daily averages went above 400 ppm for the first time at Mauna Loa station in May 2013 (Scripps, 2013). This station holds the longest running record of direct measurements of atmospheric CO_2 concentration (Tans and Keeling, 2014). The global monthly average concentration was above 400 ppm in March through May 2015 for the first time (Dlugokencky and Tans, 2015; Fig. 1), while at Mauna Loa the seasonally corrected monthly average concentration reached 400 ppm in March 2015 and continued to rise. The atmospheric CO_2 increase above pre-industrial levels was, initially, primarily caused by the release of carbon to the atmosphere from deforestation and other land-use-change activities (Ciais et al., 2013). While emissions from fossil fuels started before the industrial era, they only became the dominant source of anthropogenic emissions to the atmosphere from around 1920, and their relative share has continued to increase until present. Anthropogenic emissions occur on top of an active natural carbon cycle that circulates carbon between the atmosphere, ocean, and terrestrial biosphere reservoirs on timescales from days to millennia, while exchanges with geologic reservoirs occur at longer timescales (Archer et al., 2009).

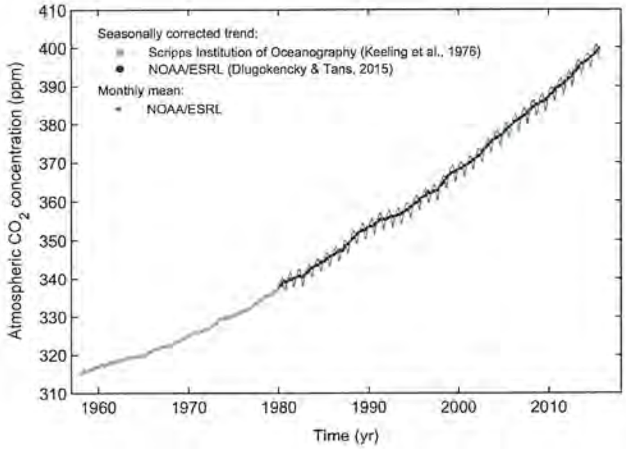

Figure 1. Surface average atmospheric CO_2 concentration, deseasonalised (ppm). The 1980–2015 monthly data are from NOAA/ESRL (Dlugokencky and Tans, 2015) and are based on an average of direct atmospheric CO_2 measurements from multiple stations in the marine boundary layer (Masarie and Tans, 1995). The 1958–1979 monthly data are from the Scripps Institution of Oceanography, based on an average of direct atmospheric CO_2 measurements from the Mauna Loa and South Pole stations (Keeling et al., 1976). To take into account the difference of mean CO_2 between the NOAA/ESRL and the Scripps station networks used here, the Scripps surface average (from two stations) was harmonised to match the NOAA/ESRL surface average (from multiple stations) by adding the mean difference of 0.542 ppm, calculated here from overlapping data during 1980–2012. The mean seasonal cycle is also shown from 1980.

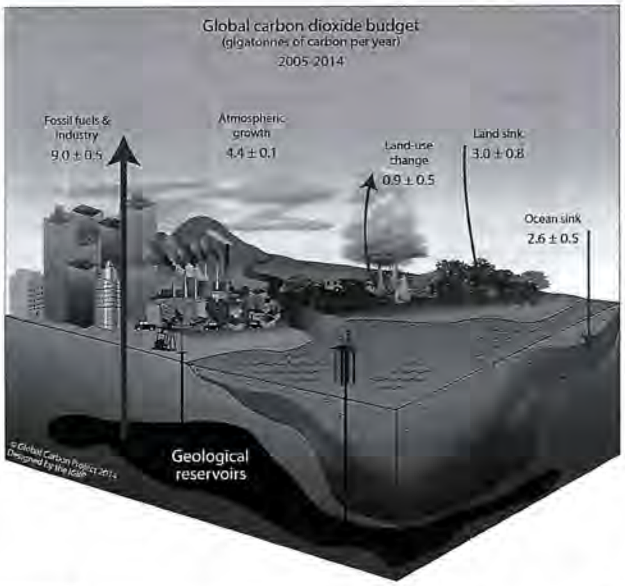

Figure 2. Schematic representation of the overall perturbation of the global carbon cycle caused by anthropogenic activities, averaged globally for the decade 2005–2014. The arrows represent emission from fossil fuels and industry (E_{FF}), emissions from deforestation and other land-use change (E_{LUC}), the growth of carbon in the atmosphere (G_{ATM}) and the uptake of carbon by the "sinks" in the ocean (S_{OCEAN}) and land (S_{LAND}) reservoirs. All fluxes are in units of $GtC\,yr^{-1}$, with uncertainties reported as $\pm 1\sigma$ (68 % confidence that the real value lies within the given interval) as described in the text. This figure is an update of one prepared by the International Geosphere-Biosphere Programme for the Global Carbon Project (GCP), first presented in Le Quéré (2009).

The global carbon budget presented here refers to the mean, variations, and trends in the perturbation of CO_2 in the atmosphere, referenced to the beginning of the industrial era. It quantifies the input of CO_2 to the atmosphere by emissions from human activities, the growth of CO_2 in the atmosphere, and the resulting changes in the storage of carbon in the land and ocean reservoirs in response to increasing atmospheric CO_2 levels, climate, and variability, and other anthropogenic and natural changes (Fig. 2). An understanding of this perturbation budget over time and the underlying variability and trends of the natural carbon cycle is necessary to understand the response of natural sinks to changes in climate, CO_2 and land-use-change drivers, and the permissible emissions for a given climate stabilisation target.

The components of the CO_2 budget that are reported annually in this paper include separate estimates for (1) the CO_2 emissions from fossil fuel combustion and oxidation and cement production (E_{FF}; $GtC\,yr^{-1}$), (2) the CO_2 emissions resulting from deliberate human activities on land leading to land-use change (E_{LUC}; $GtC\,yr^{-1}$), (3) the growth rate of CO_2 in the atmosphere (G_{ATM}; $GtC\,yr^{-1}$), and the uptake of CO_2 by the "CO_2 sinks" in (4) the ocean (S_{OCEAN}; $GtC\,yr^{-1}$) and (5) on land (S_{LAND}; $GtC\,yr^{-1}$). The CO_2 sinks as defined here include the response of the land and ocean to elevated CO_2 and changes in climate and other environmental conditions. The global emissions and their partitioning among the atmosphere, ocean, and land are in balance:

$$E_{FF} + E_{LUC} = G_{ATM} + S_{OCEAN} + S_{LAND}. \qquad (1)$$

G_{ATM} is usually reported in $ppm\,yr^{-1}$, which we convert to units of carbon mass, $GtC\,yr^{-1}$, using 1 ppm = 2.12 GtC (Ballantyne et al., 2012; Prather et al., 2012; Table 1). We also include a quantification of E_{FF} by country, computed with both territorial- and consumption-based accounting (see Sect. 2.1.1).

Equation (1) partly omits two kinds of processes. The first is the net input of CO_2 to the atmosphere from the chemical oxidation of reactive carbon-containing gases from sources other than fossil fuels (e.g. fugitive anthropogenic CH_4 emissions, industrial processes, and changes in biogenic emissions from changes in vegetation, fires, wetlands), primarily methane (CH_4), carbon monoxide (CO), and volatile organic compounds such as isoprene and terpene. CO emissions are currently implicit in E_{FF} while anthropogenic CH_4 emissions are not and thus their inclusion would result in a small increase in E_{FF}. The second is the anthropogenic per-

Table 1. Factors used to convert carbon in various units (by convention, unit 1 = unit 2 · conversion).

Unit 1	Unit 2	Conversion	Source
GtC (gigatonnes of carbon)	ppm (parts per million)[a]	2.12[b]	Ballantyne et al. (2012)
GtC (gigatonnes of carbon)	PgC (petagrams of carbon)	1	SI unit conversion
$GtCO_2$ (gigatonnes of carbon dioxide)	GtC (gigatonnes of carbon)	3.664	44.01/12.011 in mass equivalent
GtC (gigatonnes of carbon)	MtC (megatonnes of carbon)	1000	SI unit conversion

[a] Measurements of atmospheric CO_2 concentration have units of dry-air mole fraction. "ppm" is an abbreviation for micromole per mole of dry air. [b] The use of a factor of 2.12 assumes that all the atmosphere is well mixed within one year. In reality, only the troposphere is well mixed and the growth rate of CO_2 in the less well-mixed stratosphere is not measured by sites from the NOAA network. Using a factor of 2.12 makes the approximation that the growth rate of CO_2 in the stratosphere equals that of the troposphere on a yearly basis and reflects the uncertainty in this value.

turbation to carbon cycling in terrestrial freshwaters, estuaries, and coastal areas, which modifies lateral fluxes from land ecosystems to the open ocean; the evasion CO_2 flux from rivers, lakes, and estuaries to the atmosphere; and the net air–sea anthropogenic CO_2 flux of coastal areas (Regnier et al., 2013). The inclusion of freshwater fluxes of anthropogenic CO_2 would affect the estimates of, and partitioning between, S_{LAND} and S_{OCEAN} in Eq. (1) in complementary ways, but would not affect the other terms. These flows are omitted in absence of annual information on the natural versus anthropogenic perturbation terms of these loops of the carbon cycle, and they are discussed in Sect. 2.7.

The CO_2 budget has been assessed by the Intergovernmental Panel on Climate Change (IPCC) in all assessment reports (Ciais et al., 2013; Denman et al., 2007; Prentice et al., 2001; Schimel et al., 1995; Watson et al., 1990), as well as by others (e.g. Ballantyne et al., 2012). These assessments included budget estimates for the decades of the 1980s, 1990s (Denman et al., 2007) and, most recently, the period 2002–2011 (Ciais et al., 2013). The IPCC methodology has been adapted and used by the Global Carbon Project (GCP, www.globalcarbonproject.org), which has coordinated a cooperative community effort for the annual publication of global carbon budgets up to the year 2005 (Raupach et al., 2007; including fossil emissions only), 2006 (Canadell et al., 2007), 2007 (published online; GCP, 2007), 2008 (Le Quéré et al., 2009), 2009 (Friedlingstein et al., 2010), 2010 (Peters et al., 2012b), 2012 (Le Quéré et al., 2013; Peters et al., 2013), 2013 (Le Quéré et al., 2014), and most recently 2014 (Friedlingstein et al., 2014; Le Quéré et al., 2015). The carbon budget year refers to the initial year of publication. Each of these papers updated previous estimates with the latest available information for the entire time series. From 2008, these publications projected fossil fuel emissions for one additional year using the projected world gross domestic product (GDP) and estimated trends in the carbon intensity of the global economy.

We adopt a range of ±1 standard deviation (σ) to report the uncertainties in our estimates, representing a likelihood of 68 % that the true value will be within the provided range if the errors have a Gaussian distribution. This choice reflects the difficulty of characterising the uncertainty in the CO_2 fluxes between the atmosphere and the ocean and land reservoirs individually, particularly on an annual basis, as well as the difficulty of updating the CO_2 emissions from land-use change. A likelihood of 68 % provides an indication of our current capability to quantify each term and its uncertainty given the available information. For comparison, the Fifth Assessment Report of the IPCC (AR5) generally reported a likelihood of 90 % for large data sets whose uncertainty is well characterised, or for long time intervals less affected by year-to-year variability. Our 68 % uncertainty value is near the 66 % which the IPCC characterises as "likely" for values falling into the $\pm 1\sigma$ interval. The uncertainties reported here combine statistical analysis of the underlying data and expert judgement of the likelihood of results lying outside this range. The limitations of current information are discussed in the paper and have been examined in detail elsewhere (Ballantyne et al., 2015).

All quantities are presented in units of gigatonnes of carbon (GtC, 10^{15} gC), which is the same as petagrams of carbon (PgC; Table 1). Units of gigatonnes of CO_2 (or billion tonnes of CO_2) used in policy are equal to 3.664 multiplied by the value in units of GtC.

This paper provides a detailed description of the data sets and methodology used to compute the global carbon budget estimates for the period pre-industrial (1750) to 2014 and in more detail for the period 1959 to 2014. We also provide decadal averages starting in 1960 and including the last decade (2005–2014), results for the year 2014, and a projection of E_{FF} for year 2015. Finally we provide cumulative emissions from fossil fuels and land-use change since year 1750, the pre-industrial period, and since year 1870, the reference year for the cumulative carbon estimate used by the IPCC (AR5) based on the availability of global temperature data (Stocker et al., 2013). This paper is intended to be updated every year using the format of "living data" to keep a record of budget versions and the changes in new data, revision of data, and changes in methodology that lead to changes in estimates of the carbon budget. Additional materials associated with the release of each new version will be posted on the GCP website (http://www.globalcarbonproject.org/carbonbudget). Data associated with this release are also available through the Global

Carbon Atlas (http://www.globalcarbonatlas.org). With this approach, we aim to provide the highest transparency and traceability in the reporting of CO_2, the key driver of climate change.

2 Methods

Multiple organisations and research groups around the world generated the original measurements and data used to complete the global carbon budget. The effort presented here is thus mainly one of synthesis, where results from individual groups are collated, analysed, and evaluated for consistency. We facilitate access to original data with the understanding that primary data sets will be referenced in future work (see Table 2 for how to cite the data sets). Descriptions of the measurements, models, and methodologies follow below and in-depth descriptions of each component are described elsewhere (e.g. Andres et al., 2012; Houghton et al., 2012).

This is the tenth version of the "global carbon budget" (see Introduction for details) and the fourth revised version of the "global carbon budget living data update". It is an update of Le Quéré et al. (2015), including data to year 2014 (inclusive) and a projection for fossil fuel emissions for year 2015. The main changes from Le Quéré et al. (2015) are (1) the use of national emissions for E_{FF} from the United Nations Framework Convention on Climate Change (UNFCCC) where available; (2) the projection of E_{FF} for 2015 is based on national emissions projections for China and USA, as well as GDP corrected for recent changes in the carbon intensity of the global economy for the rest of the world; and (3) that we apply minimum criteria of realism to select ocean data products and process models. The main methodological differences between annual carbon budgets are summarised in Table 3.

2.1 CO_2 emissions from fossil fuels and industry (E_{FF})

2.1.1 Emissions from fossil fuels and industry and their uncertainty

The calculation of global and national CO_2 emissions from fossil fuels, including gas flaring and cement production (E_{FF}), relies primarily on energy consumption data, specifically data on hydrocarbon fuels, collated and archived by several organisations (Andres et al., 2012). These include the Carbon Dioxide Information Analysis Center (CDIAC), the International Energy Agency (IEA), the United Nations (UN), the United States Department of Energy (DoE) Energy Information Administration (EIA), and more recently also the Planbureau voor de Leefomgeving (PBL) Netherlands Environmental Assessment Agency. Where available, we use national emissions estimated by the countries themselves and reported to the UNFCCC for the period 1990–2012 (42 countries). We assume that national emissions reported to the UNFCCC are the most accurate because national experts have access to additional and country-specific information, and because these emission estimates are periodically audited for each country through an established international methodology overseen by the UNFCCC. We also use global and national emissions estimated by CDIAC (Boden et al., 2013). The CDIAC emission estimates are the only data set that extends back in time to 1751 with consistent and well-documented emissions from fossil fuels, cement production, and gas flaring for all countries and their uncertainty (Andres et al., 2014, 2012, 1999); this makes the data set a unique resource for research of the carbon cycle during the fossil fuel era.

The global emissions presented here are from CDIAC's analysis, which provides an internally consistent global estimate including bunker fuels, minimising the effects of lower-quality energy trade data. Thus the comparison of global emissions with previous annual carbon budgets is not influenced by the use of data from UNFCCC national reports.

