tries, and the stabilisation of emissions transfer when averaged over Annex B countries during the past decade. In 2013, the biggest emitters from a consumption perspective were China (23 % of the global total), USA (16 %), EU28 (12 %), and India (6 %).

Based on fire activity, the global CO_2 emissions from land-use change are estimated as 1.1 ± 0.5 GtC in 2014, similar to the 2005–2014 average of $0.9 \pm 0.5\,\mathrm{GtC\,yr^{-1}}$ and the DGVM estimate for 2014 of $1.4 \pm 0.5\,\mathrm{GtC\,yr^{-1}}$. However, the estimated annual variability is not generally consistent between methods, except that all methods estimate that variability in E_{LUC} is small relative to the variability from S_{LAND} (Fig. 6a). This could be partly due to the design of the DGVM experiments, which use flux differences between simulations with and without land-cover change, and thus may overestimate variability, e.g. due to fires in forest regions where the contemporary forest cover is smaller than pre-industrial cover used in the "without land-cover-change" runs. The extrapolated land-cover input data for 2013–2014 in the DGVM may also explain part of the discrepancy.

3.2.2 Partitioning

The atmospheric CO_2 growth rate was 3.9 ± 0.2 GtC in 2014 (1.83 ± 0.09 ppm; Fig. 4; Dlugokencky and Tans, 2015). This is below the 2005–2014 average of $4.4 \pm 0.1\,\mathrm{GtC\,yr^{-1}}$, though the interannual variability in atmospheric growth rate is large.

The ocean CO_2 sink was $2.9 \pm 0.5\,\mathrm{GtC\,yr^{-1}}$ in 2014, an increase of $0.1\,\mathrm{GtC\,yr^{-1}}$ over 2013 according to ocean models. Seven of the eight ocean models produce an increase in the ocean CO_2 sink in 2014 compared to 2013, with the last model producing a very small reduction. However, of the two data products available over that period, Rödenbeck et al. (2014) produce a decrease of $-0.1\,\mathrm{GtC\,yr^{-1}}$, while Landschützer et al. (2015) produce an increase of $0.2\,\mathrm{GtC\,yr^{-1}}$. Thus there is no overall consistency in the annual change in the ocean CO_2 sink, although there is an indication of increasing convergence among products for the assessment of multi-year changes, as suggested by the time-series correlations reported in Sect. 2.4.3 (see also Landschützer et al., 2015). A small increase in the ocean CO_2 sink in 2014 would be consistent with the observed El Niño neutral conditions and continued rising atmospheric CO_2. All estimates suggest an ocean CO_2 sink for 2014 that is larger than the 2005–2014 average of $2.6 \pm 0.5\,\mathrm{GtC\,yr^{-1}}$.

The terrestrial CO_2 sink calculated as the residual from the carbon budget was 4.1 ± 0.9 GtC in 2014, 1.1 GtC higher than the $3.0 \pm 0.8\,\mathrm{GtC\,yr^{-1}}$ averaged over 2005–2014 (Fig. 4). This is among the largest S_{LAND} calculated since 1959, equal to year 2011 (Poulter et al., 2014) and 2011. In contrast to 2011, when La Niña conditions prevailed, and 1991, when the Pinatubo eruption occurred, the large S_{LAND} in 2014 occurred under neutral El Niño conditions. The DGVM mean produced a sink of 3.6 ± 0.9 GtC in 2014, $0.7\,\mathrm{GtC\,yr^{-1}}$ over the 2005–2014 average (Table 7), smaller but still consistent with observations (Poulter et al., 2014). In the DGVM ensemble, 2014 is the fifth largest S_{LAND}, after 1974, 2011, 2004, and 2000. There is no agreement between models and inversions on the regional origin of the 2014 flux anomaly (Fig. 8).

Cumulative emissions for 1870–2014 were 400 ± 20 GtC for E_{FF}, and 145 ± 50 GtC for E_{LUC} based on the bookkeeping method of Houghton et al. (2012) for 1870–1996 and a combination with fire-based emissions for 1997–2014 as described in Sect. 2.2 (Table 10). The cumulative emissions are rounded to the nearest 5 GtC. The total cumulative emissions for 1870–2014 are 545 ± 55 GtC. These emissions were partitioned among the atmosphere (230 ± 5 GtC based on atmospheric measurements in ice cores of 288 ppm (Sect. "Global atmospheric CO_2 growth rate estimates"; Joos and Spahni, 2008) and recent direct measurements of 397.2 ppm; Dlugokencky and Tans, 2014), ocean (155 ± 20 GtC using Khatiwala et al., 2013, prior to 1959 and Table 8 otherwise), and land (160 ± 60 GtC by the difference).

Cumulative emissions for the early period 1750–1869 were 3 GtC for E_{FF}, and about 45 GtC for E_{LUC} (rounded to nearest 5), of which 10 GtC were emitted in the period 1850–1870 (Houghton et al., 2012) and 30 GtC were emitted in the period 1750–1850 based on the average of four publications (22 GtC by Pongratz et al., 2009; 15 GtC by van Minnen et al., 2009; 64 GtC by Shevliakova et al., 2009; and 24 GtC by Zaehle et al., 2011). The growth in atmospheric CO_2 during that time was about 25 GtC, and the ocean uptake about 20 GtC, implying a land uptake of 5 GtC. These numbers have large relative uncertainties but balance within the limits of our understanding.

Cumulative emissions for 1750–2014 based on the sum of the two periods above (before rounding to the nearest 5 GtC) were 405 ± 20 GtC for E_{FF}, and 190 ± 65 GtC for E_{LUC}, for a total of 590 ± 70 GtC, partitioned among the atmosphere (255 ± 5 GtC), ocean (170 ± 20 GtC), and land (165 ± 70 GtC).

Cumulative emissions through to year 2015 can be estimated based on the 2015 projections of E_{FF} (Sect. 3.2), the largest contributor, and assuming a constant E_{LUC} of 0.9 GtC. For 1870–2015, these are 555 ± 55 GtC ($2040 \pm 200\,\mathrm{GtCO_2}$) for total emissions, with about 75 % contribution from E_{FF} (410 ± 20 GtC) and about 25 % contribution from E_{LUC} (145 ± 50 GtC). Cumulative emissions since year 1870 are higher than the emissions of 515 [445 to 585] GtC reported by the IPCC (Stocker et al., 2013) because they include an additional 43 GtC from emissions in 2012–2015 (mostly from E_{FF}). The uncertainty presented here ($\pm 1\sigma$) is smaller than the range of 90 % used by IPCC, but both estimates overlap within their uncertainty ranges.

Table 10. Cumulative CO_2 emissions for the periods 1750–2014, 1870–2014, and 1870–2015 in gigatonnes of carbon (GtC). We also provide the 1850–2005 time period used in a number of model evaluation publications. All uncertainties are reported as $\pm 1\sigma$. All values are rounded to the nearest 5 GtC as in Stocker et al. (2013), reflecting the limits of our capacity to constrain cumulative estimates. Thus some columns will not exactly balance because of rounding errors.

Units of GtC	1750–2014	1850–2005	1870–2014	1870–2015
Emissions				
Fossil fuels and industry (E_{FF})	405 ± 20	320 ± 15	400 ± 20	$410 \pm 20^*$
Land-use-change emissions (E_{LUC})	190 ± 65	150 ± 55	145 ± 50	$145 \pm 50^*$
Total emissions	590 ± 70	470 ± 55	545 ± 55	$555 \pm 55^*$
Partitioning				
Atmospheric growth rate (G_{ATM})	255 ± 5	195 ± 5	230 ± 5	
Ocean sink (S_{OCEAN})	170 ± 20	160 ± 20	155 ± 20	
Residual terrestrial sink (S_{LAND})	165 ± 70	115 ± 60	160 ± 60	

* The extension to year 2015 uses the emissions projections for fossil fuels and industry for 2015 of 9.7 GtC (Sect. 3.2) and assumes a constant E_{LUC} flux (Sect. 2.2).

