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The legacy of our CO_2 emissions: a clash of scientific facts, politics and ethics

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Abstract Of the carbon dioxide that we emit, a substantial fraction remains in the atmosphere for thousands of years. Combined with the slow response of the climate system, this results in the global temperature increase resulting from CO_2 being nearly proportional to the total emitted amount of CO_2 since preindustrial times. This has a number of simple but far-reaching consequences that raise important questions for climate change mitigation, policy and ethics. Even if anthropogenic emissions of CO_2 were stopped, most of the realized climate change would persist for centuries and thus be irreversible on human timescales, yet standard economic thinking largely discounts these long-term intergenerational effects. Countries and generations to first order contribute to both past and future climate change in proportion to their total emissions. A global temperature target implies a CO_2 "budget" or "quota", a finite amount of CO_2 that society is allowed to emit to stay below the target. Distributing that budget over time and between countries is an ethical challenge that our world has so far failed to address. Despite the simple relationship between CO_2 emissions and temperature, the consequences for climate policy and for sharing the responsibility of reducing global CO_2 emissions can only be drawn in combination with judgments about equity, fairness, the value of future generations and our attitude towards risk.

1 Introduction

Expectations were very high when government delegates met for the United Nations (UN) climate negotiations in Copenhagen in 2009. Many policymakers and scientists expected that the overwhelming scientific evidence for human-induced climate change would inevitably lead to political action and a new agreement between all countries to drastically reduce CO_2 emissions. The conference ended in frustration, and in the five years since, little has happened. The failure was not because of lack of scientific evidence, but because scientific evidence does not imply

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consensus on political action. For some, climate change defines an existential threat to societies that requires an urgent solution, while for others it is "better understood as a persistent condition that must be coped with and can only be partially managed more – or less – well" (Prins et al. 2010). Climate change is a 'wicked problem', a tangle of causes and effects, all interconnected, loaded with uncertainties, involving stakeholders with different views, at times referred to as a 'social mess' (Lazarus 2009). Some have argued it is worse – a 'super-wicked problem' – in that delaying action will make it worse and more costly, in that it is global yet there is no global institutional framework to enforce a solution, and in that those who cause it are not those affected most (Lazarus 2009). Yet despite the complexity of the societal issues and the climate system, there are powerful emerging relationships between the emitted CO_2 and the resulting warming. They are simple, maybe inconveniently simple for policy because of the inevitable consequences they imply. Here we provide an overview of scientific facts related to the carbon budget idea, discuss its policy implications, and indicate where ethical considerations and value judgments are required. The scientific basis for the carbon budget is well established, but we argue that a broader context and dialogue with social scientists is needed when operationalizing this knowledge. We do not intend to defend specific ethical viewpoints here, but simply provide a list of facts that may serve as a starting point for an ethical discussion on fairness and burden sharing in climate change.

2 Some carbon is forever

The response of temperature to a one-time emission pulse of a gas is determined by the dependence of the radiative forcing on the concentration of the gas (causing a change in the radiative balance), and the residence time of the gas in the atmosphere (Solomon et al. 2010). That lifetime ranges from weeks for aerosols to thousands of years for Hexafluorethan (C_2F_6). CO_2 is contrast does not have a single lifetime. About half of each year's CO_2 emissions currently remain in the atmosphere (the so-called airborne fraction); the rest is taken up by the ocean and land biosphere. The response of the atmospheric concentration (Fig. 1b) to an emission (Fig. 1a) is characterized by several reservoirs and processes that remove carbon on multiple timescales: decades for the biosphere and the surface ocean, centuries for the deep ocean, and even longer for sediments formed from shell-building (calcifying) organisms. Depending on the size of the emission pulse, about 15–40 % of the carbon remains in the atmosphere longer than 1000 years (Joos et al. 2013; Plattner et al. 2008; Zickfeld et al. 2013). The radiative forcing per concentration unit CO_2 decreases for higher CO_2, but the airborne fraction of emissions increases as the efficiency of the ocean and biosphere sink decrease. Fact 1 is that CO_2 is the largest contributor to the total forcing and surface warming both in the past and future (Huber and Knutti 2012), and a large fraction of the CO_2 emitted stays in the atmosphere for centuries and longer.

3 Commitment and irreversibility

The ocean today acts like a huge heat sink. It has absorbed about 90 % of the energy increase of the Earth since 1950 (Church et al. 2011). The atmosphere and land adjusts within hours to years to a change in radiative forcing, but the ocean takes centuries to respond (Plattner et al. 2008; Zickfeld et al. 2013). As a result, global surface warming would continue to increase for centuries if we kept atmospheric concentrations fixed (Meehl et al. 2005; Plattner et al. 2008). If emissions of a certain gas are eliminated entirely, the forcing decreases on a timescale determined by the respective lifetime of the gas in the atmosphere. For CO_2, the timescales on