During the period 1959–2011, the emissions from fossil fuels estimated by CDIAC are based primarily on energy data provided by the UN Statistics Division (UN, 2014a, b; Table 4). When necessary, fuel masses/volumes are converted to fuel energy content using coefficients provided by the UN and then to CO_2 emissions using conversion factors that take into account the relationship between carbon content and energy (heat) content of the different fuel types (coal, oil, gas, gas flaring) and the combustion efficiency (to account, for example, for soot left in the combustor or fuel otherwise lost or discharged without oxidation). Most data on energy consumption and fuel quality (carbon content and heat content) are available at the country level (UN, 2014a). In general, CO_2 emissions for equivalent primary energy consumption are about 30 % higher for coal compared to oil, and 70 % higher for coal compared to natural gas (Marland et al., 2007). All estimated fossil fuel emissions are based on the mass flows of carbon and assume that the fossil carbon emitted as CO or CH_4 will soon be oxidised to CO_2 in the atmosphere and can be accounted for with CO_2 emissions (see Sect. 2.7).

Our emissions totals for the UNFCCC-reporting countries were recorded as in the UNFCCC submissions, which have a slightly larger system boundary than CDIAC. Additional emissions come from carbonates other than in cement manufacture, and thus UNFCCC totals will be slightly higher than CDIAC totals in general, although there are multiple sources for differences. We use the CDIAC method to report emissions by fuel type (e.g. all coal oxidation is reported under "coal", regardless of whether oxidation results from combustion as an energy source), which differs slightly from UNFCCC.

For the most recent 2–3 years when the UNFCCC estimates and UN statistics used by CDIAC are not yet available (or there was insufficient time to process and verify them), we generated preliminary estimates based on the BP annual energy review by applying the growth rates of en-

Table 2. How to cite the individual components of the global carbon budget presented here.

Component	Primary reference
Global emissions from fossil fuels and industry (E_{FF}), total and by fuel type	Boden et al. (2015; CDIAC: http://cdiac.ornl.gov/trends/emis/meth_reg.html)
National territorial emissions from fossil fuels and industry (E_{FF})	CDIAC source: Boden et al. (2015; CDIAC: http://cdiac.ornl.gov/trends/emis/meth_reg.html) UNFCCC source (2015; http://unfccc.int/national_reports/annex_i_ghg_inventories/national_inventories_submissions/items/8108.php; accessed May 2015)
National consumption-based emissions from fossil fuels and industry (E_{FF}) by country (consumption)	Peters et al. (2011b) updated as described in this paper
Land-use-change emissions (E_{LUC})	Houghton et al. (2012) combined with Giglio et al. (2013)
Atmospheric CO_2 growth rate (G_{ATM})	Dlugokencky and Tans (2015; NOAA/ESRL: http://www.esrl.noaa.gov/gmd/ccgg/trends/global.html; accessed 12 October 2015)
Ocean and land CO_2 sinks (S_{OCEAN} and S_{LAND})	This paper for S_{OCEAN} and S_{LAND} and references in Table 6 for individual models.

ergy consumption (coal, oil, gas) for 2013–2014 to the UNFCCC national emissions in 2012, and for 2012–2014 for the CDIAC national and global emissions in 2011 (BP, 2015). BP's sources for energy statistics overlap with those of the UN data, but are compiled more rapidly from about 70 countries covering about 96 % of global emissions. We use the BP values only for the year-to-year rate of change, because the rates of change are less uncertain than the absolute values and we wish to avoid discontinuities in the time series when linking the UN-based data with the BP data. These preliminary estimates are replaced by the more complete UNFCCC or CDIAC data based on UN statistics when they become available. Past experience and work by others (Andres et al., 2014; Myhre et al., 2009) show that projections based on the BP rate of change are within the uncertainty provided (see Sect. 3.2 and the Supplement from Peters et al., 2013).

Estimates of emissions from cement production by CDIAC are based on data on growth rates of cement production from the US Geological Survey up to year 2013 (van Oss, 2013), and up to 2014 for the top 18 countries (representing 85 % of global production; USGS, 2015). For countries without data in 2014 we use the 2013 values (zero growth). Some fraction of the CaO and MgO in cement is returned to the carbonate form during cement weathering, but this is generally regarded to be small and is ignored here.

Estimates of emissions from gas flaring by CDIAC are calculated in a similar manner to those from solid, liquid, and gaseous fuels, and rely on the UN Energy Statistics to supply the amount of flared or vented fuel. For emission years 2012–2014, flaring is assumed constant from 2011 (emission year) UN-based data. The basic data on gas flaring report atmospheric losses during petroleum production and processing that have large uncertainty and do not distinguish between gas that is flared as CO_2 or vented as CH_4. Fugitive emissions of CH_4 from the so-called upstream sector (e.g. coal mining and natural gas distribution) are not included in the accounts of CO_2 emissions except to the extent that they are captured in the UN energy data and counted as gas "flared or lost".

The published CDIAC data set includes 250 countries and regions. This expanded list includes countries that no longer exist, such as the USSR and East Pakistan. For the carbon budget, we reduce the list to 216 countries by reallocating emissions to the currently defined territories. This involved both aggregation and disaggregation, and does not change global emissions. Examples of aggregation include merging East and West Germany to the currently defined Germany. Examples of disaggregation include reallocating the emissions from former USSR to the resulting independent countries. For disaggregation, we use the emission shares when the current territory first appeared. The disaggregated estimates should be treated with care when examining countries' emissions trends prior to their disaggregation. For the most recent years, 2012–2014, the BP statistics are more aggregated, but we retain the detail of CDIAC by applying the growth rates of each aggregated region in the BP data set to its constituent individual countries in CDIAC.

Estimates of CO_2 emissions show that the global total of emissions is not equal to the sum of emissions from all countries. This is largely attributable to emissions that occur in international territory, in particular the combustion of fuels used in international shipping and aviation (bunker fuels), where the emissions are included in the global totals but are not attributed to individual countries. In practice, the emissions from international bunker fuels are calculated based on where the fuels were loaded, but they are not included with national emissions estimates. Other differences occur because globally the sum of imports in all countries is not equal to the sum of exports and because of differing treatment of oxidation of non-fuel uses of hydrocarbons (e.g. as

Table 3. Main methodological changes in the global carbon budget since first publication. Unless specified below, the methodology was identical to that described in the current paper. Furthermore, methodological changes introduced in one year are kept for the following years unless noted. Empty cells mean there were no methodological changes introduced that year.

Publication year[a]	Fossil fuel emissions			LUC emissions	Reservoirs			Uncertainty & other changes
	Global	Country (territorial)	Country (consumption)		Atmosphere	Ocean	Land	
2006 Raupach et al. (2007)		Split in regions						
2007 Canadell et al. (2007)				E_{LUC} based on FAO-FRA 2005; constant E_{LUC} for 2006	1959–1979 data from Mauna Loa; data after 1980 from global average	Based on one ocean model tuned to reproduced observed 1990s sink		$\pm 1\sigma$ provided for all components
2008 (online)				Constant E_{LUC} for 2007				
2009 Le Quéré et al. (2009)		Split between Annex B and non-Annex B	Results from an independent study discussed	Fire-based emission anomalies used for 2006–2008		Based on four ocean models normalised to observations with constant delta	First use of five DGVMs to compare with budget residual	
2010 Friedlingstein et al. (2010)	Projection for current year based on GDP	Emissions for top emitters		E_{LUC} updated with FAO-FRA 2010				
2011 Peters et al. (2012b)			Split between Annex B and non-Annex B					
2012 Le Quéré et al. (2013) Peters et al. (2013)		129 countries from 1959	129 countries and regions from 1990–2010 based on GTAP8.0	E_{LUC} for 1997–2011 includes interannual anomalies from fire-based emissions	All years from global average	Based on five ocean models normalised to observations with ratio	Ten DGVMs available for S_{LAND}; first use of four models to compare with E_{LUC}	
2013 Le Quéré et al. (2014)		250 countries[b]	134 countries and regions 1990–2011 based on GTAP8.1, with detailed estimates for years 1997, 2001, 2004, and 2007	E_{LUC} for 2012 estimated from 2001–2010 average		Based on six models compared with two data products to year 2011	Coordinated DGVM experiments for S_{LAND} and E_{LUC}	Confidence levels; cumulative emissions; budget from 1750
2014 Le Quéré et al. (2015)	Three years of BP data	Three years of BP data	Extended to 2012 with updated GDP data	E_{LUC} for 1997–2013 includes interannual anomalies from fire-based emissions		Based on seven models compared with three data products to year 2013	Based on 10 models	Inclusion of breakdown of the sinks in three latitude bands and comparison with three atmospheric inversions
2015 (this study)		National emissions from UNFCCC extended to 2014 also provided (along with CDIAC)	Detailed estimates introduced for 2011 based on GTAP9			Based on eight models compared with two data products to year 2014	Based on 10 models with assessment of minimum realism	The decadal uncertainty for the DGVM ensemble mean now uses $\pm 1\sigma$ of the decadal spread across models

[a] The naming convention of the budgets has changed. Up to and including 2010, the budget year (Carbon Budget 2010) represented the latest year of the data. From 2012, the budget year (Carbon Budget 2012) refers to the initial publication year. [b] The CDIAC database has about 250 countries, but we show data for about 216 countries since we aggregate and disaggregate some countries to be consistent with current country definitions (see Sect. 2.1.1 for more details).

solvents, lubricants, feedstocks), and changes in stock (Andres et al., 2012).

The uncertainty of the annual emissions from fossil fuels and industry for the globe has been estimated at ±5 % (scaled down from the published ±10 % at $\pm 2\sigma$ to the use of $\pm 1\sigma$ bounds reported here; Andres et al., 2012). This is consistent with a more detailed recent analysis of uncertainty of ±8.4 % at $\pm 2\sigma$ (Andres et al., 2014) and at the high end of the range of ±5–10 % at $\pm 2\sigma$ reported by Ballantyne et al. (2015). This includes an assessment of uncertainties in the amounts of fuel consumed, the carbon and heat contents of fuels, and the combustion efficiency. While in the budget we consider a fixed uncertainty of ±5 % for all years, in reality the uncertainty, as a percentage of the emissions, is growing with time because of the larger share of global emissions from non-Annex B countries (emerging economies and developing countries) with less precise statistical systems (Marland et al., 2009). For example, the uncertainty in Chinese emissions has been estimated at around ±10 % (for $\pm 1\sigma$; Gregg et al., 2008), and important potential biases have been identified that suggest China's emissions could be overestimated in published studies (Liu et al., 2015). Generally, emissions from mature economies with good statistical bases have an uncertainty of only a few percent (Marland, 2008). Further research is needed before we can quantify the time evolution of the uncertainty and its temporal error correlation structure. We note that, even if they are presented as 1σ estimates, uncertainties in emissions are likely to be mainly country-specific systematic errors related to underlying biases of energy statistics and to the accounting method used by each country. We assign a medium confidence to the results presented here because they are based on indirect estimates of emissions using energy data (Durant et al., 2010). There is only limited and indirect evidence for emissions, although there is a high agreement among the available estimates within the given uncertainty (Andres et al., 2014, 2012), and emission estimates are consistent with a range of other observations (Ciais et al., 2013), even though their regional and national partitioning is more uncertain (Francey et al., 2013).

2.1.2 Emissions embodied in goods and services

National emission inventories take a territorial (production) perspective and "include greenhouse gas emissions and removals taking place within national territory and offshore areas over which the country has jurisdiction" (Rypdal et al., 2006). That is, emissions are allocated to the country where and when the emissions actually occur. The territorial emission inventory of an individual country does not include the emissions from the production of goods and services produced in other countries (e.g. food and clothes) that are used for consumption. Consumption-based emission inventories for an individual country constitute another attribution point of view that allocates global emissions to products that are consumed within a country, and are conceptually calculated as the territorial emissions minus the "embedded" territorial emissions to produce exported products plus the emissions in other countries to produce imported products (consumption = territorial − exports + imports). The difference between the territorial- and consumption-based emission inventories is the net transfer (exports minus imports) of emissions from the production of internationally traded products. Consumption-based emission attribution results (e.g. Davis and Caldeira, 2010) provide additional information to territorial-based emissions that can be used to understand emission drivers (Hertwich and Peters, 2009), quantify emission (virtual) transfers by the trade of products between countries (Peters et al., 2011b), and potentially design more effective and efficient climate policy (Peters and Hertwich, 2008).

We estimate consumption-based emissions by enumerating the global supply chain using a global model of the economic relationships between economic sectors within and between every country (Andrew and Peters, 2013; Peters et al., 2011a). Due to availability of the input data, detailed estimates are made for the years 1997, 2001, 2004, 2007, and 2011 (using the methodology of Peters et al., 2011b) using economic and trade data from the Global Trade and Analysis Project version 9 (GTAP; Narayanan et al., 2015). The results cover 57 sectors and 140 countries and regions. The results are extended into an annual time series from 1990 to the latest year of the fossil fuel emissions or GDP data (2013 in this budget), using GDP data by expenditure in current exchange rate of US dollars (USD; from the UN National Accounts Main Aggregates Database; UN, 2014c) and time series of trade data from GTAP (based on the methodology in Peters et al., 2011b).

We estimate the sector-level CO_2 emissions using our own calculations based on the GTAP data and methodology, include flaring and cement emissions from CDIAC, and then scale the national totals (excluding bunker fuels) to match the CDIAC estimates from the most recent carbon budget. We do not include international transportation in our estimates of national totals, but we do include them in the global total. The time series of trade data provided by GTAP covers the period 1995–2011 and our methodology uses the trade shares as this data set. For the period 1990–1994 we assume the trade shares of 1995, while for 2012 and 2013 we assume the trade shares of 2011.

Comprehensive analysis of the uncertainty of consumption emissions accounts is still lacking in the literature, although several analyses of components of this uncertainty have been made (e.g. Dietzenbacher et al., 2012; Inomata and Owen, 2014; Karstensen et al., 2015; Moran and Wood, 2014). For this reason we do not provide an uncertainty estimate for these emissions, but based on model comparisons and sensitivity analysis, they are unlikely to be larger than for the territorial emission estimates (Peters et al., 2012a). Uncertainty is expected to increase for more detailed results, and to decrease with aggregation (Peters et al., 2011b; e.g. the results for Annex B countries will be more accurate than the sector results for an individual country).

The consumption-based emissions attribution method considers the CO_2 emitted to the atmosphere in the production of products, but not the trade in fossil fuels (coal, oil, gas). It is also possible to account for the carbon trade in fossil fuels (Davis et al., 2011), but we do not present those data here. Peters et al. (2012a) additionally considered trade in biomass.

The consumption data do not modify the global average terms in Eq. (1) but are relevant to the anthropogenic carbon cycle as they reflect the trade-driven movement of emissions across the Earth's surface in response to human activities. Furthermore, if national and international climate policies continue to develop in an unharmonised way, then the trends reflected in these data will need to be accommodated by those developing policies.

2.1.3 Growth rate in emissions

We report the annual growth rate in emissions for adjacent years (in percent per year) by calculating the difference between the two years and then comparing to the emissions in the first year: $\left[\frac{E_{FF(t_{0+1})}-E_{FF(t_0)}}{E_{FF(t_0)}}\right] \times 100\,\%\,yr^{-1}$. This is the simplest method to characterise a 1-year growth compared to the previous year and is widely used. We apply a leap-year adjustment to ensure valid interpretations of annual growth rates. This would affect the growth rate by about $0.3\,\%\,yr^{-1}$ (1/365) and causes growth rates to go up approximately 0.3 % if the first year is a leap year and down 0.3 % if the second year is a leap year.

The relative growth rate of E_{FF} over time periods of greater than 1 year can be re-written using its logarithm equivalent as follows:

$$\frac{1}{E_{FF}}\frac{dE_{FF}}{dt}=\frac{d(\ln E_{FF})}{dt}. \qquad (2)$$

Here we calculate relative growth rates in emissions for multi-year periods (e.g. a decade) by fitting a linear trend to $\ln(E_{FF})$ in Eq. (2), reported in percent per year. We fit the logarithm of E_{FF} rather than E_{FF} directly because this method ensures that computed growth rates satisfy Eq. (6). This method differs from previous papers (Canadell et al., 2007; Le Quéré et al., 2009; Raupach et al., 2007) that computed the fit to E_{FF} and divided by average E_{FF} directly, but the difference is very small ($< 0.05\,\%$) in the case of E_{FF}.