4 Discussion

Each year when the global carbon budget is published, each component for all previous years is updated to take into account corrections that are the result of further scrutiny and verification of the underlying data in the primary input data sets. The updates have generally been relatively small and focused on the most recent years, except for land-use change, where they are more significant but still generally within the provided uncertainty range (Fig. 9). The difficulty in accessing land-cover-change data to estimate E_{LUC} is the key problem to providing continuous records of emissions in this sector. Current FAO estimates are based on statistics reported at the country level and are not spatially explicit. Advances in satellite recovery of land-cover change could help to keep track of land-use change through time (Achard et al., 2014; Harris et al., 2012). Revisions in E_{LUC} for the 2008/2009 budget were the result of the release of FAO (2010), which contained a major update to forest-cover change for the period 2000–2005 and provided the data for the following 5 years to 2010 (Fig. 9b). The differences this year could be attributable to both the different data and the different methods. Updates to values for any given year in each component of the global carbon budget were highest at $0.82\,GtC\,yr^{-1}$ for the atmospheric growth rate (from a correction to year 1979), $0.24\,GtC\,yr^{-1}$ for fossil fuels and industry, and $0.52\,GtC\,yr^{-1}$ for the ocean CO_2 sink (from a change from one to multiple models; Fig. 9). The update for the residual land CO_2 sink was also large (Fig. 9e), with a maximum value of $0.83\,GtC\,yr^{-1}$, directly reflecting revisions in other terms of the budget.

Our capacity to separate the carbon budget components can be evaluated by comparing the land CO_2 sink estimated through two approaches: (1) the budget residual (S_{LAND}), which includes errors and biases from all components, and (2) the land CO_2 sink estimate by the DGVM ensemble, which is based on our understanding of processes of how the land responds to increasing CO_2, climate, and variability. Furthermore, the inverse model estimates which formally merge observational constraints with process-based models to close the global budget can provide constraints on the total land flux. These estimates are generally close (Fig. 6), both for the mean and for the interannual variability. The annual estimates from the DGVM over 1959 to 2014 correlate with the annual budget residual with $r = 0.71$ (Sect. 2.5.2; Fig. 6). The DGVMs produce a decadal mean and standard deviation across models of $3.0 \pm 0.4\,GtC\,yr^{-1}$ for the period 2005–2014, fully consistent with the estimate of $3.0 \pm 0.8\,GtC\,yr^{-1}$ produced with the budget residual (Table 7). New insights into total surface fluxes arise from the comparison with the atmospheric inversions, and their regional breakdown already provides a semi-independent way to validate the results. The comparison shows a first-order consistency between inversions and process models but with a lot of discrepancies, particularly for the allocation of the mean land sink between the tropics and the Northern Hemisphere. Understanding these discrepancies and further analysis of regional carbon budgets would provide additional information to quantify and improve our estimates, as has been undertaken by the project REgional Carbon Cycle Assessment and Processes (RECCAP; Canadell et al., 2012–2013).

Annual estimates of each component of the global carbon budgets have their limitations, some of which could be improved with better data and/or better understanding of carbon dynamics. The primary limitations involve resolving fluxes on annual timescales and providing updated estimates for recent years for which data-based estimates are not yet available or only beginning to emerge. Of the various terms in the global budget, only the burning of fossil fuels and atmospheric growth rate terms are based primarily on empirical inputs supporting annual estimates in this carbon budget. The data on fossil fuels and industry are based on sur-

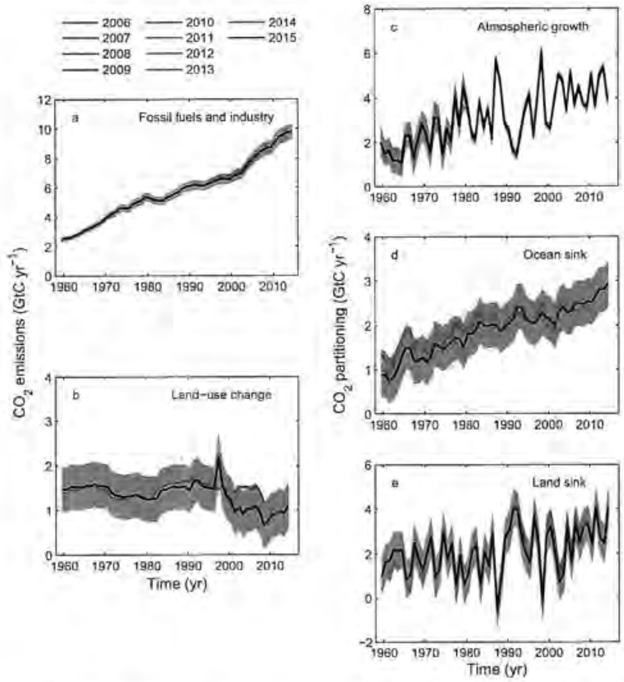

Figure 9. Comparison of global carbon budget components released annually by GCP since 2006. CO$_2$ emissions from both **(a)** fossil fuels and industry (E_{FF}) and **(b)** land-use change (E_{LUC}), as well as their partitioning among **(c)** the atmosphere (G_{ATM}), **(d)** the ocean (S_{OCEAN}), and **(e)** the land (S_{LAND}). See legend for the corresponding years, with the 2006 carbon budget from Raupach et al. (2007), 2007 from Canadell et al. (2007), 2008 released online only, 2009 from Le Quéré et al. (2009), 2010 from Friedlingstein et al. (2010), 2011 from Peters et al. (2012b), 2012 from Le Quéré et al. (2013), 2013 from Le Quéré et al. (2014), and 2014 from Le Quéré et al. (2015) and this year's budget (2015; this study). The budget year generally corresponds to the year when the budget was first released. All values are in GtC yr^{-1}.

vey data in all countries. The other terms can be provided on an annual basis only through the use of models. While these models represent the current state of the art, they provide only simulated changes in primary carbon budget components. For example, the decadal trends in global ocean uptake and the interannual variations associated with El Niño–Southern Oscillation (i.e. ENSO) are not directly constrained by observations, although many of the processes controlling these trends are sufficiently well known that the model-based trends still have value as benchmarks for further validation. Data-based products for the ocean CO$_2$ sink provide new ways to evaluate the model results, and could be used directly as data become more rapidly available and methods for creating such products improve. However, there are still large discrepancies among data-based estimates, in large part due to the lack of routine data sampling, that preclude their direct use for now (see Rödenbeck et al., 2015). Estimates of land-use-change emissions and their year-to-year variability have even larger uncertainty, and many of the underlying data are not available as an annual update. Efforts are underway to work with annually available satellite area change data or FAO-reported data in combination with fire data and modelling to provide annual updates for future budgets. The best resolved changes are in atmospheric growth (G_{ATM}), fossil fuel emissions (E_{FF}), and, by difference, the change in the sum of the remaining terms ($S_{OCEAN} + S_{LAND} - E_{LUC}$). The variations from year-to-year in these remaining terms are largely model-based at this time. Further efforts to increase the availability and use of annual data for estimating the remaining terms with annual to decadal resolution are especially needed.