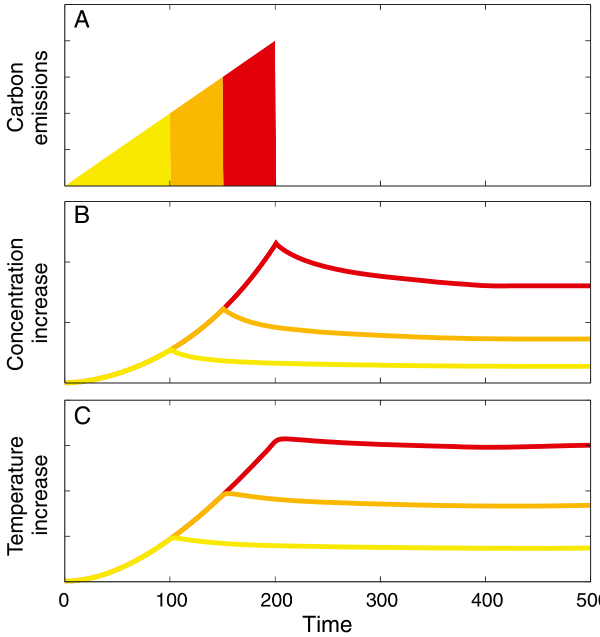

Fig. 1 (**a**) Anthropogenic CO_2 emissions, (**b**) atmospheric CO_2 concentration and (**c**) global mean surface temperature for zero emissions experiments. Scenarios are idealized and no units are given, but the results are based on carbon cycle climate model MAGICC that resolves the relevant timescales and feedbacks (Meinshausen et al. 2011a, 2011b)

which it is removed from the atmosphere (Fig. 1b) by the ocean and biosphere are similar to those for ocean heat uptake. The decreasing forcing compensates the realization of the committed warming, and as a result temperature remains nearly constant for centuries if CO_2 emissions are stopped (Friedlingstein et al. 2011; Frölicher et al. 2014; Gillett et al. 2013, 2011; Matthews and Caldeira 2008; Plattner et al. 2008; Solomon et al. 2009), as shown in Fig. 1c. Sea level rise from thermal expansion and melting of large ice sheets, however, would continue for millennia after surface temperatures are stabilized (see IPCC (2013a) sections 12.5, 13.5). Eliminating emissions of short-lived greenhouse gases would result in a cooling, whereas eliminating aerosols would result in an rapid warming of a few tenths of a degree (IPCC 2013a, FAQ 12.3). In summary, fact 2 is that climate change is irreversible in the sense that a large fraction would persist for millennia even if CO_2 emissions are stopped. Past emissions commit many future generations to changes and challenges we do not know how to deal with today, and potentially to impacts we may not even be aware of today. From a radiative forcing point of view, climate change is reversible if CO_2 is removed actively from the atmosphere (see below), but some aspects, like sea level rise, will not be reversed for hundreds of years even when concentrations are returned to near preindustrial levels (Solomon et al. 2010). Despite the fact that Article 3 of the UNFCCC specifically emphasizes "threats of serious or irreversible damage" (UNFCCC 1992), those results have only recently gotten much attention.

Commitment warming and irreversibility have often been misinterpreted, by arguing that there would be further warming in the pipeline from past emissions, and that irreversibility implies it cannot be avoided, but both are incorrect (Matthews and Solomon 2013). Further warming could largely be avoided if emissions were stopped today. Based on the model average, fact 3 is that there is little or no warming commitment beyond the amount that has been observed so far. Additional future warming (above current levels) is largely determined by future emissions, and the real commitment and inertia is in infrastructure and society that are currently emitting CO_2 (Davis et al. 2010; Matthews and Solomon 2013).

4 Inconveniently simple carbon budgets

At higher CO_2 concentrations, an additional ton emitted causes a larger increase in the atmospheric CO_2 burden, but an additional ton of CO_2 in the atmosphere causes a smaller increase in radiative forcing. Those two effects approximately compensate, and as a result peak warming is approximately proportional to the cumulative CO_2 emissions since preindustrial (Allen et al. 2009a; Gillett et al. 2013; Gregory et al. 2009; Matthews and Caldeira 2008; Matthews et al. 2009; Meinshausen et al. 2009; Zickfeld et al. 2012, 2013). The linearity is robust across a wide range of models, but the increase in temperature per unit carbon emitted is uncertain. This Transient Climate Response to Cumulative Carbon Emissions (TCRE) is estimated by the recent IPCC Fifth Assessment Report (IPCC 2013a) to likely (>66 % probability) be in the range 0.8–2.5 °C/1000 GtC (1 GtC=10^{15} grams of carbon=3.67 $GtCO_2$) for emissions up to about 2000 GtC and until temperatures peak. The linearity argument and the range for TCRE are based on a range models as well as observed greenhouse gas attributable warming due to historical emissions (IPCC 2013a, section 12.5.4). Results for several emission scenarios are shown in Fig. 2 for CO_2 only (grey) and for multi-gas scenarios (colors). The latter show more warming because non-CO_2 forcings contribute additional warming. The uncertainty in TCRE is mainly due to the uncertainty in equilibrium climate sensitivity and the transient response to increased CO_2 (Gillett et al. 2013; Knutti and Hegerl 2008).

Fact 4 is that every ton of CO_2 adds about the same amount of warming, no matter when and where it is emitted. TCRE, the warming per unit of carbon emissions, is a property of the Earth System, largely independent of the scenario. Any global temperature target therefore implies a limited CO_2 "budget", a finite amount of CO_2 that we are allowed to emit to stay below the target, irrespective of the scenario that leads to those emissions. The term "carbon budget" emerged because of the similarity to a financial budget that must be shared between people and over the year. For simplicity, we assume for the moment that decisions on non-CO_2 forcings are made independently. Obvious from the same relationship is fact 5 that countries and generations approximately contribute to past and future climate change in proportion to their total cumulative emissions.