2.1.4 Emissions projections

Energy statistics from BP are normally available around June for the previous year. To gain insight into emission trends for the current year (2015), we provide an assessment of global emissions for E_{FF} by combining individual assessments of emissions for China and the USA (the two biggest emitting countries), as well as the rest of the world.

We specifically estimate emissions in China because the evidence suggests a departure from the long-term trends in the carbon intensity of the economy used in emissions projections in previous global carbon budgets (e.g. Le Quéré et al., 2015), resulting from significant drops in industrial production against continued growth in economic output. This departure could be temporary (Jackson et al., 2015). Our 2015 estimate for China uses (1) apparent consumption of coal for January to August estimated using production data from the National Bureau of Statistics (2015b), imports and exports of coal from China Customs Statistics (General Administration of Customs of the People's Republic of China, 2015a, b), and from partial data on stock changes from industry sources (China Coal Industry Association, 2015; China Coal Resource, 2015); (2) apparent consumption of oil and gas for January to June from the National Energy Administration (2015); and (3) production of cement reported for January to August (National Bureau of Statistics of China, 2015b). Using these data, we estimate the change in emissions for the corresponding months in 2015 compared to 2014 assuming constant emission factors. We then assume that the relative changes during the first 6–8 months will persist throughout the year. The main sources of uncertainty are from the incomplete data on stock changes, the carbon content of coal, and the assumption of persistent behaviour for the rest of 2015. These are discussed further in Sect. 3.2.1. We tested our new method using data available in October 2014 to make a 2014 projection of coal consumption and cement production, both of which changed substantially in 2014. For the apparent consumption of coal we would have projected a change of −3.2 % in coal use for 2014, compared to −2.9 % reported by the National Bureau of Statistics of China in February 2015, while for the production of cement we would have projected a change of +3.5 %, compared to a realised change of +2.3 %. In both cases, the projection is consistent with the sign of the realised change. This new method should be more reliable as it is based on actual data, even if they are preliminary. Note that the growth rates we project for China are unaffected by recent upwards revisions of Chinese energy consumption statistics (National Bureau of Statistics of China, 2015a), as all data used here dates from after the revised period. The revisions do, however, affect the absolute value of the time series up to 2013, and hence the absolute value for 2015 extrapolated from that time series using projected growth rates. Further, because the revisions will increase China's share of total global emissions, the projected growth rate of global emissions will also be affected slightly. This effect is discussed in the Results section.

For the USA, we use the forecast of the US Energy Information Administration (EIA) "Short-term energy outlook" (October 2015) for emissions from fossil fuels. This is based on an energy forecasting model which is revised monthly, and takes into account heating-degree days, household expenditures by fuel type, energy markets, policies, and other effects. We combine this with our estimate of emissions from cement production using the monthly US cement data from USGS for January–July, assuming changes in cement production over the first 7 months apply throughout the year. We estimate an uncertainty range using the revisions of historical October forecasts made by the EIA 1 year later. These revisions were less than 2 % during 2009–2014 (when a forecast was done), except for 2011, when it was −4.0 %. We thus use a conservative uncertainty range of −4.0 to +1.8 % around the central forecast.

For the rest of the world, we use the close relationship between the growth in GDP and the growth in emissions (Raupach et al., 2007) to project emissions for the current year. This is based on the so-called Kaya identity (also called IPAT identity, the acronym standing for human impact (I) on the environment, which is equal to the product of population (P), affluence (A), and technology (T)), whereby E_{FF} ($\mathrm{GtC\,yr^{-1}}$) is decomposed by the product of GDP ($\mathrm{USD\,yr^{-1}}$) and the fossil fuel carbon intensity of the economy (I_{FF}; $\mathrm{GtC\,USD^{-1}}$) as follows:

$$E_{\mathrm{FF}} = \mathrm{GDP} \times I_{\mathrm{FF}}. \tag{3}$$

Such product-rule decomposition identities imply that the relative growth rates of the multiplied quantities are additive. Taking a time derivative of Eq. (3) gives

$$\frac{\mathrm{d}E_{\mathrm{FF}}}{\mathrm{d}t} = \frac{\mathrm{d}(\mathrm{GDP} \times I_{\mathrm{FF}})}{\mathrm{d}t} \tag{4}$$

and applying the rules of calculus

$$\frac{\mathrm{d}E_{\mathrm{FF}}}{\mathrm{d}t} = \frac{\mathrm{dGDP}}{\mathrm{d}t} \times I_{\mathrm{FF}} + \mathrm{GDP} \times \frac{\mathrm{d}I_{\mathrm{FF}}}{\mathrm{d}t}. \tag{5}$$

Finally, dividing Eq. (5) by (3) gives

$$\frac{1}{E_{\mathrm{FF}}}\frac{\mathrm{d}E_{\mathrm{FF}}}{\mathrm{d}t} = \frac{1}{\mathrm{GDP}}\frac{\mathrm{dGDP}}{\mathrm{d}t} + \frac{1}{I_{\mathrm{FF}}}\frac{\mathrm{d}I_{\mathrm{FF}}}{\mathrm{d}t}, \tag{6}$$

where the left-hand term is the relative growth rate of E_{FF} and the right-hand terms are the relative growth rates of GDP and I_{FF}, respectively, which can simply be added linearly to give overall growth rate. The growth rates are reported in percent by multiplying each term by 100 %. As preliminary estimates of annual change in GDP are made well before the end of a calendar year, making assumptions on the growth rate of I_{FF} allows us to make projections of the annual change in $\mathrm{CO_2}$ emissions well before the end of a calendar year. The I_{FF} is based on GDP in constant PPP (purchasing power parity) from the IEA up to 2012 (IEA/OECD, 2014) and extended using the IMF growth rates for 2013 and 2014 (IMF, 2015). Experience of the past year has highlighted that the interannual variability in I_{FF} is the largest source of uncertainty in the GDP-based emissions projections. We thus use the standard deviation of the annual I_{FF} for the period 2005–2014 as a measure of uncertainty, reflecting $\pm 1\sigma$ as in the rest of the carbon budget. This is $\pm 1.4\,\%\,\mathrm{yr^{-1}}$ for the rest of the world (global emissions minus China and USA).

The 2015 projection for the world is made of the sum of the projections for China, the USA, and the rest of the world. The uncertainty is added quadratically among the three regions. The uncertainty here reflects the best of our expert opinion.

2.2 $\mathrm{CO_2}$ emissions from land use, land-use change, and forestry (E_{LUC})

Land-use-change emissions reported here (E_{LUC}) include $\mathrm{CO_2}$ fluxes from deforestation, afforestation, logging (forest degradation and harvest activity), shifting cultivation (cycle of cutting forest for agriculture and then abandoning), and regrowth of forests following wood harvest or abandonment of agriculture. Only some land management activities (Table 5) are included in our land-use-change emissions estimates (e.g. emissions or sinks related to management and management changes of established pasture and croplands are not included). Some of these activities lead to emissions of $\mathrm{CO_2}$ to the atmosphere, while others lead to $\mathrm{CO_2}$ sinks. E_{LUC} is the net sum of all anthropogenic activities considered. Our annual estimate for 1959–2010 is from a bookkeeping method (Sect. 2.2.1) primarily based on net forest area change and biomass data from the Forest Resource Assessment (FRA) of the Food and Agriculture Organization (FAO), which is only available at intervals of 5 years. We use the FAO FRA 2010 here (Houghton et al., 2012). Interannual variability in emissions due to deforestation and degradation has been coarsely estimated from satellite-based fire activity in tropical forest areas (Sect. 2.2.2; Giglio et al., 2013; van der Werf et al., 2010). The bookkeeping method is used to quantify the E_{LUC} over the time period of the available data, and the satellite-based deforestation fire information to incorporate interannual variability (E_{LUC} flux annual anomalies) from tropical deforestation fires. The satellite-based deforestation and degradation fire emissions estimates are available for years 1997–2014. We calculate the global annual anomaly in deforestation and degradation fire emissions in tropical forest regions for each year, compared to the 1997–2010 period, and add this annual flux anomaly to the E_{LUC} estimated using the bookkeeping method that is available up to 2010 only and assumed constant at the 2010 value during the period 2011–2014. We thus assume that all land management activities apart from deforestation and degradation do not vary significantly on a year-to-year basis. Other sources of interannual variability (e.g. the impact of climate variability on regrowth fluxes) are accounted for in S_{LAND}. In addition, we use results from dynamic global vegetation models (see Sect. 2.2.3 and Table 6) that calculate net land-use-change $\mathrm{CO_2}$ emissions in response to land-cover-change reconstructions prescribed to each model in order to help quantify the uncertainty in E_{LUC} and to explore the consistency of

Table 4. Data sources used to compute each component of the global carbon budget. National emissions from UNFCCC are provided directly and thus no additional data sources need citing in this table.

Component	Process	Data source	Data reference
E_{FF} (global and CDIAC national)	Fossil fuel combustion and oxidation and gas flaring	UN Statistics Division to 2011	UN (2014a, b)
		BP for 2012–2014	BP (2015)
	Cement production	US Geological Survey	van Oss (2015) USGS (2015)
E_{LUC}	Land-cover change (deforestation, afforestation, and forest regrowth)	Forest Resource Assessment (FRA) of the Food and Agriculture Organization (FAO)	FAO (2010)
	Wood harvest	FAO Statistics Division	FAOSTAT (2010)
	Shifting agriculture	FAO FRA and Statistics Division	FAO (2010) FAOSTAT (2010)
	Interannual variability from peat fires and climate – land management interactions (1997–2013)	Global Fire Emissions Database (GFED4)	Giglio et al. (2013)
G_{ATM}	Change in atmospheric CO_2 concentration	1959–1980: CO_2 Program at Scripps Institution of Oceanography and other research groups	Keeling et al. (1976)
		1980–2015: US National Oceanic and Atmospheric Administration Earth System Research Laboratory	Dlugokencky and Tans (2015) Ballantyne et al. (2012)
S_{OCEAN}	Uptake of anthropogenic CO_2	1990–1999 average: indirect estimates based on CFCs, atmospheric O_2, and other tracer observations	Manning and Keeling (2006) Keeling et al. (2011) McNeil et al. (2003) Mikaloff Fletcher et al. (2006) as assessed by the IPCC in Denman et al. (2007)
	Impact of increasing atmospheric CO_2, climate, and variability	Ocean models	Table 6
S_{LAND}	Response of land vegetation to: Increasing atmospheric CO_2 concentration Climate and variability Other environmental changes	Budget residual	

our understanding. The three methods are described below, and differences are discussed in Sect. 3.2.

2.2.1 Bookkeeping method

Land-use-change CO_2 emissions are calculated by a bookkeeping method approach (Houghton, 2003) that keeps track of the carbon stored in vegetation and soils before deforestation or other land-use change, and the changes in forest age classes, or cohorts, of disturbed lands after land-use change, including possible forest regrowth after deforestation. The approach tracks the CO_2 emitted to the atmosphere immediately during deforestation, and over time due to the follow-up decay of soil and vegetation carbon in different pools, including wood product pools after logging and deforestation. It also tracks the regrowth of vegetation and associated build-up of soil carbon pools after land-use change. It considers transitions between forests, pastures, and cropland; shifting cultivation; degradation of forests where a fraction of the trees is removed; abandonment of agricultural land; and forest management such as wood harvest and, in the USA, fire management. In addition to tracking logging debris on the forest floor, the bookkeeping method tracks the fate of carbon contained in harvested wood products that is eventually emitted back to the atmosphere as CO_2, although a detailed treatment of the lifetime in each product pool is not performed (Earles et al., 2012). Harvested wood products are partitioned into three pools with different turnover times. All

Table 5. Comparison of the processes included in the E_{LUC} of the global carbon budget and the DGVMs. See Table 6 for model references. All models include deforestation and forest regrowth after abandonment of agriculture (or from afforestation activities on agricultural land).

	Bookkeeping	CLM4.5BGC	ISAM	JSBACH	JULES	LPJ-GUESS	LPJ	LPJmL	OCNv1.r240	ORCHIDEE	VISIT
Wood harvest and forest degradation[a]	yes	yes	yes	yes	no	no	no	no	yes	no	yes[b]
Shifting cultivation	yes	yes	no	yes	no	no	no	no	no	no	yes
Cropland harvest	yes	yes	yes	yes[c]	no	yes	no	yes	yes	yes	yes
Peat fires	no	yes	no	no	no	no	no	no	no	no	no
Fire simulation and/or suppression	for US only	yes	no	yes	no	yes	yes	yes	no	no	yes
Climate and variability	no	yes	yes	yes	yes	yes	yes	yes	yes	yes	yes
CO_2 fertilisation	no	yes	yes	yes	yes	yes	yes	yes	yes	yes	yes
Carbon–nitrogen interactions, including N deposition	no	yes	yes	no	no	no	no	no	yes	no	no

[a] Refers to the routine harvest of established managed forests rather than pools of harvested products. [b] Wood stems are harvested according to the land-use data. [c] Carbon from crop harvest is entirely transferred into the litter pools.

fuelwood is assumed burnt in the year of harvest ($1.0\,\text{yr}^{-1}$). Pulp and paper products are oxidised at a rate of $0.1\,\text{yr}^{-1}$, timber is assumed to be oxidised at a rate of $0.01\,\text{yr}^{-1}$, and elemental carbon decays at $0.001\,\text{yr}^{-1}$. The general assumptions about partitioning wood products among these pools are based on national harvest data (Houghton, 2003).

The primary land-cover-change and biomass data for the bookkeeping method analysis is the Forest Resource Assessment of the FAO, which provides statistics on forest-cover change and management at intervals of 5 years (FAO, 2010). The data are based on countries' self-reporting, some of which integrates satellite data in more recent assessments (Table 4). Changes in land cover other than forest are based on annual, national changes in cropland and pasture areas reported by the FAO Statistics Division (FAOSTAT, 2010). Land-use-change country data are aggregated by regions. The carbon stocks on land (biomass and soils), and their response functions subsequent to land-use change, are based on FAO data averages per land-cover type, per biome, and per region. Similar results were obtained using forest biomass carbon density based on satellite data (Baccini et al., 2012). The bookkeeping method does not include land ecosystems' transient response to changes in climate, atmospheric CO_2, and other environmental factors, but the growth/decay curves are based on contemporary data that will implicitly reflect the effects of CO_2 and climate at that time. Results from the bookkeeping method are available from 1850 to 2010.

2.2.2 Fire-based interannual variability in E_{LUC}

Land-use-change-associated CO_2 emissions calculated from satellite-based fire activity in tropical forest areas (van der Werf et al., 2010) provide information on emissions due to tropical deforestation and degradation that are complementary to the bookkeeping approach. They do not provide a direct estimate of E_{LUC} as they do not include non-combustion processes such as respiration, wood harvest, wood products, or forest regrowth. Legacy emissions such as decomposition from on-ground debris and soils are not included in this method either. However, fire estimates provide some insight into the year-to-year variations in the subcomponent of the total E_{LUC} flux that result from immediate CO_2 emissions during deforestation caused, for example, by the interactions between climate and human activity (e.g. there is more burning and clearing of forests in dry years) that are not represented by other methods. The "deforestation fire emissions" assume an important role of fire in removing biomass in the deforestation process, and thus can be used to infer gross instantaneous CO_2 emissions from deforestation using satellite-derived data on fire activity in regions with active deforestation. The method requires information on the fraction of total area burned associated with deforestation versus other types of fires, and this information can be merged with information on biomass stocks and the fraction of the biomass lost in a deforestation fire to estimate CO_2 emissions. The satellite-based deforestation fire emissions are limited to the tropics, where fires result mainly from human activities. Tropical deforestation is the largest and most variable single contributor to E_{LUC}.