Our approach also depends on the reliability of the energy and land-cover-change statistics provided at the country level, and are thus potentially subject to biases. Thus it is critical to develop multiple ways to estimate the carbon balance at the global and regional level, including estimates from the inversion of atmospheric CO$_2$ concentration, the use of other oceanic and atmospheric tracers, and the compilation of emissions using alternative statistics (e.g. sectors). It is also important to challenge the consistency of information across observational streams, for example to contrast the coherence of temperature trends with those of CO$_2$ sink trends. Multiple approaches ranging from global to regional scale would greatly help increase confidence and reduce uncertainty in CO$_2$ emissions and their fate.

5 Conclusions

The estimation of global CO$_2$ emissions and sinks is a major effort by the carbon cycle research community that requires a combination of measurements and compilation of statistical estimates and results from models. The delivery of an annual carbon budget serves two purposes. First, there is a large demand for up-to-date information on the state of the anthropogenic perturbation of the climate system and its underpinning causes. A broad stakeholder community relies on the data sets associated with the annual carbon budget including scientists, policy makers, businesses, journalists, and the broader society increasingly engaged in adapting to and mitigating human-driven climate change. Second, over the last decade we have seen unprecedented changes in the human and biophysical environments (e.g. increase in the growth of fossil fuel emissions, ocean temperatures, and strength of the land sink), which call for more frequent assessments of the state of the planet, and by implications a better understanding of the future evolution of the carbon cycle, as well as the requirements for climate change mitigation and adaptation. Both the ocean and the land surface presently remove a large fraction of anthropogenic emissions. Any significant change in the function of carbon sinks is of great importance to climate policymaking, as they affect the excess carbon dioxide remaining in the atmosphere and therefore the compatible emissions for any climate stabilisation target. Better constraints of carbon cycle models against contemporary data sets raise the capacity for the models to become more accurate at future projections.

This all requires more frequent, robust, and transparent data sets and methods that can be scrutinised and replicated. After 10 annual releases from the GCP, the effort is growing and the traceability of the methods has become increasingly complex. Here, we have documented in detail the data sets and methods used to compile the annual updates of the global carbon budget, explained the rationale for the choices made, the limitations of the information, and finally highlighted the need for additional information where gaps exist.

This paper will help, via "living data", to keep track of new budget updates. The evolution over time of the carbon budget is now a key indicator of the anthropogenic perturbation of the climate system, and its annual delivery joins a set of other climate indicators to monitor the evolution of human-induced climate change, such as the annual updates on the global surface temperature, sea level rise, and minimum Arctic sea ice extent.

Appendix A

Table A1. Attribution of fCO_2 measurements for years 2013–2014 used in addition to SOCAT v3 (Bakker et al., 2014, 2015) to inform ocean data products.

Vessel	Start date yyyy-mm-dd	End date yyyy-mm-dd	Regions	No. of samples	Principal Investigators	DOI (if available)/comment
Atlantic Companion	2014-02-21	2014-02-26	North Atlantic	2462	Steinhoff, T., M. Becker and A. Körtzinger	
Atlantic Companion	2014-04-26	2014-05-02	North Atlantic	3036	Steinhoff, T., M. Becker and A. Körtzinger	
Atlantic Companion	2014-05-31	2014-06-04	North Atlantic	2365	Steinhoff, T., M. Becker and A. Körtzinger	
Atlantic Companion	2014-06-16	2014-06-22	North Atlantic	6124	Steinhoff, T., M. Becker and A. Körtzinger	
Atlantic Companion	2014-08-27	2014-08-30	North Atlantic	3963	Steinhoff, T., M. Becker and A. Körtzinger	
Atlantic Companion	2014-09-28	2014-10-04	North Atlantic	7239	Steinhoff, T., M. Becker and A. Körtzinger	
Benguela Stream	2014-07-15	2014-07-20	North Atlantic	4523	Schuster, U.	
Benguela Stream	2013-12-28	2014-01-05	North Atlantic, Tropical Atlantic	6241	Schuster, U.	
Benguela Stream	2014-01-08	2014-01-13	North Atlantic, Tropical Atlantic	4400	Schuster, U.	
Benguela Stream	2014-02-23	2014-03-02	North Atlantic, Tropical Atlantic	6014	Schuster, U.	
Benguela Stream	2014-02-23	2014-03-02	North Atlantic, Tropical Atlantic	5612	Schuster, U.	
Benguela Stream	2014-04-18	2014-04-27	North Atlantic, Tropical Atlantic	7376	Schuster, U.	
Benguela Stream	2014-04-30	2014-05-08	North Atlantic, Tropical Atlantic	6819	Schuster, U.	
Benguela Stream	2014-05-17	2014-05-25	North Atlantic, Tropical Atlantic	6390	Schuster, U.	
Benguela Stream	2014-06-14	2014-06-21	North Atlantic, Tropical Atlantic	3397	Schuster, U.	
Benguela Stream	2014-06-25	2014-07-03	North Atlantic, Tropical Atlantic	6624	Schuster, U.	
Benguela Stream	2014-07-23	2014-07-31	North Atlantic, Tropical Atlantic	6952	Schuster, U.	
Benguela Stream	2014-11-12	2014-11-20	North Atlantic, Tropical Atlantic	5043	Schuster, U.	
Benguela Stream	2014-12-10	2014-12-19	North Atlantic, Tropical Atlantic	7046	Schuster, U.	
Benguela Stream	2014-12-10	2014-12-19	North Atlantic, Tropical Atlantic	7046	Schuster, U.	
Cap Blanche	2014-02-01	2014-02-13	Tropical Pacific, Southern Ocean	6148	Feely, R., C. Cosca, S. Alin and G. Lebon	
Cap Blanche	2014-03-27	2014-04-10	Tropical Pacific, Southern Ocean	6428	Feely, R., C. Cosca, S. Alin and G. Lebon	
Cap Blanche	2014-05-23	2014-06-05	Tropical Pacific, Southern Ocean	6016	Feely, R., C. Cosca, S. Alin and G. Lebon	
Cap Blanche	2014-07-18	2014-07-30	Tropical Pacific, Southern Ocean	5394	Feely, R., C. Cosca, S. Alin and G. Lebon	
Cap Blanche	2014-09-12	2014-09-25	Tropical Pacific, Southern Ocean	6083	Feely, R., C. Cosca, S. Alin and G. Lebon	
Cap Blanche	2014-11-13	2014-11-26	Tropical Pacific, Southern Ocean	5876	Feely, R., C. Cosca, S. Alin and G. Lebon	
Cap Vilano	2013-02-01	2013-02-13	Tropical Pacific, Southern Ocean	4709	Cosca, C., R. Feely, S. Alin and G. Lebon	
Cap Vilano	2013-03-28	2013-04-11	Tropical Pacific, Southern Ocean	5390	Cosca, C., R. Feely, S. Alin and G. Lebon	
Cap Vilano	2013-05-24	2013-06-06	Tropical Pacific, Southern Ocean	5096	Cosca, C., R. Feely, S. Alin and G. Lebon	
Colibri	2014-07-04	2014-07-15	North Atlantic, Tropical Atlantic	4853	Lefèvre, N. and D. Diverrès	
Colibri	2014-08-27	2014-09-03	North Atlantic, Tropical Atlantic	3881	Lefèvre, N., and D. Diverrès	
Colibri	2014-09-12	2014-09-23	North Atlantic, Tropical Atlantic	5940	Lefèvre, N., and D. Diverrès	
Colibri	2014-10-25	2014-11-04	North Atlantic, Tropical Atlantic	5725	Lefèvre, N. and D. Diverrès	
Colibri	2014-07-18	2014-07-19	Tropical Atlantic	313	Lefèvre, N. and D. Diverrès	
Explorer of the Seas	2013-06-25	2013-06-27	North Atlantic	672	Wanninkhof, R., D. Pierrot and L. Barbero	doi:10.3334/CDIAC/OTG.VOS_EXP2014
Explorer of the Seas	2013-07-06	2013-07-11	North Atlantic	1496	Wanninkhof, R., D. Pierrot and L. Barbero	doi:10.3334/CDIAC/OTG.VOS_EXP2014
Explorer of the Seas	2013-07-20	2013-07-25	North Atlantic	1375	Wanninkhof, R., D. Pierrot and L. Barbero	doi:10.3334/CDIAC/OTG.VOS_EXP2014

Table A1. Continued.