The linear relationship in Fig. 2 would appear to be a simple useful policy framework (Allen et al. 2009a; Matthews et al. 2012; Meinshausen et al. 2009) in that only the total emissions of CO_2 over time need to limited, irrespective of the scenario, yet it has caused tensions in the political negotiations. It has become obvious that mitigating short-lived gases will not address CO_2 (which dominates future warming) (Rogelj et al. 2014b), and that time is running out. For temperature increase to likely (>66 %) remain below 2 °C relative to preindustrial (UNFCCC 2010), the carbon budget is about 800 GtC. About 535 GtC have been emitted between 1870 and 2013 (IPCC 2013b). At annual emissions of about 10 GtC/yr, the remaining budget would last less than 30 years (Friedlingstein et al. 2014). Fact 6 therefore is that global CO_2 emissions need to decrease quickly and strongly to likely keep warming below 2 °C, because about two thirds of the CO_2 emissions have already been emitted. A higher temperature target would provide more time but simply postpones the decarbonisation

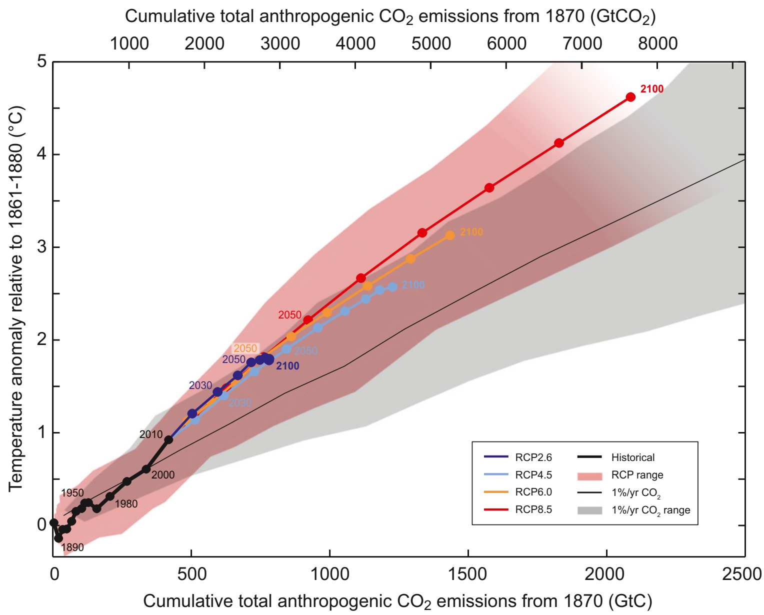

Fig. 2 Global mean surface temperature increase as a function of cumulative total global CO_2, reproduced from IPCC (2013b). Results from climate-carbon cycle models for each RCP scenario until 2100 are shown with coloured lines and decadal means (dots). Some decadal means are labeled, e.g., 2050 indicating the decade 2040–2049. Model results over the historical period are indicated in black. The coloured plume illustrates the uncertainty. Results for a scenario with only CO_2 emissions are given by the thin black line and grey area. For a specific amount of cumulative CO_2 emissions, those exhibit lower warming than those driven by RCPs, which include additional non-CO_2 forcings

required. Not all changes are proportional to cumulative emissions, sea level for example depends on the timing of emissions.

An additional fact 7 is that the fossil fuel reserves are much bigger than the budget allowed for the limiting warming to below 2 °C. As consequence, some carbon will need to remain in the ground, or be sequestered again (Allen et al. 2009b; Meinshausen et al. 2009; Rogner et al. 2012).

5 Dealing with uncertainty and risk

With a central value of the TCRE range of 1.65 °C per 1000 GtC and considering only CO_2, the 2 °C target implies a carbon budget of about 1200 GtC, but that would imply a 50 % probability of exceeding the target. To achieve the goal with higher probability requires a lower budget (Fig. 3c). To likely (>66 %) remain below 2 °C the budget is about 1000 GtC. If non-CO_2 forcings are considered as in the RCP scenarios, the budget is further reduced to about 800 GtC (Fig. 3b) (IPCC 2013b).

Fact 8 is that we do not know exactly how big the carbon budget is; we can only say that it is smaller than X for a given likelihood that we can pick. A higher likelihood of achieving the desired goal implies a smaller budget (Fig. 3c). Uncertainty is often misused to argue for delaying mitigation until we know more, but in fact the opposite is true. To prevent "dangerous interference with the climate