Fire emissions associated with deforestation and tropical peat burning are based on the Global Fire Emissions Database (GFED4; accessed October 2015) described in van der Werf et al. (2010) but with updated burned area (Giglio et al., 2013) as well as burned area from relatively small fires that are detected by satellite as thermal anomalies but not mapped by the burned area approach (Randerson et al., 2012). The burned area information is used as input data in a modified version of the satellite-driven Carnegie–Ames–Stanford Approach (CASA) biogeochemical model to estimate carbon emissions associated with fires, keeping track of what fraction of fire emissions was due to deforestation (see van der Werf et al., 2010). The CASA model uses different assumptions to compute decay functions compared to the bookkeeping method, and does not include historical emissions or regrowth from land-use change prior to the availability of satellite data. Comparing coincident CO emissions and their atmospheric fate with satellite-derived CO concentrations allows for some validation of this approach (e.g. van der Werf et al., 2008). Results from the fire-based method to estimate land-use-change emissions anomalies added to the bookkeeping mean E_{LUC} estimate are available from 1997 to 2014. Our combination of land-use-change CO_2 emissions where the variability in annual CO_2 deforestation emissions is diagnosed from fires assumes that year-to-year variability is dominated by variability in deforestation.

2.2.3 Dynamic global vegetation models (DGVMs)

Land-use-change CO_2 emissions have been estimated using an ensemble of 10 DGVMs. New model experiments up to year 2014 have been coordinated by the project "Trends and drivers of the regional-scale sources and sinks of carbon dioxide" (TRENDY; Sitch et al., 2015). We use only models that have estimated land-use-change CO_2 emissions and the terrestrial residual sink following the TRENDY protocol (see Sect. 2.5.2), thus providing better consistency in the assessment of the causes of carbon fluxes on land. Models use their latest configurations, summarised in Tables 5 and 6.

The DGVMs were forced with historical changes in land-cover distribution, climate, atmospheric CO_2 concentration, and N deposition. As further described below, each historical DGVM simulation was repeated with a time-invariant pre-industrial land-cover distribution, allowing for estimation of, by difference with the first simulation, the dynamic evolution of biomass and soil carbon pools in response to prescribed land-cover change. All DGVMs represent deforestation and (to some extent) regrowth, the most important components of E_{LUC}, but they do not represent all processes resulting directly from human activities on land (Table 5). DGVMs represent processes of vegetation growth and mortality, as well as decomposition of dead organic matter associated with natural cycles, and include the vegetation and soil carbon response to increasing atmospheric CO_2 levels and to climate variability and change. In addition, three models explicitly simulate the coupling of C and N cycles and account for atmospheric N deposition (Table 5). The DGVMs are independent of the other budget terms except for their use of atmospheric CO_2 concentration to calculate the fertilisation effect of CO_2 on primary production.

The DGVMs used a consistent land-use-change data set (Hurtt et al., 2011), which provided annual, half-degree, fractional data on cropland, pasture, primary vegetation, and secondary vegetation, as well as all underlying transitions between land-use states, including wood harvest and shifting cultivation. This data set used the HYDE (Klein Goldewijk et al., 2011) spatially gridded maps of cropland, pasture, and ice/water fractions of each grid cell as an input. The HYDE data are based on annual FAO statistics of change in agricultural area available to 2012 (FAOSTAT, 2010). For the years 2013 and 2014, the HYDE data were extrapolated by country for pastures and cropland separately based on the trend in agricultural area over the previous 5 years. The HYDE data are independent of the data set used in the bookkeeping method (Houghton, 2003, and updates), which is based primarily on forest area change statistics (FAO, 2010). Although the HYDE land-use-change data set indicates whether land-use changes occur on forested or non-forested land, typically only the changes in agricultural areas are used by the models and are implemented differently within each model (e.g. an increased cropland fraction in a grid cell can either be at the expense of grassland, or forest, the latter resulting in deforestation; land-cover fractions of the non-agricultural land differ between models). Thus the DGVM forest area and forest area change over time is not consistent with the Forest Resource Assessment of the FAO forest area data used for the bookkeeping model to calculate E_{LUC}. Similarly, model-specific assumptions are applied to convert deforested biomass or deforested area, and other forest product pools, into carbon in some models (Table 5).

The DGVM runs were forced by either 6-hourly CRU-NCEP or by monthly CRU temperature, precipitation, and cloud cover fields (transformed into incoming surface radiation) based on observations and provided on a 0.5° × 0.5° grid and updated to 2014 (CRU TS3.23; Harris et al., 2015). The forcing data include both gridded observations of climate and global atmospheric CO_2, which change over time (Dlugokencky and Tans, 2015), and N deposition (as used in three models, Table 5; Lamarque et al., 2010). E_{LUC} is diagnosed in each model by the difference between a model simulation with prescribed historical land-cover change and a simulation with constant, pre-industrial land-cover distribution. Both simulations were driven by changing atmospheric CO_2, climate, and in some models N deposition over the period 1860–2014. Using the difference between these two DGVM simulations to diagnose E_{LUC} is not fully consistent with the definition of E_{LUC} in the bookkeeping method (Gasser and Ciais, 2013; Pongratz et al., 2014). The DGVM approach to diagnose land-use-change CO_2 emissions would be expected to produce systematically higher E_{LUC} emissions than the bookkeeping approach if all the parameters of the two approaches were the same, which is not the case (see Sect. 2.5.2).

2.2.4 Other published E_{LUC} methods

Other methods have been used to estimate CO_2 emissions from land-use change. We describe some of the most important methodological differences between the approach used here and other published methods, and for completion, we explain why they are not used in the budget.

Different definitions (e.g. the inclusion of fire management) for E_{LUC} can lead to significantly different estimates

Table 6. References for the process models and data products included in Figs. 6–8.

Model/data name	Reference	Change from Le Quéré et al. (2015)
Dynamic global vegetation models		
CLM4.5BGC[a]	Oleson et al. (2013)	No change
ISAM	Jain et al. (2013)[b]	We accounted for crop harvest for C3 and C4 crops based on Arora and Boer (2005) and agricultural soil carbon loss due to tillage (Jain et al., 2005)
JSBACH	Reick et al. (2013)[c]	Not applicable (first use of this model)
JULES[e]	Clark et al. (2011)[e]	Updated JULES version 4.3 compared to v3.2 for last year's budget. A number of small code changes, but no change in major science sections with the exception of an update in the way litter flux is calculated.
LPJ-GUESS	B. Smith et al. (2014)	Implementation of C / N interactions in soil and vegetation, including a complete update of the soil organic matter scheme
LPJ[f]	Sitch et al. (2003)	No change
LPJmL	Bondeau et al. (2007)[g]	Not applicable (first use of this model)
OCNv1.r240	Zaehle et al. (2011)[h]	Revised photosynthesis parameterisation allowing for temperature acclimation as well as cold and heat effects on canopy processes. Revised grassland phenology. Included wood harvest as a driver to simulate harvest and post-harvest regrowth. Using Hurtt land-use data set
ORCHIDEE	Krinner et al. (2005)	Revised parameters values for photosynthetic capacity for boreal forests (following assimilation of FLUXNET data), updated parameters values for stem allocation, maintenance respiration and biomass export for tropical forests (based on literature) and, CO_2 down-regulation process added to photosynthesis.
VISIT	Kato et al. (2013)[i]	No change
Data products for land-use-change emissions		
Bookkeeping	Houghton et al. (2012)	No change
Fire-based emissions	van der Werf et al. (2010)	No change
Ocean biogeochemistry models		
NEMO-PlankTOM5	Buitenhuis et al. (2010)[j]	No change
NEMO-PISCES (IPSL)[k]	Aumont and Bopp (2006)	No change
CCSM-BEC	Doney et al. (2009)	No change; small differences in the mean flux are caused by a change in how global and annual means were computed
MICOM-HAMOCC (NorESM-OC)	Assmann et al. (2010)[l,m]	Revised light penetration formulation and parameters for ecosystem module, revised salinity restoring scheme enforcing salt conservation, new scheme enforcing global freshwater balance, and model grid changed from displaced pole to tripolar
MPIOM-HAMOCC	Ilyina et al. (2013)	No change
NEMO-PISCES (CNRM)	Séférian et al. (2013)[n]	No change
CSIRO	Oke et al. (2013)	No change
MITgcm-REcoM2	Hauck et al. (2013)[o]	Not applicable (first use of this model)
Data products for ocean CO_2 flux		
Landschützer[p]	Landschützer et al. (2015)	No change
Jena CarboScope[p]	Rödenbeck et al. (2014)	Updated to version oc_1.2gcp2015
Atmospheric inversions for total CO_2 fluxes (land-use change + land + ocean CO_2 fluxes)		
CarbonTracker	Peters et al. (2010)	Updated to version CTE2015. Updates include using CO_2 observations from obspack_co2_1_GLOBALVIEWplus_v1.0_2015-07-30 (NOAA/ESRL, 2015b), prior SiBCASA biosphere and fire fluxes on 3-hourly resolution and fossil fuel emissions for 2010–2014 scaled to updated global totals.
Jena CarboScope	Rödenbeck et al. (2003)	Updated to version s81_v3.7
MACC[q]	Chevallier et al. (2005)	Updated to version 14.2. Updates include a change of the convection scheme and a revised data selection.

[a] Community Land Model 4.5. [b] See also El-Masri et al. (2013). [c] See also Goll et al. (2015). [d] Joint UK Land Environment Simulator. [e] See also Best et al. (2011). [f] Lund–Potsdam–Jena. [g] The LPJmL (Lund–Potsdam–Jena managed Land) version used also includes developments described in Rost et al. (2008; river routing and irrigation), Fader et al. (2010; agricultural management), Biemans et al. (2011; reservoir management), Schaphoff et al. (2013; permafrost and 5 layer hydrology), and Waha et al. (2012; sowing data) (sowing dates). [h] See also Zaehle et al. (2010) and Friend (2010). [i] See also Ito and Inatomi (2012). [j] With no nutrient restoring below the mixed layer depth. [k] Referred to as LSCE in previous carbon budgets. [l] With updates to the physical model as described in Tjiputra et al. (2013). [m] Further information (e.g. physical evaluation) for these models can be found in Danabasoglu et al. (2014). [n] Using winds from Atlas et al. (2011). [o] A few changes have been applied to the ecosystem model. (1) The constant Fe : C ratio was substituted by a constant Fe : N ratio. (2) A sedimentary iron source was implemented. (3) the following parameters were changed: CHL_N_max = 3.78, Fe2N = 0.033, deg_CHL_d = 0.1, Fe2N_d = 0.033, ligandStabConst = 200, constantIronSolubility = 0.02. [p] Updates using SOCATv3 plus new 2012–2014 data. [q] The MACCv14.2 CO_2 inversion system, initially described by Chevallier et al. (2005), relies on the global tracer transport model LMDZ (see also Supplement of Chevallier, 2015; Hourdin et al., 2006).

within models (Gasser and Ciais, 2013; Hansis et al., 2015; Pongratz et al., 2014) as well as between models and other approaches (Houghton et al., 2012; P. Smith et al., 2014). FAO uses the IPCC approach called "Tier 1" (e.g. Tubiello et al., 2015) to produce a "Land use – forest land" estimate from the Forest Resources Assessment data used in the bookkeeping method described in Sect. 2.2.1 (MacDicken, 2015). The Tier 1-type method applies a nationally reported mean forest carbon stock change (above and below ground living biomass) to nationally reported net forest area change, across all forest land combined (planted and natural forests). The methods implicitly assume instantaneous loss or gain of mean forest. Thus the Tier 1 approach provides an estimate of attributable emissions from the process of land-cover change, but it does not distribute these emissions through time. It also captures a fraction of what the global modelling approach considers residual carbon flux (S_{LAND}), it does not consider loss of soil carbon, and there are no legacy fluxes. Land-use fluxes estimated with this method were $0.47\,\mathrm{GtC\,yr^{-1}}$ in 2001–2010 and $0.22\,\mathrm{GtC\,yr^{-1}}$ in 2011–2015 (Federici et al., 2015). This estimate is not directly comparable with E_{LUC} used here because of the different boundary conditions.

Recent advances in satellite data leading to higher-resolution area change data (e.g. Hansen et al., 2013) and estimates of biomass in live vegetation (e.g. Baccini et al., 2012; Saatchi et al., 2011) have led to several satellite-based estimates of CO_2 emissions due to tropical deforestation (typically gross loss of forest area; Achard and House, 2015). These include estimates of $1.0\,\mathrm{GtC\,yr^{-1}}$ for 2000 to 2010 (Baccini et al., 2012), $0.8\,\mathrm{GtC\,yr^{-1}}$ for 2000 to 2005 (Harris et al., 2012), $0.9\,\mathrm{GtC\,yr^{-1}}$ for 2000 to 2010 for net area change (Achard et al., 2014), and $1.3\,\mathrm{GtC\,yr^{-1}}$ 2000 to 2010 (Tyukavina et al., 2015). These estimates include belowground carbon biomass using a scaling factor. Some estimate soil carbon loss, some assume instantaneous emissions, some do not account for regrowth fluxes, and none account for legacy fluxes from land-use change prior to the availability of satellite data. They are mostly estimates of tropical deforestation only, and do not capture regrowth flux after abandonment or planting (Achard and House, 2015). These estimates are also difficult to compare with E_{LUC} used here because they do not fully include legacy fluxes and forest regrowth.

2.2.5 Uncertainty assessment for E_{LUC}

Differences between the bookkeeping, the addition of fire-based interannual variability to the bookkeeping, and DGVM methods originate from three main sources: the land-cover-change data set, the different approaches used in models, and the different processes represented (Table 5). We examine the results from the 10 DGVMs and of the bookkeeping method to assess the uncertainty in E_{LUC}.

The uncertainties in annual E_{LUC} estimates are examined using the standard deviation across models, which averages $0.4\,\mathrm{GtC\,yr^{-1}}$ from 1959 to 2014 (Table 7). The mean of the multi-model E_{LUC} estimates is consistent with a combination of the bookkeeping method and fire-based emissions (Le Quéré et al., 2014), with the multi-model mean and bookkeeping method differing by less than $0.5\,\mathrm{GtC\,yr^{-1}}$ over 85 % of the time. Based on this comparison, we assess that an uncertainty of $\pm 0.5\,\mathrm{GtC\,yr^{-1}}$ provides a semi-quantitative measure of uncertainty for annual emissions, and reflects our best value judgment that there is at least 68 % chance ($\pm 1\sigma$) that the true land-use-change emission lies within the given range, for the range of processes considered here. This is consistent with the uncertainty analysis of Houghton et al. (2012), which partly reflects improvements in data on forest area change using data, and partly more complete understanding and representation of processes in models.

The uncertainties in the decadal E_{LUC} estimates are also examined using the DGVM ensemble, although they are likely correlated between decades. The correlations between decades come from (1) common biases in system boundaries (e.g. not counting forest degradation in some models); (2) common definition for the calculation of E_{LUC} from the difference of simulations with and without land-use change (a source of bias vs. the unknown truth); (3) common and uncertain land-cover-change input data which also cause a bias, though if a different input data set is used each decade, decadal fluxes from DGVMs may be partly decorrelated; and (4) model structural errors (e.g. systematic errors in biomass stocks). In addition, errors arising from uncertain DGVM parameter values would be random, but they are not accounted for in this study, since no DGVM provided an ensemble of runs with perturbed parameters.

Prior to 1959, the uncertainty in E_{LUC} is taken as ±33 %, which is the ratio of uncertainty to mean from the 1960s (Table 7), the first decade available. This ratio is consistent with the mean standard deviation of DGMVs' land-use-change emissions over 1870–1958 (0.38 GtC) over the multi-model mean (1.1 GtC).

2.3 Atmospheric CO_2 growth rate (G_{ATM})

Global atmospheric CO_2 growth rate estimates

The atmospheric CO_2 growth rate is provided by the US National Oceanic and Atmospheric Administration Earth System Research Laboratory (NOAA/ESRL; Dlugokencky and Tans, 2015), which is updated from Ballantyne et al. (2012). For the 1959–1980 period, the global growth rate is based on measurements of atmospheric CO_2 concentration averaged from the Mauna Loa and South Pole stations, as observed by the CO_2 Program at Scripps Institution of Oceanography (Keeling et al., 1976). For the 1980–2014 time period, the global growth rate is based on the average of multiple stations selected from the marine boundary layer sites with well-mixed background air (Ballantyne et al., 2012), after fitting each station with a smoothed curve as a func-

Table 7. Comparison of results from the bookkeeping method and budget residuals with results from the DGVMs and inverse estimates for the periods 1960–1969, 1970–1979, 1980–1989, 1990–1999, 2000–2009, the last decade, and the last year available. All values are in GtC yr^{-1}. The DGVM uncertainties represents $\pm 1\sigma$ of the decadal or annual (for 2014 only) estimates from the 10 individual models; for the inverse models all three results are given where available.