Vessel	Start date yyyy-mm-dd	End date yyyy-mm-dd	Regions	No. of samples	Principal Investigators	DOI (if available)/comment
Explorer of the Seas	2013-08-03	2013-08-08	North Atlantic	1436	Wanninkhof, R., D. Pierrot and L. Barbero	doi:10.3334/CDIAC/OTG.VOS_EXP2014
Explorer of the Seas	2013-08-17	2013-08-22	North Atlantic	1138	Wanninkhof, R., D. Pierrot and L. Barbero	doi:10.3334/CDIAC/OTG.VOS_EXP2014
Explorer of the Seas	2014-04-08	2014-04-09	North Atlantic	209	Wanninkhof, R., D. Pierrot and L. Barbero	doi:10.3334/CDIAC/OTG.VOS_EXP2014
Explorer of the Seas	2014-04-19	2014-04-24	North Atlantic	1424	Wanninkhof, R., D. Pierrot and L. Barbero	doi:10.3334/CDIAC/OTG.VOS_EXP2014
Explorer of the Seas	2014-05-03	2014-05-08	North Atlantic	1512	Wanninkhof, R., D. Pierrot and L. Barbero	doi:10.3334/CDIAC/OTG.VOS_EXP2014
Explorer of the Seas	2014-05-17	2014-05-22	North Atlantic	1349	Wanninkhof, R., D. Pierrot and L. Barbero	doi:10.3334/CDIAC/OTG.VOS_EXP2014
Explorer of the Seas	2014-05-31	2014-06-05	North Atlantic	1194	Wanninkhof, R., D. Pierrot and L. Barbero	doi:10.3334/CDIAC/OTG.VOS_EXP2014
Explorer of the Seas	2014-06-14	2014-06-19	North Atlantic	1142	Wanninkhof, R., D. Pierrot and L. Barbero	doi:10.3334/CDIAC/OTG.VOS_EXP2014
Explorer of the Seas	2014-06-28	2014-07-03	North Atlantic	1479	Wanninkhof, R., D. Pierrot and L. Barbero	doi:10.3334/CDIAC/OTG.VOS_EXP2014
Explorer of the Seas	2014-07-12	2014-07-17	North Atlantic	1489	Wanninkhof, R., D. Pierrot and L. Barbero	doi:10.3334/CDIAC/OTG.VOS_EXP2014
Explorer of the Seas	2014-07-26	2014-07-31	North Atlantic	1474	Wanninkhof, R., D. Pierrot and L. Barbero	doi:10.3334/CDIAC/OTG.VOS_EXP2014
Explorer of the Seas	2014-08-09	2014-08-14	North Atlantic	1468	Wanninkhof, R., D. Pierrot and L. Barbero	doi:10.3334/CDIAC/OTG.VOS_EXP2014
Explorer of the Seas	2014-08-23	2014-08-28	North Atlantic	1277	Wanninkhof, R., D. Pierrot and L. Barbero	doi:10.3334/CDIAC/OTG.VOS_EXP2014
Explorer of the Seas	2014-08-29	2014-09-06	North Atlantic	2846	Wanninkhof, R., D. Pierrot and L. Barbero	doi:10.3334/CDIAC/OTG.VOS_EXP2014
Explorer of the Seas	2014-09-06	2014-09-11	North Atlantic	1479	Wanninkhof, R., D. Pierrot and L. Barbero	doi:10.3334/CDIAC/OTG.VOS_EXP2014
Explorer of the Seas	2014-09-11	2014-09-20	North Atlantic	2956	Wanninkhof, R., D. Pierrot and L. Barbero	doi:10.3334/CDIAC/OTG.VOS_EXP2014
Explorer of the Seas	2014-09-20	2014-09-22	North Atlantic	728	Wanninkhof, R., D. Pierrot and L. Barbero	doi:10.3334/CDIAC/OTG.VOS_EXP2014
Explorer of the Seas	2014-10-04	2014-10-09	North Atlantic	1444	Wanninkhof, R., D. Pierrot and L. Barbero	doi:10.3334/CDIAC/OTG.VOS_EXP2014
Explorer of the Seas	2014-10-18	2014-10-23	North Atlantic	1504	Wanninkhof, R., D. Pierrot and L. Barbero	doi:10.3334/CDIAC/OTG.VOS_EXP2014
Explorer of the Seas	2013-04-02	2013-04-07	North Atlantic, Tropical Atlantic	1301	Wanninkhof, R., D. Pierrot and L. Barbero	doi:10.3334/CDIAC/OTG.VOS_EXP2014
Explorer of the Seas	2013-06-27	2013-07-06	North Atlantic, Tropical Atlantic	3329	Wanninkhof, R., D. Pierrot and L. Barbero	doi:10.3334/CDIAC/OTG.VOS_EXP2014
Explorer of the Seas	2013-07-11	2013-07-20	North Atlantic, Tropical Atlantic	3372	Wanninkhof, R., D. Pierrot and L. Barbero	doi:10.3334/CDIAC/OTG.VOS_EXP2014
Explorer of the Seas	2013-07-25	2013-08-03	North Atlantic, Tropical Atlantic	3350	Wanninkhof, R., D. Pierrot and L. Barbero	doi:10.3334/CDIAC/OTG.VOS_EXP2014
Explorer of the Seas	2013-08-08	2013-08-17	North Atlantic, Tropical Atlantic	3393	Wanninkhof, R., D. Pierrot and L. Barbero	doi:10.3334/CDIAC/OTG.VOS_EXP2014
Explorer of the Seas	2014-04-01	2014-04-05	North Atlantic, Tropical Atlantic	1189	Wanninkhof, R., D. Pierrot and L. Barbero	doi:10.3334/CDIAC/OTG.VOS_EXP2014
Explorer of the Seas	2014-04-10	2014-04-19	North Atlantic, Tropical Atlantic	3297	Wanninkhof, R., D. Pierrot and L. Barbero	doi:10.3334/CDIAC/OTG.VOS_EXP2014
Explorer of the Seas	2014-04-24	2014-05-03	North Atlantic, Tropical Atlantic	2968	Wanninkhof, R., D. Pierrot and L. Barbero	doi:10.3334/CDIAC/OTG.VOS_EXP2014
Explorer of the Seas	2014-05-08	2014-05-17	North Atlantic, Tropical Atlantic	3324	Wanninkhof, R., D. Pierrot and L. Barbero	doi:10.3334/CDIAC/OTG.VOS_EXP2014
Explorer of the Seas	2014-05-22	2014-05-31	North Atlantic, Tropical Atlantic	2850	Wanninkhof, R., D. Pierrot and L. Barbero	doi:10.3334/CDIAC/OTG.VOS_EXP2014
Explorer of the Seas	2014-06-05	2014-06-14	North Atlantic, Tropical Atlantic	3374	Wanninkhof, R., D. Pierrot and L. Barbero	doi:10.3334/CDIAC/OTG.VOS_EXP2014
Explorer of the Seas	2014-06-19	2014-06-28	North Atlantic, Tropical Atlantic	3386	Wanninkhof, R., D. Pierrot and L. Barbero	doi:10.3334/CDIAC/OTG.VOS_EXP2014
Explorer of the Seas	2014-07-03	2014-07-12	North Atlantic, Tropical Atlantic	3397	Wanninkhof, R., D. Pierrot and L. Barbero	doi:10.3334/CDIAC/OTG.VOS_EXP2014
Explorer of the Seas	2014-07-17	2014-07-26	North Atlantic, Tropical Atlantic	3404	Wanninkhof, R., D. Pierrot and L. Barbero	doi:10.3334/CDIAC/OTG.VOS_EXP2014
Explorer of the Seas	2014-07-31	2014-08-09	North Atlantic, Tropical Atlantic	3392	Wanninkhof, R., D. Pierrot and L. Barbero	doi:10.3334/CDIAC/OTG.VOS_EXP2014
Explorer of the Seas	2014-08-14	2014-08-23	North Atlantic, Tropical Atlantic	3307	Wanninkhof, R., D. Pierrot and L. Barbero	doi:10.3334/CDIAC/OTG.VOS_EXP2014
Explorer of the Seas	2014-09-25	2014-10-04	North Atlantic, Tropical Atlantic	2967	Wanninkhof, R., D. Pierrot and L. Barbero	doi:10.3334/CDIAC/OTG.VOS_EXP2014
Explorer of the Seas	2014-10-09	2014-10-18	North Atlantic, Tropical Atlantic	3069	Wanninkhof, R., D. Pierrot and L. Barbero	doi:10.3334/CDIAC/OTG.VOS_EXP2014