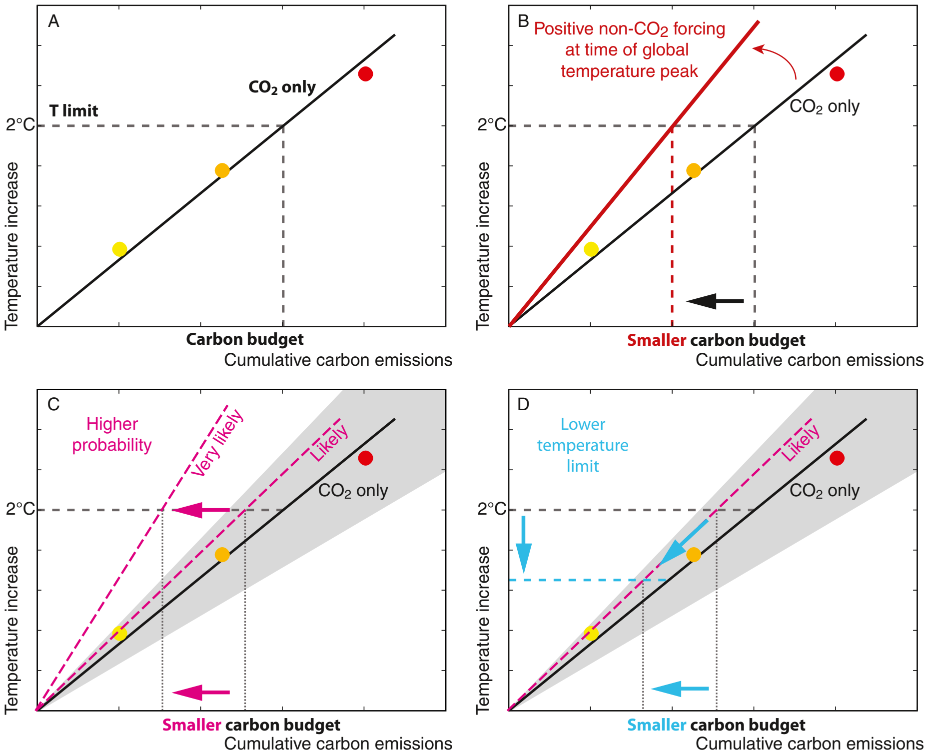

Fig. 3 Overview of aspects influencing the amount of cumulative carbon emissions consistent with a given global temperature target. (**a**) Proportionality of global-mean temperature increase to cumulative emissions of carbon. Coloured dots correspond to the cases shown in Fig. 1. (**b**) Positive non-CO_2 forcing reduces the allowed carbon budget for a given temperature limit. (**c**) Choosing a higher likelihood of staying below a given temperature limit reduces the budget. (**d**) Choosing a lower temperature limit also reduces the budget. Grey areas indicate a range covered by models as in Fig. 2

system", the stated goal of the UNFCCC, with any likelihood greater than even odds means that that a larger uncertainty implies stronger emission reduction targets to be on the safe side (Rogelj et al. 2014a). Illustrated in Fig. 3c, a wider grey range (assuming a fixed median) has the same effect as moving from the "likely" to the "very likely" line, and reduces the budget. For a given climate target, e.g., 2 °C warming above preindustrial, and a likelihood of succeeding, the estimate of the compatible CO_2 emissions is a purely scientific problem. How much risk we are willing to take on the other hand is a question of values and intergenerational justice.

Currently, the target discussed in the UNFCCC is to limit warming to below 2 °C relative to "preindustrial levels" with a "likely" (>66 %) chance (UNFCCC 2010) (though a 50 % chance is mentioned). In IPCC AR5, "the terms preindustrial and industrial refer, somewhat arbitrarily, to the periods before and after 1750, respectively" (IPCC 2013a). So the world has a target relative to a "somewhat arbitrary" baseline, and there are no global instrumental temperature data, and no trustworthy emission data (in particular for land use) to estimate historical CO_2 emissions between about 1750 and 1850. This causes further difficulties in the climate negotiations.

6 Valuing the future and sharing the burden

How would we distribute a pie between ten kids in a fair way? One would probably give a tenth to each. However, imagine two kids have eaten two thirds of the pie, and we can only distribute the rest. The two who already ate much want more, because they are addicted. The others want the rest because they are hungry. Some argue they should get compensation in the form of other sweets because there is not much left. What would now be a fair distribution? Already in this simple example, different interpretations of fairness can be defended. One could argue for dividing the remaining pie equally, but may also argue for taking into account historic responsibility.

The problem we are facing is similar, with the cumulative carbon budget being the carbon pie to be distributed, and other sweets being a compensation or alternatives to carbon-intensive development. Much of the CO_2 budget for the 2 °C target has already been emitted in the past, and how the remainder should be distributed is debated. The challenge is to find a ’fair’ allocation of the remaining carbon budget, between countries, between people within a country, and over time.

Schemes to ‘share the burden’ often consider one or both of the following two aspects: responsibility (how much one has contributed to the problem) and capacity (or capability, how well one is placed to do something about it). Both aspects can be defined in many ways and are subject to value judgments. The importance of these two criteria is illustrated by their inclusion in the Rio Declaration, which states that “in view of the different contributions to global environmental degradation, states have common but differentiated responsibilities.” Similar words appear in the Framework Convention on Climate Change (UNFCCC), which states that parties should act to protect the climate system “on the basis of equality and in accordance with their common but differentiated responsibilities and respective capabilities”. How these responsibilities are translated in a commensurate level of action is subject to debate (Friman and Strandberg 2014).

‘Capacity’ can be interpreted in many ways: gross domestic product (GDP), human development index, knowhow of and access to the mitigation technologies, etc. Responsibility can also be defined in various ways, for example as the contribution in terms of historical emissions, the contribution to historical warming, or the contribution to current radiative forcing.

Obvious from emission data is fact 9, that past and current greenhouse gas emissions have been extremely unevenly distributed amongst various actors, with a large share of global emissions emitted by a few countries. Not all people have benefited equally of these greenhouse gas emissions. Critical in assessing how historical emissions translate in responsibility, is defining when a country can be held accountable for its emissions. One may argue that current generations are not liable for what their ancestors did, and that earlier generations did not know the consequence of their actions (Baer 2002). With half of the historical emissions occurring in the last 40 years, the latter argument however is quickly fading away. How to account for historical emissions is an ethical question, but fact 10 is that, taking into account all drivers of change, the historical contribution to present climate change (in contrast to emissions, see fact 9) is extremely unevenly distributed between countries, no matter how we measure the contributions (Matthews et al. 2014). The relative contributions of countries are rapidly changing, with economies in transition like China catching up quickly to developed countries. Since the year 2000, most of the increase in global emissions has happened in upper middle-income countries (IPCC 2014).