	Mean (GtC yr^{-1})						
	1960–1969	1970–1979	1980–1989	1990–1999	2000–2009	2005–2014	2014
Land-use-change emissions (E_{LUC})							
Bookkeeping method	1.5 ± 0.5	1.3 ± 0.5	1.4 ± 0.5	1.6 ± 0.5	1.0 ± 0.5	0.9 ± 0.5	1.1 ± 0.5
DGVMs[a]	1.2 ± 0.4	1.2 ± 0.4	1.3 ± 0.4	1.2 ± 0.4	1.2 ± 0.4	1.4 ± 0.4	1.4 ± 0.5
Residual terrestrial sink (S_{LAND})							
Budget residual	1.7 ± 0.7	1.7 ± 0.8	1.6 ± 0.8	2.6 ± 0.8	2.4 ± 0.8	3.0 ± 0.8	4.1 ± 0.9
DGVMs[a]	1.1 ± 0.6	2.1 ± 0.3	1.7 ± 0.4	2.3 ± 0.3	2.7 ± 0.4	3.0 ± 0.5	3.6 ± 0.9
Total land fluxes ($S_{\mathrm{LAND}} - E_{\mathrm{LUC}}$)							
Budget ($E_{\mathrm{FF}} - G_{\mathrm{ATM}} - S_{\mathrm{OCEAN}}$)	0.2 ± 0.5	0.4 ± 0.6	0.2 ± 0.6	1.0 ± 0.6	1.5 ± 0.6	2.1 ± 0.7	3.0 ± 0.7
DGVMs[a]	-0.1 ± 0.6	0.9 ± 0.4	0.5 ± 0.5	1.1 ± 0.5	1.5 ± 0.4	1.6 ± 0.4	2.3 ± 0.9
Inversions (CTE2015/Jena CarboScope/MACC)[b]	–/–/–	–/–/–	–/0.3[b]/0.8[b]	–/1.1[b]/1.8[b]	–/1.6[b]/2.4[b]	2.0[b]/2.0[b]/3.3[b]	2.8[b]/2.6[b]/4.2[b]

[a] Note that the decadal uncertainty calculation for the DGVMs is smaller here compared to previous global carbon budgets because it uses $\pm 1\sigma$ of the decadal estimates for the DGVMs, compared to the average of the annual $\pm 1\sigma$ estimates in previous years. It thus represents the true model range for their decadal estimates. This change was introduced to be consistent with the decadal uncertainty calculations in Table 8. [b] Estimates are not corrected for the influence of river fluxes, which would reduce the fluxes by 0.45 GtC yr^{-1} when neglecting the anthropogenic influence on land (Sect. 7.2.2). CTE2015 refers to Peters et al. (2010), Jena CarboScope to Rödenbeck et al. (2014), and MACC to Chevallier et al. (2005); see Table 6.

tion of time, and averaging by latitude band (Masarie and Tans, 1995). The annual growth rate is estimated by Dlugokencky and Tans (2015) from atmospheric CO_2 concentration by taking the average of the most recent December–January months corrected for the average seasonal cycle and subtracting this same average 1 year earlier. The growth rate in units of ppm yr^{-1} is converted to units of GtC yr^{-1} by multiplying by a factor of 2.12 GtC ppm^{-1} (Ballantyne et al., 2012) for consistency with the other components.

The uncertainty around the annual growth rate based on the multiple stations data set ranges between 0.11 and 0.72 GtC yr^{-1}, with a mean of 0.61 GtC yr^{-1} for 1959–1979 and 0.19 GtC yr^{-1} for 1980–2014, when a larger set of stations were available (Dlugokencky and Tans, 2015). It is based on the number of available stations, and thus takes into account both the measurement errors and data gaps at each station. This uncertainty is larger than the uncertainty of ± 0.1 GtC yr^{-1} reported for decadal mean growth rate by the IPCC because errors in annual growth rate are strongly anti-correlated in consecutive years leading to smaller errors for longer timescales. The decadal change is computed from the difference in concentration 10 years apart based on a measurement error of 0.35 ppm. This error is based on offsets between NOAA/ESRL measurements and those of the World Meteorological Organization World Data Centre for Greenhouse Gases (NOAA/ESRL, 2015a) for the start and end points (the decadal change uncertainty is $\sqrt{(2(0.35\,\mathrm{ppm})^2)(10\,\mathrm{yr})^{-1}}$ assuming that each yearly measurement error is independent). This uncertainty is also used in Table 8.

The contribution of anthropogenic CO and CH_4 is neglected from the global carbon budget (see Sect. 2.7.1). We assign a high confidence to the annual estimates of G_{ATM} because they are based on direct measurements from multiple and consistent instruments and stations distributed around the world (Ballantyne et al., 2012).

In order to estimate the total carbon accumulated in the atmosphere since 1750 or 1870, we use an atmospheric CO_2 concentration of 277 ± 3 or 288 ± 3 ppm, respectively, based on a cubic spline fit to ice core data (Joos and Spahni, 2008). The uncertainty of ± 3 ppm (converted to $\pm 1\sigma$) is taken directly from the IPCC's assessment (Ciais et al., 2013). Typical uncertainties in the atmospheric growth rate from ice core data are ± 1–1.5 GtC per decade as evaluated from the Law Dome data (Etheridge et al., 1996) for individual 20-year intervals over the period from 1870 to 1960 (Bruno and Joos, 1997).

2.4 Ocean CO_2 sink

Estimates of the global ocean CO_2 sink are based on a combination of a mean CO_2 sink estimate for the 1990s from observations, and a trend and variability in the ocean CO_2 sink for 1959–2014 from eight global ocean biogeochemistry models. We use two observation-based estimates of S_{OCEAN} available for recent decades to provide a qualitative assessment of confidence in the reported results.

Table 8. Decadal mean in the five components of the anthropogenic CO_2 budget for the periods 1960–1969, 1970–1979, 1980–1989, 1990–1999, 2000–2009, the last decade, and the last year available. All values are in $GtC\,yr^{-1}$. All uncertainties are reported as $\pm 1\sigma$. A data set containing data for each year during 1959–2014 is available at http://cdiac.ornl.gov/GCP/carbonbudget/2015/. Please follow the terms of use and cite the original data sources as specified on the data set.

	Mean ($GtC\,yr^{-1}$)						
	1960–1969	1970–1979	1980–1989	1990–1999	2000–2009	2005–2014	2014
Emissions							
Fossil fuels and industry (E_{FF})	3.1 ± 0.2	4.7 ± 0.2	5.5 ± 0.3	6.4 ± 0.3	7.8 ± 0.4	9.0 ± 0.5	9.8 ± 0.5
Land-use-change emissions (E_{LUC})	1.5 ± 0.5	1.3 ± 0.5	1.4 ± 0.5	1.6 ± 0.5	1.0 ± 0.5	0.9 ± 0.5	1.1 ± 0.5
Partitioning							
Atmospheric growth rate (G_{ATM})	1.7 ± 0.1	2.8 ± 0.1	3.4 ± 0.1	3.1 ± 0.1	4.0 ± 0.1	4.4 ± 0.1	3.9 ± 0.2
Ocean sink (S_{OCEAN})*	1.1 ± 0.5	1.5 ± 0.5	2.0 ± 0.5	2.2 ± 0.5	2.3 ± 0.5	2.6 ± 0.5	2.9 ± 0.5
Residual terrestrial sink (S_{LAND})	1.7 ± 0.7	1.7 ± 0.8	1.6 ± 0.8	2.6 ± 0.8	2.4 ± 0.8	3.0 ± 0.8	4.1 ± 0.9

* The uncertainty in S_{OCEAN} for the 1990s is directly based on observations, while that for other decades combines the uncertainty from observations with the model spread (Sect. 2.4.3).

2.4.1 Observation-based estimates

A mean ocean CO_2 sink of $2.2 \pm 0.4\,GtC\,yr^{-1}$ for the 1990s was estimated by the IPCC (Denman et al., 2007) based on indirect observations and their spread: ocean/land CO_2 sink partitioning from observed atmospheric O_2 / N_2 concentration trends (Manning and Keeling, 2006), an oceanic inversion method constrained by ocean biogeochemistry data (Mikaloff Fletcher et al., 2006), and a method based on penetration timescale for CFCs (McNeil et al., 2003). This is comparable with the sink of $2.0 \pm 0.5\,GtC\,yr^{-1}$ estimated by Khatiwala et al. (2013) for the 1990s, and with the sink of 1.9 to $2.5\,GtC\,yr^{-1}$ estimated from a range of methods for the period 1990–2009 (Wanninkhof et al., 2013), with uncertainties ranging from ± 0.3 to $\pm 0.7\,GtC\,yr^{-1}$. The most direct way for estimating the observation-based ocean sink is from the product of (sea–air pCO_2 difference) × (gas transfer coefficient). Estimates based on sea–air pCO_2 are fully consistent with indirect observations (Wanninkhof et al., 2013), but their uncertainty is larger mainly due to difficulty in capturing complex turbulent processes in the gas transfer coefficient (Sweeney et al., 2007) and because of uncertainties in the pre-industrial river-induced outgassing of CO_2 (Jacobson et al., 2007).

Both observation-based estimates compute the ocean CO_2 sink and its variability using interpolated measurements of surface ocean fugacity of CO_2 (pCO_2 corrected for the non-ideal behaviour of the gas; Pfeil et al., 2013). The measurements were from the Surface Ocean CO_2 Atlas (SOCAT v3; Bakker et al., 2014, 2015), which contains 14.5 million data to the end of 2014. This was extended with 1.4 million additional measurements over years 2013–2014 (see data attribution Table A1 in Appendix A), submitted to SOCAT but not yet fully quality controlled following standard SOCAT procedures. Revisions and corrections to previously reported measurements were also included where they were available. All new data were subjected to an automated quality control system to detect and remove the most obvious errors (e.g. incorrect reporting of metadata such as position, wrong units, clearly unrealistic data). The combined SOCAT v3 and preliminary new 2013–2014 measurements were mapped using a data-driven diagnostic method (Rödenbeck et al., 2013) and a combined self-organising map and feed-forward neural network (Landschützer et al., 2014). The global observation-based estimates were adjusted to remove a background (not part of the anthropogenic ocean flux) ocean source of CO_2 to the atmosphere of $0.45\,GtC\,yr^{-1}$ from river input to the ocean (Jacobson et al., 2007) in order to make them comparable to S_{OCEAN}, which only represents the annual uptake of anthropogenic CO_2 by the ocean. Several other data-based products are available, but they partly show large discrepancies with observed variability that need to be resolved. Here we used the two data products that had the best fit to observations, distinctly better than most in their representation of tropical and global variability (Rödenbeck et al., 2015).

We use the data-based product of Khatiwala et al. (2009) updated by Khatiwala et al. (2013) to estimate the anthropogenic carbon accumulated in the ocean during 1765–1958 (60.2 GtC) and 1870–1958 (47.5 GtC), and assume an oceanic uptake of 0.4 GtC for 1750–1765 (for which time no data are available) based on the mean uptake during 1765–1770. The estimate of Khatiwala et al. (2009) is based on regional disequilibrium between surface pCO_2 and atmospheric CO_2, and a Green's function utilising transient ocean tracers like CFCs and ^{14}C to ascribe changes through time.

It does not include changes associated with changes in ocean circulation, temperature, and climate, but these are thought to be small over the time period considered here (Ciais et al., 2013). The uncertainty in cumulative uptake of ±20 GtC (converted to $\pm 1\sigma$) is taken directly from the IPCC's review of the literature (Rhein et al., 2013), or about ±30 % for the annual values (Khatiwala et al., 2009).

2.4.2 Global ocean biogeochemistry models

The trend in the ocean CO_2 sink for 1959–2014 is computed using a combination of eight global ocean biogeochemistry models (Table 6). The models represent the physical, chemical, and biological processes that influence the surface ocean concentration of CO_2 and thus the air–sea CO_2 flux. The models are forced by meteorological reanalysis and atmospheric CO_2 concentration data available for the entire time period. Models do not include the effects of anthropogenic changes in nutrient supply. They compute the air–sea flux of CO_2 over grid boxes of 1 to 4° in latitude and longitude. The ocean CO_2 sink for each model is normalised to the observations by dividing the annual model values by their average over 1990–1999 and multiplying this with the observation-based estimate of 2.2 $\mathrm{GtC\,yr^{-1}}$ (obtained from Manning and Keeling, 2006; McNeil et al., 2003; Mikaloff Fletcher et al., 2006). The ocean CO_2 sink for each year (t) in $\mathrm{GtC\,yr^{-1}}$ is therefore

$$S_{\mathrm{OCEAN}}(t) = \frac{1}{n}\sum_{m=1}^{m=n} \frac{S^{m}_{\mathrm{OCEAN}}(t)}{S^{m}_{\mathrm{OCEAN}}(1990\text{–}1999)} \times 2.2\,\mathrm{GtC\,yr^{-1}}, \tag{7}$$

where n is the number of models. This normalisation ensures that the ocean CO_2 sink for the global carbon budget is based on observations, whereas the trends and annual values in CO_2 sinks are from model estimates. The normalisation based on a ratio assumes that if models over- or underestimate the sink in the 1990s, it is primarily due to the process of diffusion, which depends on the gradient of CO_2. Thus a ratio is more appropriate than an offset as it takes into account the time dependence of CO_2 gradients in the ocean. The mean uncorrected ocean CO_2 sink from the eight models for 1990–1999 ranges between 1.6 and 2.4 $\mathrm{GtC\,yr^{-1}}$, with a multi-model mean of 1.9 $\mathrm{GtC\,yr^{-1}}$.

2.4.3 Uncertainty assessment for S_{OCEAN}

The uncertainty around the mean ocean sink of anthropogenic CO_2 was quantified by Denman et al. (2007) for the 1990s (see Sect. 2.4.1). To quantify the uncertainty around annual values, we examine the standard deviation of the normalised model ensemble. We use further information from the two data-based products to assess the confidence level. The average standard deviation of the normalised ocean model ensemble is 0.13 $\mathrm{GtC\,yr^{-1}}$ during 1980–2010 (with a maximum of 0.27), but it increases as the model ensemble goes back in time, with a standard deviation of 0.22 $\mathrm{GtC\,yr^{-1}}$ across models in the 1960s. We estimate that the uncertainty in the annual ocean CO_2 sink is about ±0.5 $\mathrm{GtC\,yr^{-1}}$ from the fractional uncertainty of the data uncertainty of ±0.4 $\mathrm{GtC\,yr^{-1}}$ and standard deviation across models of up to ±0.27 $\mathrm{GtC\,yr^{-1}}$, reflecting both the uncertainty in the mean sink from observations during the 1990s (Denman et al., 2007; Sect. 2.4.1) and in the interannual variability as assessed by models.

We examine the consistency between the variability in the model-based and the data-based products to assess confidence in S_{OCEAN}. The interannual variability in the ocean fluxes (quantified as the standard deviation) of the two data-based estimates for 1986–2014 (where they overlap) is ±0.38 $\mathrm{GtC\,yr^{-1}}$ (Rödenbeck et al., 2014) and ±0.40 $\mathrm{GtC\,yr^{-1}}$ (Landschützer et al., 2015), compared to ±0.27 $\mathrm{GtC\,yr^{-1}}$ for the normalised model ensemble. The standard deviation includes a component of trend and decadal variability in addition to interannual variability, and their relative influence differs across estimates. The phase is generally consistent between estimates, with a higher ocean CO_2 sink during El Niño events. The annual data-based estimates correlate with the ocean CO_2 sink estimated here with a correlation of $r = 0.51$ (0.34 to 0.58 for individual models), and $r = 0.71$ (0.54 to 0.72) for the data-based estimates of Rödenbeck et al. (2014) and Landschützer et al. (2015), respectively (simple linear regression), but their mutual correlation is only 0.55. The use of annual data for the correlation may reduce the strength of the relationship because the dominant source of variability associated with El Niño events is less than 1 year. We assess a medium confidence level to the annual ocean CO_2 sink and its uncertainty because they are based on multiple lines of evidence, and the results are consistent in that the interannual variability in the model and data-based estimates are all generally small compared to the variability in atmospheric CO_2 growth rate. Nevertheless the various results do not show agreement in interannual variability on the global scale or for the relative roles of the annual and decadal variability compared to the trend.