Table A1. Continued.

Vessel	Start date yyyy-mm-dd	End date yyyy-mm-dd	Regions	No. of samples	Principal Investigators	DOI (if available)/comment
Explorer of the Seas	2014-10-23	2014-11-01	North Atlantic, Tropical Atlantic	3074	Wanninkhof, R., D. Pierrot and L. Barbero	doi:10.3334/CDIAC/OTG.VOS_EXP2014
Explorer of the Seas	2014-11-01	2014-11-11	North Atlantic, Tropical Atlantic	1809	Wanninkhof, R., D. Pierrot and L. Barbero	doi:10.3334/CDIAC/OTG.VOS_EXP2014
Explorer of the Seas	2014-11-21	2014-11-24	North Atlantic, Tropical Atlantic	567	Wanninkhof, R., D. Pierrot and L. Barbero	doi:10.3334/CDIAC/OTG.VOS_EXP2014
Explorer of the Seas	2014-12-04	2014-12-13	North Atlantic, Tropical Atlantic	3773	Wanninkhof, R., D. Pierrot and L. Barbero	doi:10.3334/CDIAC/OTG.VOS_EXP2014
Explorer of the Seas	2014-12-23	2014-12-27	North Atlantic, Tropical Atlantic	1516	Wanninkhof, R., D. Pierrot and L. Barbero	doi:10.3334/CDIAC/OTG.VOS_EXP2014
Explorer of the Seas	2014-12-27	2015-01-04	North Atlantic, Tropical Atlantic	1315	Wanninkhof, R., D. Pierrot and L. Barbero	doi:10.3334/CDIAC/OTG.VOS_EXP2014
Explorer of the Seas	2014-11-25	2014-11-29	Tropical Atlantic	1653	Wanninkhof, R., D. Pierrot and L. Barbero	doi:10.3334/CDIAC/OTG.VOS_EXP2014
Explorer of the Seas	2014-11-29	2014-12-04	Tropical Atlantic	1680	Wanninkhof, R., D. Pierrot and L. Barbero	doi:10.3334/CDIAC/OTG.VOS_EXP2014
Explorer of the Seas	2014-12-14	2014-12-18	Tropical Atlantic	899	Wanninkhof, R., D. Pierrot and L. Barbero	doi:10.3334/CDIAC/OTG.VOS_EXP2014
Explorer of the Seas	2014-12-18	2014-12-23	Tropical Atlantic	1787	Wanninkhof, R., D. Pierrot and L. Barbero	doi:10.3334/CDIAC/OTG.VOS_EXP2014
Finnmaid	2012-01-13	2014-12-31	North Atlantic	22 000	Rehder, G. and M. Glockzin	
G.O. Sars	2014-07-08	2014-11-16	Arctic, North Atlantic	24 405	Lauvset, S.K. and I. Skjelvan	
Gordon Gunter	2014-02-20	2014-02-26	North Atlantic	22 000	Wanninkhof, R., D. Pierrot and L. Barbero	doi:10.3334/CDIAC/OTG.AOML_BIGELOW_ECOAST_2014
Gordon Gunter	2014-03-01	2014-03-09	North Atlantic	3742	Wanninkhof, R., D. Pierrot and L. Barbero	doi:10.3334/CDIAC/OTG.AOML_BIGELOW_ECOAST_2014
Gordon Gunter	2014-03-11	2014-04-03	North Atlantic	8189	Wanninkhof, R., D. Pierrot and L. Barbero	doi:10.3334/CDIAC/OTG.AOML_BIGELOW_ECOAST_2014
Gordon Gunter	2014-04-08	2014-04-28	North Atlantic	7753	Wanninkhof, R., D. Pierrot and L. Barbero	doi:10.3334/CDIAC/OTG.AOML_BIGELOW_ECOAST_2014
Gordon Gunter	2014-06-06	2014-06-13	North Atlantic, Tropical Atlantic	3338	Wanninkhof, R., D. Pierrot and L. Barbero	doi:10.3334/CDIAC/OTG.AOML_BIGELOW_ECOAST_2014
Gordon Gunter	2014-07-04	2014-07-16	Tropical Atlantic	5399	Wanninkhof, R., D. Pierrot and L. Barbero	doi:10.3334/CDIAC/OTG.AOML_BIGELOW_ECOAST_2014
Gordon Gunter	2014-07-21	2014-07-30	Tropical Atlantic	4074	Wanninkhof, R., D. Pierrot and L. Barbero	doi:10.3334/CDIAC/OTG.AOML_BIGELOW_ECOAST_2014
Henry B. Bigelow	2014-03-29	2014-04-04	North Atlantic	2196	Wanninkhof, R., D. Pierrot and L. Barbero	doi:10.3334/CDIAC/OTG.AOML_BIGELOW_ECOAST_2014
Henry B. Bigelow	2014-04-11	2014-04-25	North Atlantic	6651	Wanninkhof, R., D. Pierrot and L. Barbero	doi:10.3334/CDIAC/OTG.AOML_BIGELOW_ECOAST_2014
Henry B. Bigelow	2014-05-06	2014-05-16	North Atlantic	4302	Wanninkhof, R., D. Pierrot and L. Barbero	doi:10.3334/CDIAC/OTG.AOML_BIGELOW_ECOAST_2014
Henry B. Bigelow	2014-05-16	2014-05-23	North Atlantic	3233	Wanninkhof, R., D. Pierrot and L. Barbero	doi:10.3334/CDIAC/OTG.AOML_BIGELOW_ECOAST_2014
Henry B. Bigelow	2014-05-27	2014-06-01	North Atlantic	2085	Wanninkhof, R., D. Pierrot and L. Barbero	doi:10.3334/CDIAC/OTG.AOML_BIGELOW_ECOAST_2014
Henry B. Bigelow	2014-06-18	2014-07-01	North Atlantic	5458	Wanninkhof, R., D. Pierrot and L. Barbero	doi:10.3334/CDIAC/OTG.AOML_BIGELOW_ECOAST_2014
Henry B. Bigelow	2014-07-25	2014-07-30	North Atlantic	2226	Wanninkhof, R., D. Pierrot and L. Barbero	doi:10.3334/CDIAC/OTG.AOML_BIGELOW_ECOAST_2014
Henry B. Bigelow	2014-08-05	2014-08-16	North Atlantic	5231	Wanninkhof, R., D. Pierrot and L. Barbero	doi:10.3334/CDIAC/OTG.AOML_BIGELOW_ECOAST_2014
Henry B. Bigelow	2014-09-08	2014-09-19	North Atlantic	4847	Wanninkhof, R., D. Pierrot and L. Barbero	doi:10.3334/CDIAC/OTG.AOML_BIGELOW_ECOAST_2014
Henry B. Bigelow	2014-09-23	2014-10-03	North Atlantic	4620	Wanninkhof, R., D. Pierrot and L. Barbero	doi:10.3334/CDIAC/OTG.AOML_BIGELOW_ECOAST_2014
Henry B. Bigelow	2014-10-07	2014-10-23	North Atlantic	7736	Wanninkhof, R., D. Pierrot and L. Barbero	doi:10.3334/CDIAC/OTG.AOML_BIGELOW_ECOAST_2014
Henry B. Bigelow	2014-10-28	2014-11-13	North Atlantic	6615	Wanninkhof, R., D. Pierrot and L. Barbero	doi:10.3334/CDIAC/OTG.AOML_BIGELOW_ECOAST_2014
James Clark Ross	2014-03-20	2014-04-12	North Atlantic	2113	Kitidis, V. and I. Brown	
Laurence M. Gould	2012-12-31	2013-02-06	Southern Ocean	10 816	Sweeney, C., T. Takahashi, T. Newberger and D.R. Munro	accessed from CDIAC on 08/06/2015
Laurence M. Gould	2013-02-13	2013-02-24	Southern Ocean	2030	Sweeney, C., T. Takahashi, T. Newberger and D.R. Munro	accessed from CDIAC on 08/06/2015
Laurence M. Gould	2013-03-11	2013-04-07	Southern Ocean	4110	Sweeney, C., T. Takahashi, T. Newberger and D.R. Munro	accessed from CDIAC on 08/06/2015
Laurence M. Gould	2013-04-13	2013-05-05	Southern Ocean	4099	Sweeney, C., T. Takahashi, T. Newberger and D.R. Munro	accessed from CDIAC on 08/06/2015
Laurence M. Gould	2013-05-12	2013-05-24	Southern Ocean	3171	Sweeney, C., T. Takahashi, T. Newberger and D.R. Munro	accessed from CDIAC on 08/06/2015
Laurence M. Gould	2013-06-01	2013-07-05	Southern Ocean	3808	Sweeney, C., T. Takahashi, T. Newberger and D.R. Munro	accessed from CDIAC on 08/06/2015
Laurence M. Gould	2013-09-14	2013-09-26	Southern Ocean	3410	Sweeney, C., T. Takahashi, T. Newberger and D.R. Munro	accessed from CDIAC on 08/06/2015
Laurence M. Gould	2013-10-05	2013-10-22	Southern Ocean	2284	Sweeney, C., T. Takahashi, T. Newberger and D.R. Munro	accessed from CDIAC on 08/06/2015