Much has been written about possible interpretations of capacity and responsibility (Baer 2002; IPCC 2014). We simply note fact 11, that the global carbon budget for any temperature target implies a global commons problem. CO_2 has global consequences, no matter where it is emitted; therefore, it cannot be solved without widespread action. I benefit more from burning CO_2 by producing cheap energy than I suffer now from the problems this causes. Additional obstacles in burden sharing schemes are that what may seem ethically justified may not be practical, or not acceptable to those with high political influence.

The emission allocation over time has both practical and ethical aspects. From the perspective of peak temperature, a country can emit its CO_2 emission share at any time. Warming is nearly proportional to cumulative emissions of CO_2, and the last ton emitted will determine the peak warming. In practice, there is inertia in society, in that technology cannot be scaled up at arbitrary rates, and investments in infrastructure are made with a certain lifetime of the infrastructure in mind. Behavioral changes may need generations to establish themselves.

Estimating how the CO_2 budget can be distributed over the next century, so that the overall (discounted) costs are minimal requires integrated assessment models (IAMs), which incorporate assumptions about future technology, energy systems, population growth, damages and costs, but also options to evaluate the consequences of societal choices like the acceptance of nuclear power or carbon capture and storage. Few of those assumptions are based on first principles or physical laws, and some appear questionable, e.g., the perfect foresight and cooperation, where every actor possesses all information and is cooperating in the interest of a common goal (see Stern (2013) for a critical discussion). A solution in IAMs is found through optimization, e.g., by minimizing a particular cost function or maximizing discounted welfare over time (Stanton et al. 2009) to determine cost-optimal pathways. Expressing everything in monetary terms is also problematic, as some aspects of life may have a value but no price. Still, such models give an indication of how emissions should be allocated to minimize cost, given technological and societal constraints. One ethical component appears in the discount rate. High discount rates imply larger emissions in the next few decades, leaving future risks of unproven technology or high cost to future generations. This is a question of intergenerational equity, but for a fixed carbon budget the trivial fact 12 is that higher emissions early on imply stronger reductions later on. Delay in mitigation not only reduces the allowed emission quota for future generations. It also reduces mitigation options available later (through lock-in of infrastructure), puts a greater burden on future generations in terms of costs and societal transformation, and increases the risk of failing the climate target if assumptions in technology or cost turn out to be incorrect or inacceptable (Rogelj et al. 2013a):

Burden sharing approaches provide ways to distribute emission allowances over time, and over countries and regions. We do not provide an extensive review (see Bodansky et al. 2004; den Elzen et al. 1999; Ringius et al. 2002), but simply present three illustrative approaches for fixed cumulative emissions of carbon: (1) limiting per capita emissions below a given threshold, (2) assuring that all countries have equal cumulative per capita emissions over time, and (3) burden sharing based on a responsibility-capacity indicator. Limiting per capita emissions below a given threshold assumes that per capita emissions of developing countries will never exceed the average per capita emissions of developed countries. Such a proposal was announced by India's Prime Minister at the Delhi Summit on Sustainable Development in 2008. Equal cumulative per capita emissions implies that over a given time period the sum of annual per capita emissions is equal between countries, and was suggested by China and other developing countries at the international climate talks in 2008. For the responsibility-capacity indicator, allowed emissions are distributed based on a country's level of current emissions and capacity in terms of a country's GDP over time. Details for these approaches and underlying data are given by Füssler et al. (2012).

Figure 4 shows that for all illustrative burden sharing approaches to meeting a 2 °C target, global carbon emissions need to be much lower than projected in absence of climate policy,

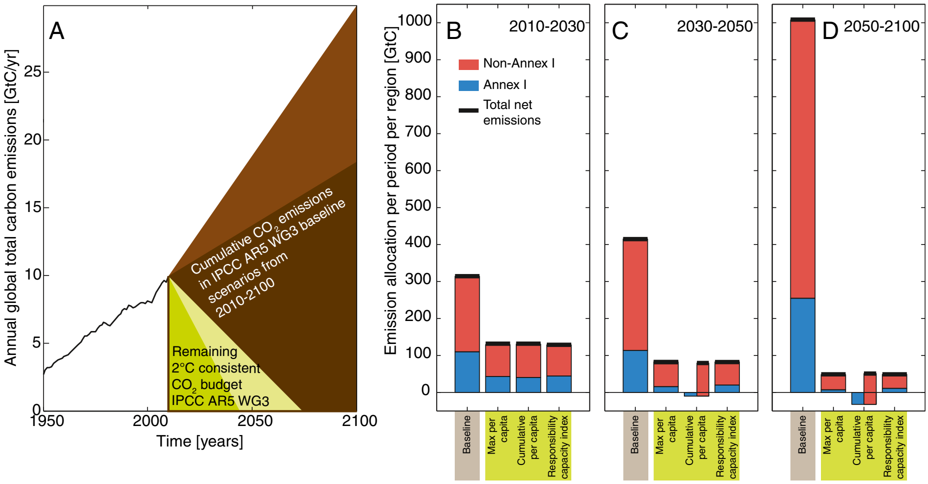

Fig. 4 Remaining carbon budgets in line with limiting warming to below 2 °C versus baseline scenarios without mitigation. (**a**) Historical carbon emissions (*black line*) and carbon emission budgets projected for the remainder of the 21st century without climate mitigation (baseline scenarios, *brown*) and with climate mitigation (*green*). The brown area indicates the size of the cumulative emissions for the baseline scenarios, the different brown shadings mark the uncertainty. The green area indicates the size of the cumulative emissions for limiting warming to below 2 °C with a *likely* chance, the different green shadings mark the uncertainty. Values are derived from IPCC (2014). Warming is determined by the time integral of emissions (*green*, *brown*) and idealized linear increase/decrease cases are shown for illustration only. (**b**, **c**, **d**) Distribution between developed (Annex I, *blue*) and developing countries (non-Annex I, *red*, total marked by black thick line) of emissions between 2010–2030, 2030–2050, and 2050–2100, respectively, in the baseline (*left bar*) and three illustrative burden sharing approaches (other bars)