2.5 Terrestrial CO_2 sink

The difference between, on the one hand, fossil fuel (E_{FF}) and land-use-change emissions (E_{LUC}) and, on the other hand, the growth rate in atmospheric CO_2 concentration (G_{ATM}) and the ocean CO_2 sink (S_{OCEAN}) is attributable to the net sink of CO_2 in terrestrial vegetation and soils (S_{LAND}), within the given uncertainties (Eq. 1). Thus, this sink can be estimated as the residual of the other terms in the mass balance budget, as well as directly calculated using DGVMs. The residual land sink (S_{LAND}) is thought to be in part because of the fertilising effect of rising atmospheric CO_2 on plant growth, N deposition, and effects of climate change such as the lengthening of the growing season in northern temperate and boreal areas. S_{LAND} does not include gross land sinks directly resulting from land-use change (e.g. regrowth of vegetation) as these are estimated as part of the net land-use flux (E_{LUC}). System boundaries make it difficult to attribute exactly CO_2 fluxes on land between S_{LAND} and E_{LUC} (Erb et al., 2013), and by design most of the uncertainties in our method are allocated to S_{LAND} for those processes that are poorly known or represented in models.

2.5.1 Residual of the budget

For 1959–2014, the terrestrial carbon sink was estimated from the residual of the other budget terms by rearranging Eq. (1):

$$S_{\mathrm{LAND}} = E_{\mathrm{FF}} + E_{\mathrm{LUC}} - (G_{\mathrm{ATM}} + S_{\mathrm{OCEAN}}). \quad (8)$$

The uncertainty in S_{LAND} is estimated annually from the root sum of squares of the uncertainty in the right-hand terms assuming the errors are not correlated. The uncertainty averages to $\pm 0.8\,\mathrm{GtC\,yr^{-1}}$ over 1959–2014 (Table 7). S_{LAND} estimated from the residual of the budget includes, by definition, all the missing processes and potential biases in the other components of Eq. (8).

2.5.2 DGVMs

A comparison of the residual calculation of S_{LAND} in Eq. (8) with estimates from DGVMs as used to estimate E_{LUC} in Sect. 2.2.3, but here excluding the effects of changes in land cover (using a constant pre-industrial land-cover distribution), provides an independent estimate of the consistency of S_{LAND} with our understanding of the functioning of the terrestrial vegetation in response to CO_2 and climate variability (Table 7). As described in Sect. 2.2.3, the DGVM runs that exclude the effects of changes in land cover include all climate variability and CO_2 effects over land, but they do not include reductions in CO_2 sink capacity associated with human activity directly affecting changes in vegetation cover and management, which by design is allocated to E_{LUC}. This effect has been estimated to have led to a reduction in the terrestrial sink by $0.5\,\mathrm{GtC\,yr^{-1}}$ since 1750 (Gitz and Ciais, 2003). The models in this configuration estimate the mean and variability in S_{LAND} based on atmospheric CO_2 and climate, and thus both terms can be compared to the budget residual. We apply three criteria for minimum model realism by including only those models with (1) steady state after spin-up, (2) net land fluxes ($S_{\mathrm{LAND}} - E_{\mathrm{LUC}}$) that are a carbon sink over the 1990s as constrained by global atmospheric and oceanic observations (McNeil et al., 2003; Manning and Keeling, 2006; Mikaloff Fletcher et al., 2006), and (3) global E_{LUC} that is a carbon source over the 1990s. Ten models met these three criteria.

The annual standard deviation of the CO_2 sink across the 10 DGVMs averages to $\pm 0.7\,\mathrm{GtC\,yr^{-1}}$ for the period 1959 to 2014. The model mean, over different decades, correlates with the budget residual with $r = 0.71$ (0.52 to $r = 0.71$ for individual models). The standard deviation is similar to that of the five model ensembles presented in Le Quéré et al. (2009), but the correlation is improved compared to $r = 0.54$ obtained in the earlier study. The DGVM results suggest that the sum of our knowledge on annual CO_2 emissions and their partitioning is plausible (see Discussion), and provide insight into the underlying processes and regional breakdown. However as the standard deviation across the DGVMs (e.g. $\pm 0.9\,\mathrm{GtC\,yr^{-1}}$ for year 2014) is of the same magnitude as the combined uncertainty due to the other components (E_{FF}, E_{LUC}, G_{ATM}, S_{OCEAN}; Table 7), the DGVMs do not provide further reduction of uncertainty on the annual terrestrial CO_2 sink compared to the residual of the budget (Eq. 8). Yet, DGVM results are largely independent of the residual of the budget, and it is worth noting that the residual method and ensemble mean DGVM results are consistent within their respective uncertainties. We attach a medium confidence level to the annual land CO_2 sink and its uncertainty because the estimates from the residual budget and averaged DGVMs match well within their respective uncertainties, and the estimates based on the residual budget are primarily dependent on E_{FF} and G_{ATM}, both of which are well constrained.

2.6 The atmospheric perspective

The worldwide network of atmospheric measurements can be used with atmospheric inversion methods to constrain the location of the combined total surface CO_2 fluxes from all sources, including fossil and land-use-change emissions and land and ocean CO_2 fluxes. The inversions assume E_{FF} to be well known, and they solve for the spatial and temporal distribution of land and ocean fluxes from the residual gradients of CO_2 between stations that are not explained by emissions. Inversions used atmospheric CO_2 data to the end of 2014 (including preliminary values in some cases), as well as three atmospheric CO_2 inversions (Table 6) to infer the total CO_2 flux over land regions and the distribution of the total land and ocean CO_2 fluxes for the mid–high-latitude Northern Hemisphere (30–90° N), tropics (30° S–30° N) and mid–high-latitude region of the Southern Hemisphere (30–90° S). We focus here on the largest and most consistent sources of information and use these estimates to comment on the consistency across various data streams and process-based estimates.

Atmospheric inversions

The three inversion systems used in this release are the CarbonTracker (Peters et al., 2010), the Jena CarboScope (Rödenbeck, 2005), and MACC (Chevallier et al., 2005). They are based on the same Bayesian inversion principles that interpret the same, for the most part, observed time series (or subsets thereof) but use different methodologies that represent some of the many approaches used in the field. This mainly concerns the time resolution of the estimates (i.e. weekly or monthly), spatial breakdown (i.e. grid size), assumed correlation structures, and mathematical approach. The details of these approaches are documented extensively in the references provided. Each system uses a different transport model, which was demonstrated to be a driving factor behind differences in atmospheric-based flux estimates, and specifically their global distribution (Stephens et al., 2007).

The three inversions use atmospheric CO_2 observations from various flask and in situ networks. They prescribe spatial and global E_{FF} that can vary from that presented here. The CarbonTracker and MACC inversions prescribed the same global E_{FF} as in Sect. 2.1.1, during 2010–2014 for CarbonTracker and during 1979–2014 in MACC. The Jena-s81_v3.7 inversion uses E_{FF} from EDGAR4.2. Different spatial and temporal distributions of E_{FF} were prescribed in each inversion.

Given their prescribed map of E_{FF}, each inversion estimates natural fluxes from a similar set of surface CO_2 measurement stations, and CarbonTracker additionally uses two sites of aircraft CO_2 vertical profiles over the Amazon and Siberia, regions where surface observations are sparse. The atmospheric transport models of each inversion are TM5 for CarbonTracker, TM3 for Jena-s81_v3.7, and LMDZ for MACC. These three models are based on the same ECMWF wind fields. The three inversions use different prior natural fluxes, which partly influences their optimised fluxes. MACC assumes that the prior land flux is zero on the annual mean in each grid cell of the transport model, so that any sink or source on land is entirely reflecting the information brought by atmospheric measurements. CarbonTracker simulates a small prior sink on land from the SIBCASA model that results from regrowth following fire disturbances of an otherwise net zero biosphere. Jena s81_v3.7 assumes a prior on the long-term mean land sink pattern, using the time-averaged net ecosystem exchange of the LPJ model. Inversion results for the sum of natural ocean and land fluxes (Fig. 8) are better constrained in the Northern Hemisphere (NH) than in the tropics, because of the higher measurement stations density in the NH.

Finally, results from atmospheric inversions include the natural CO_2 fluxes from rivers (which need to be taken into account to allow comparison to other sources) and chemical oxidation of reactive carbon-containing gases (which are neglected here). These inverse estimates are not truly independent of the other estimates presented here as the atmospheric observations include a set of observations used to estimate the global atmospheric growth rate (Sect. 2.3). However they provide new information on the regional distribution of fluxes.

We focus the analysis on two known strengths of the inverse approach: the derivation of the year-to-year changes in total land fluxes ($S_{LAND} - E_{LUC}$) consistent with the whole network of atmospheric observations, and the spatial breakdown of combined land and ocean fluxes ($S_{OCEAN} + S_{LAND} - E_{LUC}$) across large regions of the globe. The total land flux correlates well with that estimated from the budget residual (Eq. 1) with correlations for the annual time series ranging from $r = 0.89$ to 0.93, and with the DGVM multi-model mean with correlations for the annual time series ranging from $r = 0.71$ to 0.80 ($r = 0.49$ to 0.81 for individual DGVMs and inversions). The spatial breakdown is discussed in Sect. 3.1.3.

2.7 Processes not included in the global carbon budget

2.7.1 Contribution of anthropogenic CO and CH_4 to the global carbon budget

Anthropogenic emissions of CO and CH_4 to the atmosphere are eventually oxidised to CO_2 and thus are part of the global carbon budget. These contributions are omitted in Eq. (1), but an attempt is made in this section to estimate their magnitude and identify the sources of uncertainty. Anthropogenic CO emissions are from incomplete fossil fuel and biofuel burning and deforestation fires. The main anthropogenic emissions of fossil CH_4 that matter for the global carbon budget are the fugitive emissions of coal, oil, and gas upstream sectors (see below). These emissions of CO and CH_4 contribute a net addition of fossil carbon to the atmosphere.

In our estimate of E_{FF} we assumed (Sect. 2.1.1) that all the fuel burned is emitted as CO_2; thus CO anthropogenic emissions and their atmospheric oxidation into CO_2 within a few months are already counted implicitly in E_{FF} and should not be counted twice (same for E_{LUC} and anthropogenic CO emissions by deforestation fires). Anthropogenic emissions of fossil CH_4 are not included in E_{FF}, because these fugitive emissions are not included in the fuel inventories. Yet they contribute to the annual CO_2 growth rate after CH_4 gets oxidised into CO_2. Anthropogenic emissions of fossil CH_4 represent 15 % of total CH_4 emissions (Kirschke et al., 2013), that is 0.061 GtC yr^{-1} for the past decade. Assuming steady state, these emissions are all converted to CO_2 by OH oxidation and thus explain 0.06 GtC yr^{-1} of the global CO_2 growth rate in the past decade.

Other anthropogenic changes in the sources of CO and CH_4 from wildfires, biomass, wetlands, ruminants, or permafrost changes are similarly assumed to have a small effect on the CO_2 growth rate.

2.7.2 Anthropogenic carbon fluxes in the land to ocean aquatic continuum

The approach used to determine the global carbon budget considers only anthropogenic CO_2 emissions and their partitioning among the atmosphere, ocean, and land. In this analysis, the land and ocean reservoirs that take up anthropogenic

CO_2 from the atmosphere are conceived as independent carbon storage repositories. This approach thus omits that carbon is continuously displaced along the land–ocean aquatic continuum (LOAC) comprising freshwaters, estuaries, and coastal areas (Bauer et al., 2013; Regnier et al., 2013). A significant fraction of this lateral carbon flux is entirely "natural" and is thus a steady-state component of the pre-industrial carbon cycle. The remaining fraction is anthropogenic carbon entrained into the lateral transport loop of the LOAC, a perturbation that is relevant for the global carbon budget presented here.

The results of the analysis of Regnier et al. (2013) can be summarised in three points of relevance to the anthropogenic CO_2 budget. First, the anthropogenic carbon input from land to hydrosphere, F_{LH}, estimated at $1 \pm 0.5\,\mathrm{GtC\,yr^{-1}}$ is significant compared to the other terms of Eq. (1) (Table 8), and implies that only a portion of the anthropogenic CO_2 taken up by land ecosystems remains sequestered in soil and biomass pools. Second, some of the exported anthropogenic carbon is stored in the LOAC (ΔC_{LOAC}, $0.55 \pm 0.3\,\mathrm{GtC\,yr^{-1}}$) and some is released back to the atmosphere as CO_2 (E_{LOAC}, $0.35 \pm 0.2\,\mathrm{GtC\,yr^{-1}}$), the magnitude of these fluxes resulting from the combined effects of freshwaters, estuaries, and coastal seas. Third, a small fraction of anthropogenic carbon displaced by the LOAC is transferred to the open ocean, where it accumulates (F_{HO}, $0.1 \pm > 0.05\,\mathrm{GtC\,yr^{-1}}$). The anthropogenic perturbation of the carbon fluxes from land to ocean does not contradict the method used in Sect. 2.5 to define the ocean sink and residual terrestrial sink. However, it does point to the need to account for the fate of anthropogenic carbon once it is removed from the atmosphere by land ecosystems (summarised in Fig. 2). In theory, direct estimates of changes of the ocean inorganic carbon inventory over time would see the land flux of anthropogenic carbon and would thus have a bias relative to air–sea flux estimates and tracer-based reconstructions. However, currently the value is small enough to be not noticeable relative to the errors in the individual techniques.

The residual terrestrial sink in a budget that accounts for the LOAC will be larger than S_{LAND}, as the flux is partially offset by the net source of CO_2 to the atmosphere, i.e. E_{LOAC}, of $0.35 \pm 0.3\,\mathrm{GtC\,yr^{-1}}$ from rivers, estuaries, and coastal seas:

$$S_{\mathrm{LAND+LOAC}} = E_{\mathrm{FF}} + E_{\mathrm{LUC}} - (G_{\mathrm{ATM}} + S_{\mathrm{OCEAN}}) + E_{\mathrm{LOAC}}. \tag{9}$$

The residual terrestrial sink (S_{LAND}) is $3.0 \pm 0.8\,\mathrm{GtC\,yr^{-1}}$ for 2005–2014 as calculated according to Eq. (8; Table 7), while $S_{\mathrm{LAND+LOAC}}$ is $3.3 \pm 0.9\,\mathrm{GtC\,yr^{-1}}$ over the same time period. A fraction of anthropogenic CO_2 taken up by land ecosystems is exported to the LOAC (F_{LH}). With the LOAC included, we now have

$$\Delta C_{\mathrm{TE}} = S_{\mathrm{LAND+LOAC}} - E_{\mathrm{LUC}} - F_{\mathrm{LH}}, \tag{10}$$

where ΔC_{TE} is the change in annual terrestrial ecosystems carbon storage, including land vegetation, litter, and soil. ΔC_{TE} is $1.4\,\mathrm{GtC\,yr^{-1}}$ for the period 2005–2014. It is notably smaller than what would be calculated in a traditional budget that ignores the LOAC. In this case, the change in carbon storage is estimated as $2.1\,\mathrm{Gt\,C\,yr^{-1}}$ from the difference between S_{LAND} ($3.0\,\mathrm{Gt\,C\,yr^{-1}}$) and E_{LUC} ($0.9\,\mathrm{Gt\,C\,yr^{-1}}$; Table 8). All estimates of LOAC are given with low confidence, because they originate from a single source. The carbon budget presented here implicitly incorporates the fluxes from the LOAC into S_{LAND}. We do not attempt to separate these fluxes because the uncertainties in either estimate are too large, and there is insufficient information available to estimate the LOAC fluxes on an annual basis.