Table A1. Continued.

Vessel	Start date yyyy-mm-dd	End date yyyy-mm-dd	Regions	No. of samples	Principal Investigators	DOI (if available)/comment
Laurence M. Gould	2013-10-28	2013-11-15	Southern Ocean	3788	Sweeney, C., T. Takahashi, T. Newberger and D.R. Munro	accessed from CDIAC on 08/06/2015
Laurence M. Gould	2013-11-23	2013-12-19	Southern Ocean	7535	Sweeney, C., T. Takahashi, T. Newberger and D.R. Munro	accessed from CDIAC on 08/06/2015
Laurence M. Gould	2014-01-01	2014-02-07	Southern Ocean	11 783	Sweeney, C., T. Takahashi, T. Newberger and D.R. Munro	
Laurence M. Gould	2014-02-14	2014-03-16	Southern Ocean	5805	Sweeney, C., T. Takahashi, T. Newberger and D.R. Munro	
Laurence M. Gould	2014-03-22	2014-04-03	Southern Ocean	1109	Sweeney, C., T. Takahashi, T. Newberger and D.R. Munro	
Laurence M. Gould	2014-04-09	2014-05-10	Southern Ocean	3170	Sweeney, C., T. Takahashi, T. Newberger and D.R. Munro	
Laurence M. Gould	2014-06-23	2014-08-21	Southern Ocean	3615	Sweeney, C., T. Takahashi, T. Newberger and D.R. Munro	
Laurence M. Gould	2014-09-14	2014-09-26	Southern Ocean	2058	Sweeney, C., T. Takahashi, T. Newberger and D.R. Munro	
Laurence M. Gould	2014-10-08	2014-10-20	Southern Ocean	1642	Sweeney, C., T. Takahashi, T. Newberger and D.R. Munro	
Laurence M. Gould	2014-10-28	2014-11-22	Southern Ocean	6921	Sweeney, C., T. Takahashi, T. Newberger and D.R. Munro	
Laurence M. Gould	2014-11-28	2014-12-20	Southern Ocean	6476	Sweeney, C., T. Takahashi, T. Newberger and D.R. Munro	
Marion Dufresne	2014-01-09	2014-02-16	Indian Ocean, Southern Ocean	7524	Metzl, N. and C. Lo Monaco	
Mirai	2012-11-28	2013-02-13	Southern Ocean	4832	Murata, A.	
Mooring	2012-08-22	2013-07-09	North Atlantic	1507	Sutton, A.	doi:10.3334/CDIAC/OTG.TSM_NH_70W_43N
Mooring	2013-10-04	2014-04-29	North Pacific	1651	Sutton, A.	doi:10.3334/CDIAC/otg.TSM_LaPush_125W_48N
Mooring	2012-11-02	2013-06-06	Tropical Pacific	1257	Sutton, A.	
Mooring	2013-06-06	2013-11-28	Tropical Pacific	1415	Sutton, A.	
New Century 2	2014-08-11	2014-09-08	North Atlantic, Tropical Atlantic, North Pacific, Tropical Pacific	2698	Nakaoka, S.	
New Century 2	2014-12-12	2015-01-12	North Atlantic, Tropical Atlantic, North Pacific, Tropical Pacific	1811	Nakaoka, S.	
New Century 2	2014-04-11	2014-04-26	North Pacific	1608	Nakaoka, S.	
New Century 2	2014-04-27	2014-05-10	North Pacific	1442	Nakaoka, S.	
New Century 2	2014-05-13	2014-05-27	North Pacific	1408	Nakaoka, S.	
New Century 2	2014-05-28	2014-06-09	North Pacific	1392	Nakaoka, S.	
New Century 2	2014-06-12	2014-06-25	North Pacific	1220	Nakaoka, S.	
New Century 2	2014-06-25	2014-07-05	North Pacific	1174	Nakaoka, S.	
New Century 2	2014-09-10	2014-09-24	North Pacific	1108	Nakaoka, S.	
New Century 2	2014-09-25	2014-10-07	North Pacific	1004	Nakaoka, S.	
New Century 2	2014-10-11	2014-10-27	North Pacific	1001	Nakaoka, S.	
New Century 2	2014-10-28	2014-11-09	North Pacific	1174	Nakaoka, S.	
New Century 2	2014-07-14	2014-08-10	North Pacific, Tropical Pacific	2167	Nakaoka, S.	
New Century 2	2014-11-14	2014-12-12	North Pacific, Tropical Pacific	2391	Nakaoka, S.	
Nuka Arctica	2014-07-07	2014-07-15	Arctic, North Atlantic	2333	Omar, A., A. Olsen and T. Johannessen	
Nuka Arctica	2014-08-27	2014-09-05	Arctic, North Atlantic	2607	Omar, A., A. Olsen and T. Johannessen	
Nuka Arctica	2014-09-08	2014-09-18	Arctic, North Atlantic	2398	Omar, A., A. Olsen and T. Johannessen	
Nuka Arctica	2014-01-06	2014-01-12	Arctic, North Atlantic	2369	Omar, A., A. Olsen and T. Johannessen	
Nuka Arctica	2014-01-14	2014-01-24	Arctic, North Atlantic	2728	Omar, A., A. Olsen and T. Johannessen	
Nuka Arctica	2014-01-24	2014-02-01	Arctic, North Atlantic	1990	Omar, A., A. Olsen and T. Johannessen	
Nuka Arctica	2014-02-04	2014-02-14	Arctic, North Atlantic	2661	Omar, A., A. Olsen and T. Johannessen	
Nuka Arctica	2014-02-15	2014-02-22	Arctic, North Atlantic	2030	Omar, A., A. Olsen and T. Johannessen	
Nuka Arctica	2014-02-26	2014-03-05	Arctic, North Atlantic	2179	Omar, A., A. Olsen and T. Johannessen	
Nuka Arctica	2014-03-07	2014-03-13	Arctic, North Atlantic	2311	Omar, A., A. Olsen and T. Johannessen	
Nuka Arctica	2014-03-18	2014-03-27	Arctic, North Atlantic	3262	Omar, A., A. Olsen and T. Johannessen	
Nuka Arctica	2014-03-29	2014-04-05	Arctic, North Atlantic	2799	Omar, A., A. Olsen and T. Johannessen	
Nuka Arctica	2014-04-09	2014-04-17	Arctic, North Atlantic	3136	Omar, A., A. Olsen and T. Johannessen	