already in the coming two decades. This difference further increases over the course of the century. Regional contributions show large differences. Under an "equal per capita emissions" approach, the emission allocations for developed countries diminish very quickly and can become negative before 2050. Negative emission imply that this region overall removes more CO_2 from the atmosphere than it emits or buys emission allowances from developing countries, thereby providing financing for emission reductions in developing countries.

So far, we only discussed how to share the mitigation burden. But the impacts of climate change will also be highly heterogeneous in space and time. A critical question is thus how we value the far future. Standard economic theory discounts the future at several percent per year, rendering everything beyond about 50 years irrelevant from a cost perspective. Discount rates reflect judgments about how we value the current benefits of cheap fossil fuels against the damages resulting from it centuries in the future (Gollier 2010). This debate is at the heart of climate policy. The social cost of carbon (the estimated welfare cost of emitting one additional ton of CO_2) differs by more than a factor of ten between studies (Heal and Millner 2014). This reflects the ethical challenge of monetizing impacts. Fact 13 is that there are uncertainties in long-term climate change, climate impacts and their monetization, but when estimating costs, the choice of discount rates is often the dominant one (Heal and Millner 2014; Tomassini et al. 2010). Climate change from past emissions persists and continues for centuries; yet standard economic thinking largely discounts these long-term effects. The more we value the far future, the larger the damage (aggregated over time) and the more obvious the need for mitigation is, as opposed to ignoring the problem. Defining a fair share of CO_2 based on past emissions is already difficult, but defining a fair burden sharing scheme that additionally takes into account local climate change, impacts, vulnerability, and adaptive capacity is even harder.

7 A super wicked problem?

A few more difficulties are worth mentioning without a detailed discussion. Some of those have led Lazarus (2009) to label climate change as a "super wicked problem". First, impacts are unlikely to be linear in temperature, and may be abrupt for certain ecosystems, or depend on the rate of change. In fact, even climate change itself may exhibit threshold behaviour in certain regions and climate components. How to consider those uncertainties to pick a 'safe' temperature target is unclear. The implication is that impacts are not proportional to cumulative emissions. However, this does not invalidate the use of cumulative emissions for burden sharing, as the contributions of countries to the impacts still are proportional to their respective emissions.

Second, in case we fail to agree and efficiently mitigate climate change, a set of 'technical fixes' have been proposed that could reduce climate impacts in a 'climate emergency'. These geoengineering options include Carbon Dioxide Removal (CDR), the active removal of anthropogenic CO_2, e.g., through growing biomass (plants), burning them, capturing the CO_2 and sequestering it underground. The second category of geoengineering is Solar Radiation Management (SRM), the reduction of incoming net solar radiation to cool the planet. Fact 14 is that beyond technical and financial challenges, many issues with burden sharing for mitigation apply also for geoengineering: in particular, some will benefit and others will suffer. A global institution would ideally make an extremely complex, timely, lawful, authoritative decision that would be respected and obeyed by all parties, but of course, such decisions could also be made by individual countries without a global agreement.

A weaker form of the above is the use of 'negative CO_2 emissions', a moderate form of CDR. For low temperature targets, many IAMs rely on Carbon Capture and Storage (CCS), often combined with bioenergy. While CCS is technically possible, it is currently only used on a small scale, the technology is expensive, energy intensive, and social acceptance is unclear. Bioenergy can compete with food production. Many scenarios compatible with the 2 °C target assume net negative CO_2 emissions (i.e., removal by CCS exceeding emissions) before 2100. Further delaying mitigation while keeping the same climate target implies relying more on CCS, and puts the burden on future generations to fix where we have failed to act.

Third, there is some flexibility in how CO_2 is traded against reductions of other gases. Stronger reduction in non-CO_2 forcing increases the CO_2 budget somewhat. However, non-CO_2 and CO_2 emissions are partly coupled. Reduction of non-CO_2 will be an important element of mitigation, but focusing only on these misses the importance of the long-term commitment from CO_2 (Rogelj et al. 2014b).

Fourth, the discussion about uncertainty can be carried *ad absurdum*. Weitzman (2009) argued that the expected damage from climate change is infinite, essentially because the distribution of climate sensitivity (characterizing the climate response to CO_2) has a fat (polynomial) tail, such that the damage cost grows more quickly (e.g., exponential) with temperature than the probability for such temperature approaches zero (polynomial). The consequence would be to allocate all resources to the tiny possibility of a catastrophe. The debate highlights the difficulty of how to deal with uncertainties. If climate sensitivity is high, a 2 °C target without overshoot may already be unachievable from an economic and technological point of view (Rogelj et al. 2013b). The argument for 'wait and see' strategies is to wait until we know enough to optimally allocate money. That works in situations where corrective action can be implemented quickly and has an immediate benefit, but neither is the case here (Sterman 2011). When we know more about the magnitude of climate impacts, it will likely be too late to prevent them. Uncertainty is often presented as an argument to defer action, but here 'wait and see' is essentially a (small) hope that we will be lucky, and the risk of being unlucky is put on the shoulders of future generations.