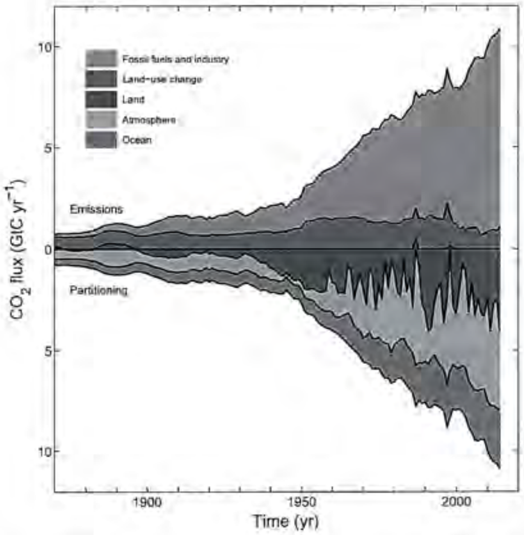

Figure 3. Combined components of the global carbon budget illustrated in Fig. 2 as a function of time, for emissions from fossil fuels and industry (E_{FF}; grey) and emissions from land-use change (E_{LUC}; brown), as well as their partitioning among the atmosphere (G_{ATM}; light blue), land (S_{LAND}; green), and oceans (S_{OCEAN}; dark blue). All time series are in $\mathrm{GtC\,yr^{-1}}$. G_{ATM} and S_{OCEAN} (and by construction also S_{LAND}) prior to 1959 are based on different methods. The primary data sources for fossil fuels and industry are from Boden et al. (2013), with uncertainty of about ±5 % (±1σ); land-use-change emissions are from Houghton et al. (2012) with uncertainties of about ±30 %; atmospheric growth rate prior to 1959 is from Joos and Spahni (2008) with uncertainties of about ±1–1.5 $\mathrm{GtC\,decade^{-1}}$ or ±0.1–0.15 $\mathrm{GtC\,yr^{-1}}$ (Bruno and Joos, 1997), and from Dlugokencky and Tans (2015) from 1959 with uncertainties of about ±0.2 $\mathrm{GtC\,yr^{-1}}$; the ocean sink prior to 1959 is from Khatiwala et al. (2013) with uncertainty of about ±30 %, and from this study from 1959 with uncertainties of about ±0.5 $\mathrm{GtC\,yr^{-1}}$; and the residual land sink is obtained by difference (Eq. 8), resulting in uncertainties of about ±50 % prior to 1959 and ±0.8 $\mathrm{GtC\,yr^{-1}}$ after that. See the text for more details of each component and their uncertainties.

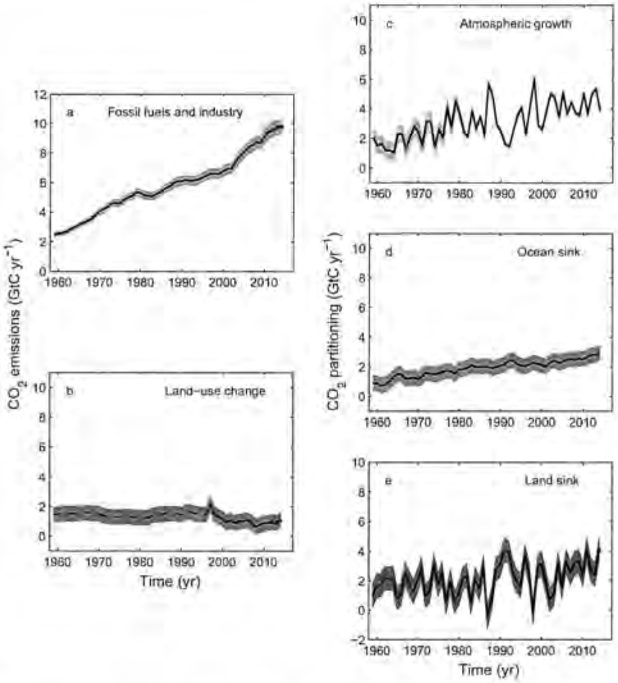

Figure 4. Components of the global carbon budget and their uncertainties as a function of time, presented individually for **(a)** emissions from fossil fuels and industry (E_{FF}), **(b)** emissions from land-use change (E_{LUC}), **(c)** atmospheric $\mathrm{CO_2}$ growth rate (G_{ATM}), **(d)** the ocean $\mathrm{CO_2}$ sink (S_{OCEAN}; positive indicates a flux from the atmosphere to the ocean), and **(e)** the land $\mathrm{CO_2}$ sink (S_{LAND}; positive indicates a flux from the atmosphere to the land). All time series are in $\mathrm{GtC\,yr^{-1}}$ with the uncertainty bounds representing $\pm 1\sigma$ in shaded colour. Data sources are as in Fig. 3. The black dots in panels **(a)**, **(b)**, and **(e)** show preliminary values for 2012, 2013, and 2014 that originate from a different data set to the remainder of the data, as explained in the text.

3 Results

3.1 Global carbon budget averaged over decades and its variability

The global carbon budget averaged over the last decade (2005–2014) is shown in Fig. 2. For this time period, 91 % of the total emissions ($E_{\mathrm{FF}} + E_{\mathrm{LUC}}$) were caused by fossil fuels and industry, and 9 % by land-use change. The total emissions were partitioned among the atmosphere (44 %), ocean (26 %), and land (30 %). All components except land-use-change emissions have grown since 1959 (Figs. 3 and 4), with important interannual variability in the atmospheric growth rate and in the land $\mathrm{CO_2}$ sink (Fig. 4), as well as some decadal variability in all terms (Table 8).

3.1.1 $\mathrm{CO_2}$ emissions

Global $\mathrm{CO_2}$ emissions from fossil fuels and industry have increased every decade from an average of $3.1 \pm 0.2\,\mathrm{GtC\,yr^{-1}}$ in the 1960s to an average of $9.0 \pm 0.5\,\mathrm{GtC\,yr^{-1}}$ during 2005–2014 (Table 8 and Fig. 5). The growth rate in these emissions decreased between the 1960s and the 1990s, from $4.5\,\%\,\mathrm{yr^{-1}}$ in the 1960s (1960–1969), $2.9\,\%\,\mathrm{yr^{-1}}$ in the 1970s (1970–1979), $1.9\,\%\,\mathrm{yr^{-1}}$ in the 1980s (1980–1989), and finally to $1.0\,\%\,\mathrm{yr^{-1}}$ in the 1990s (1990–1999), before it began increasing again in the 2000s at an average growth rate of $3.2\,\%\,\mathrm{yr^{-1}}$, decreasing to $2.2\,\%\,\mathrm{yr^{-1}}$ for the last decade (2005–2014). In contrast, $\mathrm{CO_2}$ emissions from land-use change have remained constant, in our analysis at around $1.5 \pm 0.5\,\mathrm{GtC\,yr^{-1}}$ between 1960 and 1999 and $1.0 \pm 0.5\,\mathrm{GtC\,yr^{-1}}$ during 2000–2014. The decrease in emissions from land-use change between the 1990s and 2000s is highly uncertain. It is not found in the current ensemble of the DGVMs (Fig. 6), which are otherwise consistent with the bookkeeping method within their respective uncertainty (Table 7). It is also not found in the study of tropical deforestation of Achard et al. (2014), where the fluxes in the 1990s were similar to those of the 2000s and outside our uncertainty range. A new study based on FAO data to 2015 (Federici et al., 2015) suggests that E_{LUC} decreased during 2011–2015 compared to 2001–2010.

3.1.2 Partitioning

The growth rate in atmospheric $\mathrm{CO_2}$ increased from $1.7 \pm 0.1\,\mathrm{GtC\,yr^{-1}}$ in the 1960s to $4.4 \pm 0.1\,\mathrm{GtC\,yr^{-1}}$ during 2005–2014 with important decadal variations (Table 8). Both ocean and land $\mathrm{CO_2}$ sinks increased roughly in line with the atmospheric increase, but with significant decadal variability on land (Table 8). The ocean $\mathrm{CO_2}$ sink increased from $1.1 \pm 0.5\,\mathrm{GtC\,yr^{-1}}$ in the 1960s to $2.6 \pm 0.5\,\mathrm{GtC\,yr^{-1}}$ during 2005–2014, with interannual variations of the order of a few tenths of $\mathrm{GtC\,yr^{-1}}$ generally showing an increased ocean sink during El Niño (i.e. 1982–1983, 1991–1993, 1997–1998) events (Fig. 7; Rödenbeck et al., 2014). Although there is some coherence between the ocean models and data products and among data products, their mutual correlation is weak and highlights disagreement on the exact amplitude of the interannual variability, as well as on the relative importance of the trend versus the variability (Sect. 2.4.3 and Fig. 7). As shown in Fig. 7, the two data products and most model estimates produce a mean $\mathrm{CO_2}$ sink for the 1990s that is below the mean assessed by the IPCC from indirect (but arguably more reliable) observations (Denman et al., 2007; Sect. 2.4.1). This discrepancy suggests we may need to reassess estimates of the mean ocean carbon sinks.

The land $\mathrm{CO_2}$ sink increased from $1.7 \pm 0.7\,\mathrm{GtC\,yr^{-1}}$ in the 1960s to $3.0 \pm 0.8\,\mathrm{GtC\,yr^{-1}}$ during 2005–2014, with important interannual variations of up to $2\,\mathrm{GtC\,yr^{-1}}$ generally showing a decreased land sink during El Niño events, overcompensating for the increase in ocean sink and accounting for the enhanced atmospheric growth rate during El Niño events. The high uptake anomaly around year 1991 is thought to be caused by the effect of the volcanic eruption of Mount

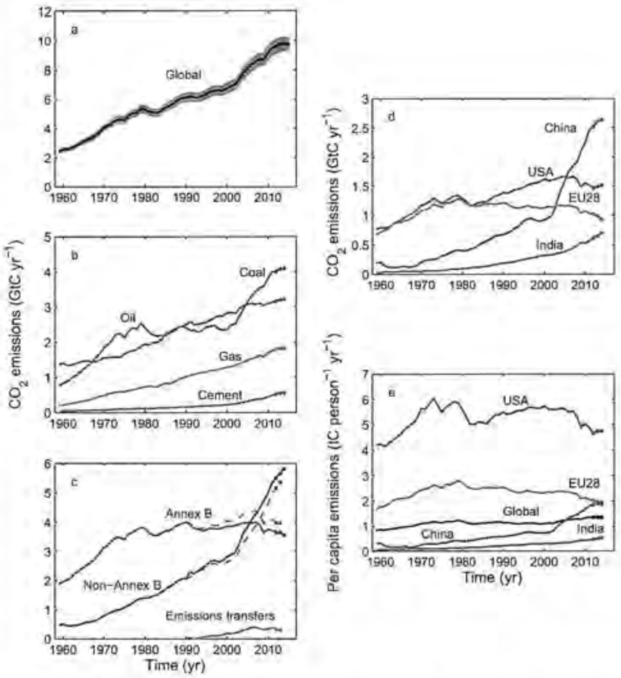

Figure 5. CO$_2$ emissions from fossil fuels and industry for **(a)** the globe, including an uncertainty of ±5 % (grey shading), the emissions extrapolated using BP energy statistics (black dots), and the emissions projection for year 2015 based on GDP projection (red dot); **(b)** global emissions by fuel type, including coal (salmon), oil (olive), gas (turquoise), and cement (purple), and excluding gas flaring, which is small (0.6 % in 2013); **(c)** territorial (full line) and consumption (dashed line) emissions for the countries listed in the Annex B of the Kyoto Protocol (salmon lines; mostly advanced economies with emissions limitations) versus non-Annex B countries (green lines) – also shown are the emissions transfers from non-Annex B to Annex B countries (light-blue line); **(d)** territorial CO$_2$ emissions for the top three country emitters (USA – olive; China – salmon; India – purple) and for the European Union (EU28, the 28 member states of the EU in 2012 – turquoise), and **(e)** per-capita emissions for the top three country emitters and the EU (all colours as in panel **d**) and the world (black). In panels **(b)** to **(e)**, the dots show the preliminary data that were extrapolated from BP energy statistics for 2012, 2013, and 2014. All time series are in GtC yr^{-1} except the per-capita emissions (panel **e**), which are in tonnes of carbon per person per year (tC person^{-1} yr^{-1}). All territorial emissions are primarily from Boden et al. (2013) except national data for the USA and EU28 for 1990–2012, which are reported by the countries to the UNFCCC as detailed in the text; consumption-based emissions are updated from Peters et al. (2011a).

Pinatubo on climate and is not generally reproduced by the DGVMs, but it is assigned to the land by the two inverse systems that include this period (Fig. 6). The larger land CO$_2$ sink during 2005–2014 compared to the 1960s is reproduced by all the DGVMs in response to combined atmospheric CO$_2$ increase, climate, and variability (3.0 ± 0.5 GtC yr^{-1} for the period 2005–2014 and average change of 1.9 GtC yr^{-1} relative to the 1960s), consistent with the budget residual and reflecting a common knowledge of the processes (Table 7). The DGVM ensemble mean of 3.0 ± 0.5 GtC yr^{-1} also reproduces the observed mean for the period 2005–2014 calculated from the budget residual (Table 7).

The total CO$_2$ fluxes on land ($S_{\mathrm{LAND}} - E_{\mathrm{LUC}}$) constrained by the atmospheric inversions show in general very good agreement with the global budget estimate, as expected given the strong constraints of G_{ATM} and the small relative uncertainty typically assumed on S_{OCEAN} and E_{FF} by inversions. The total land flux is of similar magnitude for the decadal average, with estimates for 2005–2014 from the three inversions of 2.0, 2.0, and 3.3 GtC yr^{-1} compared to 2.1 ± 0.7 GtC yr^{-1} for the total flux computed with the carbon budget from other terms in Eq. (1) (Table 7). The three inversions' total land sink would be 1.6, 1.6, and 2.9 GtC yr^{-1} when including a mean river flux adjustment of 0.45 GtC yr^{-1}, though the exact adjustment would be smaller when taking into account the anthropogenic contribution to river fluxes (Sect. 2.7.2). The interannual variability in the inversions also matched the residual-based S_{LAND} closely (Fig. 6). The total land flux from the DGVM multi-model mean also compares well with the estimate from the carbon budget and atmospheric inversions, with a decadal mean of 1.6 ± 0.4 GtC yr^{-1} (Table 7; 2005–2014), although individual models differ by several GtC for some years (Fig. 6).

3.1.3 Distribution

Figure 8 shows the partitioning of the total surface fluxes excluding emissions from fossil fuels and industry ($S_{\mathrm{OCEAN}} + S_{\mathrm{LAND}} - E_{\mathrm{LUC}}$) according to the process models in the ocean and on land, and to the three atmospheric inversions. The total surface fluxes provide information on the regional distribution of those fluxes by latitude band (Fig. 8). The global mean CO$_2$ fluxes from process models for 2005–2014 is 4.2 ± 0.5 GtC yr^{-1}. This is comparable to the fluxes of 4.7 ± 0.5 GtC yr^{-1} inferred from the remainder of the carbon budget ($E_{\mathrm{FF}} - G_{\mathrm{ATM}}$ in Eq. 1; Table 8) within their respective uncertainties. The total CO$_2$ fluxes from the three inversions range between 4.4 and 4.9 GtC yr^{-1}, consistent with the carbon budget as expected from the constraints on the inversions.

In the south (south of 30° S), the atmospheric inversions and process models all suggest a CO$_2$ sink for 2005–2014 of between 1.2 and 1.5 GtC yr^{-1} (Fig. 8), although the details of the interannual variability are not fully consistent across methods. The interannual variability in the south is low because of the dominance of ocean area with low variability compared to land areas.