Table A1. Continued.

Vessel	Start date yyyy-mm-dd	End date yyyy-mm-dd	Regions	No. of samples	Principal Investigators	DOI (if available)/comment
Nuka Arctica	2014-04-18	2014-04-25	Arctic, North Atlantic	2429	Omar, A., A. Olsen and T. Johannessen	
Nuka Arctica	2014-05-13	2014-05-18	Arctic, North Atlantic	1420	Omar, A., A. Olsen and T. Johannessen	
Nuka Arctica	2014-05-23	2014-05-31	Arctic, North Atlantic	1191	Omar, A., A. Olsen and T. Johannessen	
Nuka Arctica	2014-06-11	2014-06-12	Arctic, North Atlantic	274	Omar, A., A. Olsen and T. Johannessen	
Nuka Arctica	2014-06-13	2014-06-22	Arctic, North Atlantic	3077	Omar, A., A. Olsen and T. Johannessen	
Nuka Arctica	2014-07-26	2014-08-05	Arctic, North Atlantic	3362	Omar, A., A. Olsen and T. Johannessen	
Nuka Arctica	2014-08-08	2014-08-14	Arctic, North Atlantic	2266	Omar, A., A. Olsen and T. Johannessen	
Nuka Arctica	2014-08-15	2014-08-23	Arctic, North Atlantic	2483	Omar, A., A. Olsen and T. Johannessen	
Nuka Arctica	2014-09-20	2014-09-28	Arctic, North Atlantic	1931	Omar, A., A. Olsen and T. Johannessen	
Nuka Arctica	2014-09-28	2014-10-06	Arctic, North Atlantic	769	Omar, A., A. Olsen and T. Johannessen	
Nuka Arctica	2014-10-08	2014-10-16	Arctic, North Atlantic	1029	Omar, A., A. Olsen and T. Johannessen	
Nuka Arctica	2014-10-17	2014-10-24	Arctic, North Atlantic	1540	Omar, A., A. Olsen and T. Johannessen	
Nuka Arctica	2014-10-28	2014-11-06	Arctic, North Atlantic	648	Omar, A., A. Olsen and T. Johannessen	
Nuka Arctica	2014-11-20	2014-11-28	Arctic, North Atlantic	1451	Omar, A., A. Olsen and T. Johannessen	
Polarstern	2014-07-07	2014-08-02	Arctic	25 088	van Heuven, S. and M. Hoppema	
Polarstern	2014-08-05	2014-10-04	Arctic	55 349	van Heuven, S. and M. Hoppema	
Polarstern	2014-06-08	2014-06-30	Arctic, North Atlantic	20 871	van Heuven, S. and M. Hoppema	
Polarstern	2014-03-09	2014-04-12	North Atlantic, Tropical Atlantic, Southern Ocean	32 939	van Heuven, S. and M. Hoppema	
Polarstern	2014-10-26	2014-11-28	North Atlantic, Tropical Atlantic, Southern Ocean	30 655	van Heuven, S. and M. Hoppema	
Polarstern	2013-12-21	2014-03-04	Southern Ocean	69 740	van Heuven, S. and M. Hoppema	
Polarstern	2014-12-03	2015-01-31	Southern Ocean	28 299	van Heuven, S. and M. Hoppema	
Pourquoi Pas?	2014-05-17	2014-06-28	North Atlantic	2835	Padin, X.A. and F.F. Pérez	
Reykjafoss	2013-09-06	2013-09-17	North Atlantic	3481	Wanninkhof, R., D. Pierrot and L. Barbero	
Reykjafoss	2013-09-19	2013-09-30	North Atlantic	3991	Wanninkhof, R., D. Pierrot and L. Barbero	
Reykjafoss	2013-10-17	2013-10-25	North Atlantic	2291	Wanninkhof, R., D. Pierrot and L. Barbero	
Reykjafoss	2013-10-31	2013-11-08	North Atlantic	2715	Wanninkhof, R., D. Pierrot and L. Barbero	
Ronald H. Brown	2013-10-20	2013-10-30	Tropical Atlantic	4608	Wanninkhof, R., D. Pierrot and L. Barbero	doi:10.3334/CDIAC/OTG.VOS_RB_2013
Ronald H. Brown	2014-02-28	2014-03-13	Tropical Pacific	6052	Wanninkhof, R., D. Pierrot and L. Barbero	doi:10.3334/CDIAC/OTG.VOS_RB_2014
Santa Cruz	2014-01-17	2014-01-30	North Atlantic, Tropical Atlantic	5258	Lefèvre, N. and D. Diverrès	
Santa Cruz	2014-02-19	2014-02-28	North Atlantic, Tropical Atlantic	3251	Lefèvre, N. and D. Diverrès	
Simon Stevin	2014-08-20	2014-08-20	North Atlantic	31 827	Gkritzalis, T.	
Simon Stevin	2014-08-21	2014-08-21	North Atlantic	30 640	Gkritzalis, T.	
Simon Stevin	2014-08-22	2014-08-22	North Atlantic	5382	Gkritzalis, T.	
Simon Stevin	2014-08-25	2014-08-25	North Atlantic	508	Gkritzalis, T.	
Simon Stevin	2014-08-27	2014-08-27	North Atlantic	28 904	Gkritzalis, T.	
Simon Stevin	2014-08-28	2014-08-28	North Atlantic	15 148	Gkritzalis, T.	
Simon Stevin	2014-08-29	2014-08-29	North Atlantic	12 492	Gkritzalis, T.	
Simon Stevin	2014-09-01	2014-09-01	North Atlantic	21 372	Gkritzalis, T.	
Simon Stevin	2014-09-03	2014-09-03	North Atlantic	23069	Gkritzalis, T.	
Simon Stevin	2014-09-08	2014-09-08	North Atlantic	24 445	Gkritzalis, T.	
Simon Stevin	2014-10-22	2014-10-23	North Atlantic	28 397	Gkritzalis, T.	
Simon Stevin	2014-10-24	2014-10-24	North Atlantic	11 920	Gkritzalis, T.	
Skogafoss	2014-03-17	2014-04-11	North Atlantic	10 168	Wanninkhof, R., D. Pierrot and L. Barbero	doi:10.3334/CDIAC/OTG.VOS_SKO2014
Skogafoss	2014-05-10	2014-06-05	North Atlantic	11 010	Wanninkhof, R., D. Pierrot and L. Barbero	doi:10.3334/CDIAC/OTG.VOS_SKO2014