Finally, climate change is highly intertwined with other challenges that humanity is facing: sustainable development, urbanization, access to water, food and energy, migration, resource use, poverty and wealth disparity, to name a few.

8 Conclusions

Humans have difficulties grasping risks that they have never been exposed to, and that lie far in the future. We have developed in small communities with direct interaction, adapted to focus on well-known and immediate needs and threats (like getting food or hiding from predators), and are used to close cause-effect relationships (Pahl et al. 2014). Now we face a highly complex and interlinked commons problem that requires global cooperation, long-term planning, and investments today for benefits in the future. With the added dimension of uncertainty in climate change, impacts, adaptation, technology and societal responses, one may argue that the problem is intractable. But just because of those uncertainties, we argue that the issue requires our attention. There is a small chance that the threats from climate change are much smaller than we believe (Rogelj et al. 2014a), but there is at least an equal chance that things are worse. Uncertainty is not our friend, and there is simply too much at stake for us to resign and accept failure. Science cannot determine what is right from an ethics point of view. If it could, then there would be no room for politics and democracy. Nevertheless, natural science can help working towards a shared scientific understanding by stating facts, as highlighted above for the global carbon budget. While these facts do not imply that allocating emissions to countries is a necessary consequence for policy, they do stress that the actual amount of carbon emissions countries are responsible for (and the reduction thereof) is the only robust yardstick by which the long-term effectiveness of climate protection policies should be measured. Social science needs to point out where ethical and moral choices are required, and what a desirable world for future generations might look like. In our view, the greatest challenges to overcome may well be of a societal and political rather than technical and financial nature.

References

Allen MR, Frame DJ, Huntingford C, Jones CD, Lowe JA, Meinshausen M, Meinshausen N (2009a) Warming caused by cumulative carbon emissions towards the trillionth tonne. Nature 458:1163–1166

Allen MR, Frame DJ, Mason CF (2009b) The case for mandatory sequestration. Nat Geosci 2:813–814

Baer P (2002) Equity, greenhouse gas emissions, and global common resources. In: Schneider SH, Rosencranz A, Niles JO (eds) Climate change policy: a survey. Island Press, Washington

Bodansky D, Chou S, Jorge-Tresolini C (2004) International climate efforts beyond 2012: a survey of approaches. in Bodansky D (ed.) PEW Center on Global Climate Change, pp. 1–70

Church JA et al (2011) Revisiting the Earth's sea-level and energy budgets from 1961 to 2008. Geophys Res Lett 38:L18601

Davis S, Caldeira K, Matthews H (2010) Future CO_2 emissions and climate change from existing energy infrastructure. Science 329:1330–1333 den Elzen M, Berk M, Schaeffer M, Olivier J, Hendriks C, Metz B (1999) The Brazilian Proposal and other options for international burden sharing: an evaluation of methodological and policy aspects using the FAIR model. Rijksinstituut voor Volksgezondheid en Milieu RIVM, DGM, NOP, pp. 1–140

Friedlingstein P, Solomon S, Plattner G, Knutti R, Ciais P, Raupach M (2011) Long-term climate implications of twenty-first century options for carbon dioxide emission mitigation. Nat Clim Chang 1:457–461

Friedlingstein P et al (2014) Persistent growth of CO2 emissions and implications for reaching climate targets. Nat Geosci 7:709–715

Friman M, Strandberg G (2014) Historical responsibility for climate change: science and the science-policy interface. Wiley Interdiscip Rev Clim Chang 5:297–316

Frölicher TL, Winton M, Sarmiento JL (2014) Continued global warming after CO_2 emissions stoppage. Nat Clim Chang 4:40–44

Füssler J, Herren M, Guyer M, Rogelj J, Knutti R (2012) Emission pathways to reach 2°C target. Report by INFRAS and IAC ETH commissioned by the Swiss Federal Office for the Environment

Gillett NP, Arora VK, Zickfeld K, Marshall SJ, Merryfield AJ (2011) Ongoing climate change following a complete cessation of carbon dioxide emissions. Nat Geosci 4:83–87

Gillett NP, Arora VK, Matthews D, Allen MR (2013) Constraining the ratio of global warming to cumulative CO_2 emissions using CMIP5 simulations. J Clim 26:6844–6858

Gollier C (2010) Debating about the discount rate: the basic economic ingredients. Perspekt Wirtsch 11:38–55

Gregory JM, Jones CD, Cadule P, Friedlingstein P (2009) Quantifying carbon cycle feedbacks. J Clim 22:5232–5250

Heal GM, Millner A (2014) Agreeing to disagree on climate policy. Proc Natl Acad Sci U S A 111:3695–3698

Huber M, Knutti R (2012) Anthropogenic and natural warming inferred from changes in Earth's energy balance. Nat Geosci 5:31–36

IPCC (2013a) Climate change 2013: the physical science basis. Contribution of working group I to the fifth assessment report of the intergovernmental panel on climate change. Cambridge University Press, Cambridge

IPCC (2013b) Summary for policymakers. In: Stocker TF, Qin D, Plattner G-K, Tignor M, Allen SK, Boschung J, Nauels A, Xia Y, Bex V, Midgley PM (eds) Climate change 2013: the physical science basis. Contribution of working group I to the fifth assessment report of the intergovernmental panel on climate change. Cambridge University Press, Cambridge