In the tropics (30° S–30° N), both the atmospheric inversions and process models suggest the carbon balance in this region is close to neutral over the past decade, with fluxes for 2005–2014 ranging between −0.6 and +0.6 GtC yr^{-1}. The three inversions consistently allocate more year-to-year vari-

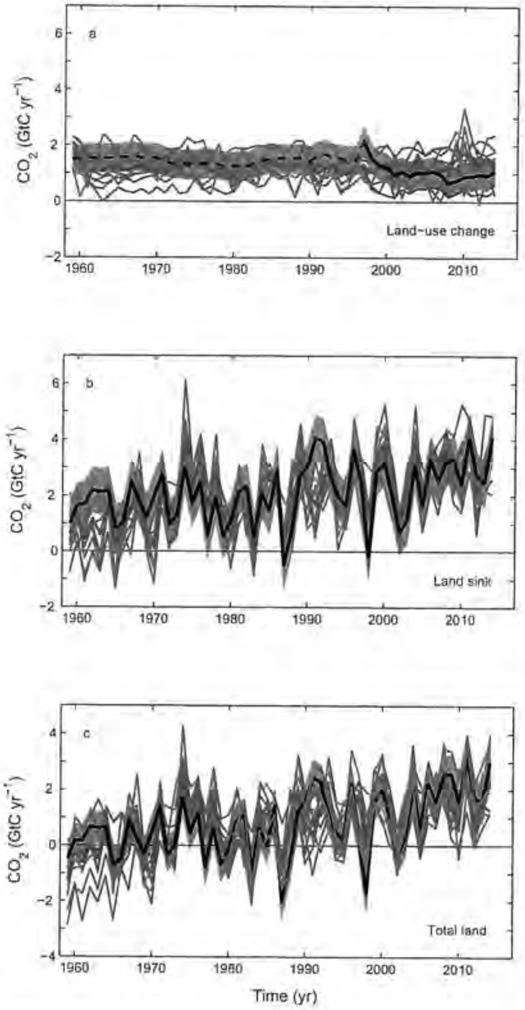

Figure 6. **(a)** Comparison of the atmosphere–land CO_2 flux showing budget values of E_{LUC} (black). CO_2 emissions from land-use change showing individual DGVM results (green) and the multi-model mean (olive), as well as fire-based results (orange); land-use-change data prior to 1997 (dashed black) highlight the start of satellite data from that year. **(b)** Land CO_2 sink (S_{LAND}; black) showing individual DGVM results (green) and multi-model mean (olive). **(c)** Total land CO_2 fluxes **(b–a)** from DGVM results (green) and the multi-model mean (olive); atmospheric inversions of Chevallier et al. (2005; MACC, v14.2) (purple), Rödenbeck et al. (2003; Jena CarboScope, s81_v3.7) (violet), and Peters et al. (2010; Carbon Tracker, vCTE2015) (salmon) (see Table 6); and the carbon balance from Eq. (1) (black). In **(c)** the inversions were adjusted for the pre-industrial land sink of CO_2 from river input, by adding a sink of 0.45 GtC yr^{-1} (Jacobson et al., 2007). This adjustment does not take into account the anthropogenic contribution to river fluxes (see Sect. 2.7.2).

ability in CO_2 fluxes to the tropics compared to the north (north of 30° N; Fig. 8). This variability is dominated by land fluxes. Inversions are consistent with each other and with the mean of process models.

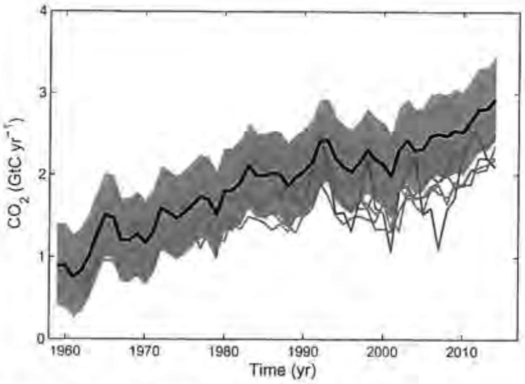

Figure 7. Comparison of the anthropogenic atmosphere–ocean CO_2 flux shows the budget values of S_{OCEAN} (black), individual ocean models before normalisation (blue), and the two ocean-data-based products (Rödenbeck et al., 2014, in salmon and Landschützer et al., 2015, in purple; see Table 6). Both data-based products were adjusted for the pre-industrial ocean source of CO_2 from river input to the ocean, which is not present in the models, by adding a sink of 0.45 GtC yr^{-1} (Jacobson et al., 2007) so as to make them comparable to S_{OCEAN}. This adjustment does not take into account the anthropogenic contribution to river fluxes (see Sect. 2.7.2).

In the north (north of 30° N), the inversions and process models are not in full agreement on the magnitude of the CO_2 sink, with the ensemble mean of the process models suggesting a total Northern Hemisphere sink for 2005–2014 of 2.3 ± 0.4 GtC yr^{-1}, while the three inversions estimate a sink of 2.5, 3.4, and 3.6 GtC yr^{-1}. The mean difference can only partly be explained by the influence of river fluxes, as this flux in the Northern Hemisphere would be less than 0.45 GtC yr^{-1}, particularly when the anthropogenic contribution to river fluxes are accounted for. The CarbonTracker inversion is within 1 standard deviation of the process models for the mean sink during their overlap period. MACC and Jena-s81_v3.7 give a higher sink in the north than the process models, and a correspondingly higher source in the tropics. Differences between CarbonTracker and MACC, Jena-s81_v3.7 may be related to differences in inter-hemispheric mixing time of their transport models, and other inversion settings. Differences also result from different fossil fuel emissions assumed in the inversions, as the inversions primarily constrain the sum of fossil fuel and land fluxes. Differences between the mean fluxes of MACC, Jena-s81_v3.7 and the ensemble of process models cannot be simply explained. They could reflect either a bias in these two inversions or missing processes or biases in the process models, such as the lack of adequate parameterisations for forest management in the north and for forest degradation emissions in tropics for the DGVMs.

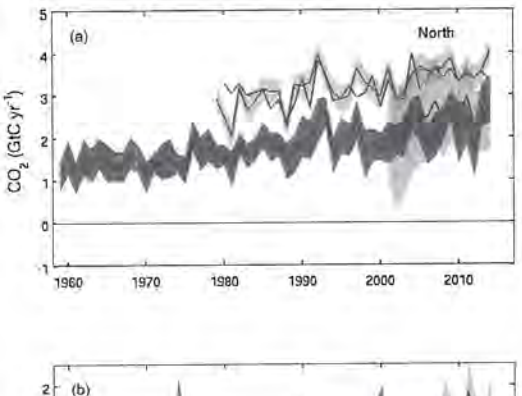

Figure 8. Atmosphere-to-surface CO_2 flux ($S_{OCEAN}+S_{LAND}-E_{LUC}$) by latitude bands for the **(a)** north (north of 30° N), **(b)** tropics (30° S–30° N), and **(c)** south (south of 30° S). Estimates from the combination of the multi-model means for the land and oceans are shown (turquoise) with $\pm 1\sigma$ of the model ensemble (in grey). Results from the three atmospheric inversions are shown in purple (Chevallier et al., 2005; MACC, v14.2), violet (Rödenbeck et al., 2003; Jena CarboScope, s81_v3.7), and salmon (Peters et al., 2010; Carbon Tracker, vCTE2015); see Table 6.

The estimated contribution of the north from process models is sensitive both to the ensemble of process models used and to the specifics of each inversion. Indeed, the process model results from Le Quéré et al. (2015) included a slightly different model ensemble (see Table 6) with no assessment of minimum model realism. The model ensemble from Le Quéré et al. (2015) showed a larger model spread and smaller sink (2.0 ± 0.8 GtC yr^{-1} for the latest decade), with also different trend in the 1960s. All three inversions show substantial differences in variability and/or trend, and one inversion substantial difference in the mean northern sink.

3.2 Global carbon budget for year 2014 and emissions projection for 2015

3.2.1 CO_2 emissions

Global CO_2 emissions from fossil fuels and industry reached 9.8 ± 0.5 GtC in 2014 (Fig. 5), distributed among coal (42 %), oil (33 %), gas (19 %), cement (5.7 %), and gas flaring (0.6 %). The first four categories increased by 0.4, 0.8, 0.4, and 2.5 % respectively over the previous year. Due to lack of data, gas flaring in 2012–2014 is assumed the same as 2011.

Emissions in 2014 were 0.6 % higher than in 2013, an increase well below the decadal average of 2.2 % yr^{-1} (2005–2014). Growth in 2014 is lower than our projection of 2.5 % yr^{-1} made last year (Le Quéré et al., 2015) based on an estimated GDP growth of 3.3 % yr^{-1} and a decrease in I_{FF} of −0.7 % yr^{-1} (Table 9), and is also outside the provided likely range of 1.3–3.5 %. The latest estimate of GDP growth for 2014 was 3.4 % yr^{-1} (IMF, 2015) and hence I_{FF} improved by 2.8 % yr^{-1}. This I_{FF} is low compared to recent years (Table 9), but not outside the range of variability observed in recent decades, suggesting that our uncertainty range may have been underestimated. Almost half of the lower growth compared to expectations can be attributed to a lower growth in emissions than anticipated in China (1.1 % compared to 4.5 % in our projection; Friedlingstein et al., 2014), which primarily reflects structural changes in China's economy (Green and Stern, 2015). Similar structural change occurred following the global financial crisis of 2008–2009 that particularly affected Western economies, which also made the emissions projections based on GDP temporarily problematic and outside of the steady behaviour assumed by the GDP/intensity approach (Peters et al., 2012b). For this reason we provide an emissions projection with explicit projection for China based on energy and cement data during January–August 2015 (see Sect. 2.1.4). Climatic variability could also have contributed to the lower emissions in China (from reported high rainfall possibly leading to higher hydropower capacity utilisation), and in Europe and the USA, where the combined emissions changes account for 37 % of the lower growth compared to expectations (Friedlingstein et al., 2014).

Using separate projections for China, the USA, and the rest of the world as described in Sect. 2.1.4, we project that the growth in global CO_2 emissions from fossil fuels and cement production will be near or slightly below zero in 2015, with a change of −0.6 % (range of −1.6 % to +0.5 %) from 2014 levels. Our method is imprecise and contains several assumptions that could influence the results beyond the given range, and as such is indicative only.

Table 9. Actual CO_2 emissions from fossil fuels and industry (E_{FF}) compared to projections made the previous year based on world GDP (IMF October 2015) and the fossil fuel intensity of GDP (I_{FF}) based on subtracting the CO_2 and GDP growth rates. The "Actual" values are the latest estimate available, and the "Projected" value for 2015 refers to those presented in this paper. A correction for leap years is applied (Sect. 2.1.3).

	E_{FF}		GDP		I_{FF}	
	Projected	Actual	Projected	Actual	Projected	Actual
2009[a]	−2.8 %	−0.5 %	−1.1 %	0.0 %	−1.7 %	−0.5 %
2010[b]	> 3 %	5.1 %	4.8 %	5.4 %	> −1.7 %	−0.3 %
2011[c]	3.1 ± 1.5 %	3.4 %	4.0 %	4.2 %	−0.9 ± 1.5 %	−0.8 %
2012[d]	2.6 % (1.9 to 3.5)	1.3 %	3.3 %	3.4 %	−0.7 %	−2.1 %
2013[e]	2.1 % (1.1 to 3.1)	1.7 %	2.9 %	3.3 %	−0.8 %	−1.6 %
2014[f]	2.5 % (1.3 to 3.5)	0.6 %	3.3 %	3.4 %	−0.7 %	−2.8 %
2015[g]	−0.6 % (−1.6 to 0.5)	–	3.1 %	–	−3.7 %	–

[a] Le Quéré et al. (2009). [b] Friedlingstein et al. (2010). [c] Peters et al. (2013). [d] Le Quéré et al. (2013). [e] Le Quéré et al. (2014). [f] Friedlingstein et al. (2014) and Le Quéré et al. (2015). [g] This study.

Within the given assumptions, global emissions decrease to 9.7 ± 0.5 GtC (35.7 ± 1.8 $GtCO_2$) in 2015, but are still 59 % above emissions in 1990.

For China, the expected change based largely on available data during January to August (see Sect. 2.1.4) is for a decrease in emissions of −3.9 % (range of −4.6 to −1.1 %) in 2015 compared to 2014. This uncertainty includes a range of −4.6 to −3.2 % considering different adjustments for stocks and no changes in the carbon content of coal, and is based on estimated decreases in apparent coal consumption (−5.3 %) and cement production (−5.0 %) and estimated growth in apparent oil (+3.2 %) and natural gas (+1.4 %) consumption. However, there are additional uncertainties from the carbon content of coal. While China's Energy Statistical Yearbooks indicate declining carbon content over recent years, preliminary data suggest an increase of up to 3 % in 2014. The Chinese government has introduced measures expressly to address the declining quality of coal (which also leads to lower carbon content) by closing lower-quality mines and placing restrictions on the quality of imported coal. Allowing for a similar increase in 2015 (0 to 3 %), we expand the uncertainty range of China's emissions growth to −4.6 to −1.1 %. Finally, China revised its emissions statistics upwards recently, which would affect the absolute value of emissions for China (but not the trend). With a slightly higher global contribution for China, our projection of global emissions "growth" for 2015 would decline further from −0.6 to −0.8 %, a small difference that falls within our uncertainty range.

For the USA, the EIA emissions projection for 2015 combined with cement data from USGS gives a decrease of −1.5 % (range of −5.5 to +0.3 %) compared to 2014. For the rest of the world, the expected growth for 2015 of +1.2 % (range of −0.2 to +2.6 %) is computed using the GDP projection for the world excluding China and the USA of 2.3 % made by the IMF (2015) and a decrease in I_{FF} of $-1.1\,\%\,\mathrm{yr}^{-1}$, which is the average from 2005 to 2014. The uncertainty range is based on the standard deviation of the interannual variability in I_{FF} during 2005–2014 of ±1.4 %.

In 2014, the largest contributions to global CO_2 emissions were from China (27 %), the USA (15 %), the EU (28 member states; 10 %), and India (7 %), with the percentages compared to the global total including bunker fuels (3.0 %). These four regions account for 59 % of global emissions. Growth rates for these countries from 2013 to 2014 were 1.2 % (China), 0.8 % (USA), −5.8 % (EU28), and 8.6 % (India). The per-capita CO_2 emissions in 2014 were $1.3\,\mathrm{tC\,person^{-1}\,yr^{-1}}$ for the globe, and were 4.8 (USA), 1.9 (China), 1.8 (EU28), and $0.5\,\mathrm{tC\,person^{-1}\,yr^{-1}}$ (India) for the four highest emitting countries (Fig. 5e).

Territorial emissions in Annex B countries have decreased slightly by $0.1\,\%\,\mathrm{yr}^{-1}$ on average from 1990 to 2013, while consumption emissions grew at $0.8\,\%\,\mathrm{yr}^{-1}$ to 2007, after which they have declined at $1.5\,\%\,\mathrm{yr}^{-1}$ (Fig. 5c). In non-Annex B countries, territorial emissions have grown at $4.4\,\%\,\mathrm{yr}^{-1}$, while consumption emissions have grown at $4.1\,\%\,\mathrm{yr}^{-1}$. In 1990, 66 % of global territorial emissions were emitted in Annex B countries (34 % in non-Annex B, and 2 % in bunker fuels used for international shipping and aviation), while in 2013 this had reduced to 38 % (58 % in non-Annex B and 3 % in bunker fuels). In terms of consumption emissions this split was 64 % in 1990 and 39 % in 2013 (34 to 55 % in non-Annex B). The difference between territorial and consumption emissions (the net emission transfer via international trade) from non-Annex B to Annex B countries has increased from near zero in 1990 to $0.3\,\mathrm{GtC\,yr^{-1}}$ around 2005 and remained relatively stable between 2006 and 2013 (Fig. 5). The increase in net emission transfers of $0.30\,\mathrm{GtC\,yr^{-1}}$ between 1990 and 2013 compares with the emission reduction of $0.37\,\mathrm{GtC\,yr^{-1}}$ in Annex B countries. These results show the importance of net emission transfer via international trade from non-Annex B to Annex B coun-