IPCC (2014) Climate change 2014: mitigation of climate change. Contribution of working group III to the fifth assessment report of the intergovernmental panel on climate change. Cambridge University Press, Cambridge

Joos F et al (2013) Carbon dioxide and climate impulse response functions for the computation of greenhouse gas metrics: a multi-model analysis. Atmos Chem Phys 13:2793–2825

Knutti R, Hegerl GC (2008) The equilibrium sensitivity of the Earth's temperature to radiation changes. Nat Geosci 1:735–743

Lazarus RJ (2009) Super wicked problems and climate change: restraining the present to liberate the future. Cornell Law Rev 94:1153–1233

Matthews H, Caldeira K (2008) Stabilizing climate requires near-zero emissions. Geophys Res Lett 35:L04705

Matthews HD, Solomon S (2013) Irreversible does not mean unavoidable. Science 340:438–439

Matthews H, Gillett N, Stott P, Zickfeld K (2009) The proportionality of global warming to cumulative carbon emissions. Nature 459:829–832

Matthews HD, Solomon S, Pierrehumbert R (2012) Cumulative carbon as a policy framework for achieving climate stabilization. Phil Trans R Soc A 370:4365–4379

Matthews HD, Graham TL, Keverian S, Lamontagne C, Seto D, Smith TJ (2014) National contributions to observed global warming. Environ Res Lett 9:014010

Meehl GA et al (2005) How much more global warming and sea level rise? Science 307:1769–1772

Meinshausen M et al (2009) Greenhouse-gas emission targets for limiting global warming to 2°C. Nature 458: 1158–1162

Meinshausen M, Raper S, Wigley T (2011a) Emulating coupled atmosphere–ocean and carbon cycle models with a simpler model, MAGICC6-Part 1: model description and calibration. Atmos Chem Phys 11:1417–1456

Meinshausen M, Wigley T, Raper S (2011b) Emulating atmosphere–ocean and carbon cycle models with a simpler model, MAGICC6-Part 2: applications. Atmos Chem Phys 11:1457–1471

Pahl S, Sheppard S, Boomsma C, Groves C (2014) Perceptions of time in relation to climate change. Wiley Interdiscip Rev Clim Chang 5:375–388

Plattner G-K et al (2008) Long-term climate commitments projected with climate-carbon cycle models. J Clim 21:2721–2751

Prins G et al (2010) The Hartwell paper: a new direction for climate policy after the crash of 2009. Institute for science, innovation & society, University of Oxford. LSE Mackinder Programme, London School of Economics and Political Science, London

Ringius L, Torvanger A, Underdal A (2002) Burden sharing and fairness principles in international climate policy. Int Environ Agree: Polit, Law Econ 2:1–22

Rogelj J, McCollum DL, O'Neill BC, Riahi K (2013a) 2020 emissions levels required to limit warming to below 2°C. Nat Clim Chang 3:405–412

Rogelj J, McCollum DL, Reisinger A, Meinshausen M, Riahi K (2013b) Probabilistic cost estimates for climate change mitigation. Nature 493:79–83

Rogelj J, Meinshausen M, Sedlacek J, Knutti R (2014a) Implications of potentially lower climate sensitivity on climate projections and policy. Environ Res Lett 9:031003

Rogelj J et al (2014b) Disentangling the effects of CO_2 and short-lived climate forcer mitigation. Proc Natl Acad Sci U S A 111:16325–16330

Rogner H-H et al (2012) Chapter 7 - energy resources and potentials. Global energy assessment - toward a sustainable future. Cambridge University Press, Cambridge, pp 423–512

Solomon S, Plattner G, Knutti R, Friedlingstein P (2009) Irreversible climate change due to carbon dioxide emissions. Proc Natl Acad Sci U S A 106:1704–1709

Solomon S, Daniel J, Sanford T, Murphy D, Plattner G, Knutti R, Friedlingstein P (2010) Persistence of climate changes due to a range of greenhouse gases. Proc Natl Acad Sci U S A 107:18354–18359

Stanton EA, Ackerman F, Kartha S (2009) Inside the integrated assessment models: four issues in climate economics. Clim Dev 1:166–184

Sterman JD (2011) Communicating climate change risks in a skeptical world. Clim Chang 108:811–826

Stern N (2013) The structure of economic modeling of the potential impacts of climate change: grafting gross underestimation of risk onto already narrow science models. J Econ Lit 51:838–859

Tomassini L, Knutti R, Plattner GK, van Vuuren DP, Stocker TF, Howarth RB, Borsuk ME (2010) Uncertainty and risk in climate projections for the 21st century: comparing mitigation to non-intervention scenarios. Clim Chang 103:399–422

UNFCCC (1992) United Nations Framework Convention on Climate Change. 1–25

UNFCCC (2010) FCCC/CP/2010/7/Add.1 Decision 1/CP.16 - The Cancun Agreements: Outcome of the work of the Ad Hoc Working Group on Long-term Cooperative Action under the Convention. 31

Weitzman ML (2009) On modeling and interpreting the economics of catastrophic climate change. Rev Econ Stat 91:1–19

Zickfeld K, Arora VK, Gillett NP (2012) Is the climate response to CO_2 emissions path dependent? Geophys Res Lett 39:L05703

Zickfeld K et al (2013) Long-term climate change commitment and reversibility: an EMIC intercomparison. J Clim 26:5782–5809