Table A1. Continued.

Vessel	Start date yyyy-mm-dd	End date yyyy-mm-dd	Regions	No. of samples	Principal Investigators	DOI (if available)/comment
Skogafoss	2014-06-07	2014-06-28	North Atlantic	6702	Wanninkhof, R., D. Pierrot and L. Barbero	doi:10.3334/CDIAC/OTG.VOS_SKO2014
Skogafoss	2014-06-29	2014-07-26	North Atlantic	7280	Wanninkhof, R., D. Pierrot and L. Barbero	doi:10.3334/CDIAC/OTG.VOS_SKO2014
Skogafoss	2014-07-27	2014-08-21	North Atlantic	5528	Wanninkhof, R., D. Pierrot and L. Barbero	doi:10.3334/CDIAC/OTG.VOS_SKO2014
Skogafoss	2014-08-22	2014-09-01	North Atlantic	3601	Wanninkhof, R., D. Pierrot and L. Barbero	doi:10.3334/CDIAC/OTG.VOS_SKO2014
Soyo-maru	2013-12-08	2013-12-19	North Pacific	10 583	Ichikawa, T. and T. Ono	
Soyo-maru	2014-02-10	2014-02-24	North Pacific	15 841	Ichikawa, T. and T. Ono	
Soyo-maru	2014-03-02	2014-03-09	North Pacific	9589	Ichikawa, T. and T. Ono	
Soyo-maru	2014-05-10	2014-05-18	North Pacific	9608	Ichikawa, T. and T. Ono	
Soyo-maru	2014-05-24	2014-06-19	North Pacific	29 872	Ichikawa, T. and T. Ono	
Soyo-maru	2014-08-22	2014-08-26	North Pacific	4162	Ichikawa, T. and T. Ono	
Soyo-maru	2014-01-24	2014-01-30	North Pacific, Tropical Pacific	8784	Ichikawa, T. and T. Ono	
Trans Future 5	2013-08-26	2013-08-27	North Pacific	58	Nakaoka, S. and Y. Nojiri	
Trans Future 5	2013-09-27	2013-09-27	North Pacific	63	Nakaoka, S. and Y. Nojiri	
Trans Future 5	2013-11-04	2013-11-05	North Pacific	58	Nakaoka, S. and Y. Nojiri	
Trans Future 5	2013-11-08	2013-11-09	North Pacific	52	Nakaoka, S. and Y. Nojiri	
Trans Future 5	2013-12-16	2013-12-16	North Pacific	56	Nakaoka, S. and Y. Nojiri	
Trans Future 5	2013-12-20	2013-12-20	North Pacific	56	Nakaoka, S. and Y. Nojiri	
Trans Future 5	2014-02-10	2014-02-10	North Pacific	77	Nakaoka, S. and Y. Nojiri	
Trans Future 5	2014-02-14	2014-02-15	North Pacific	41	Nakaoka, S. and Y. Nojiri	
Trans Future 5	2014-03-24	2014-03-25	North Pacific	63	Nakaoka, S. and Y. Nojiri	
Trans Future 5	2014-03-28	2014-03-29	North Pacific	61	Nakaoka, S. and Y. Nojiri	
Trans Future 5	2014-05-06	2014-05-07	North Pacific	73	Nakaoka, S. and Y. Nojiri	
Trans Future 5	2014-05-09	2014-05-09	North Pacific	59	Nakaoka, S. and Y. Nojiri	
Trans Future 5	2014-06-16	2014-06-17	North Pacific	70	Nakaoka, S. and Y. Nojiri	
Trans Future 5	2014-06-20	2014-06-20	North Pacific	61	Nakaoka, S. and Y. Nojiri	
Trans Future 5	2014-07-28	2014-07-29	North Pacific	71	Nakaoka, S. and Y. Nojiri	
Trans Future 5	2014-08-01	2014-08-01	North Pacific	50	Nakaoka, S. and Y. Nojiri	
Trans Future 5	2014-09-08	2014-09-08	North Pacific	55	Nakaoka, S. and Y. Nojiri	
Trans Future 5	2014-09-12	2014-09-12	North Pacific	54	Nakaoka, S. and Y. Nojiri	
Trans Future 5	2014-10-20	2014-10-21	North Pacific	53	Nakaoka, S. and Y. Nojiri	
Trans Future 5	2014-10-24	2014-10-24	North Pacific	55	Nakaoka, S. and Y. Nojiri	
Trans Future 5	2014-12-01	2014-12-01	North Pacific	52	Nakaoka, S. and Y. Nojiri	
Trans Future 5	2014-12-05	2014-12-05	North Pacific	53	Nakaoka, S. and Y. Nojiri	
Trans Future 5	2013-09-28	2013-10-09	North Pacific, Tropical Pacific	1118	Nakaoka, S. and Y. Nojiri	
Trans Future 5	2013-11-09	2013-11-18	North Pacific, Tropical Pacific	1104	Nakaoka, S. and Y. Nojiri	
Trans Future 5	2013-12-21	2014-01-02	North Pacific, Tropical Pacific	1168	Nakaoka, S. and Y. Nojiri	
Trans Future 5	2014-02-16	2014-02-25	North Pacific, Tropical Pacific	1122	Nakaoka, S. and Y. Nojiri	
Trans Future 5	2014-03-30	2014-04-09	North Pacific, Tropical Pacific	1121	Nakaoka, S. and Y. Nojiri	
Trans Future 5	2014-05-10	2014-05-19	North Pacific, Tropical Pacific	1159	Nakaoka, S. and Y. Nojiri	
Trans Future 5	2014-06-21	2014-07-02	North Pacific, Tropical Pacific	1124	Nakaoka, S. and Y. Nojiri	
Trans Future 5	2014-08-02	2014-08-11	North Pacific, Tropical Pacific	1142	Nakaoka, S. and Y. Nojiri	
Trans Future 5	2014-10-25	2014-11-04	North Pacific, Tropical Pacific	1086	Nakaoka, S. and Y. Nojiri	
Trans Future 5	2014-12-06	2014-12-15	North Pacific, Tropical Pacific	1104	Nakaoka, S. and Y. Nojiri	
Trans Future 5	2013-10-23	2013-11-03	North Pacific, Tropical Pacific, Southern Ocean	1432	Nakaoka, S. and Y. Nojiri	
Trans Future 5	2013-12-03	2013-12-15	North Pacific, Tropical Pacific, Southern Ocean	1434	Nakaoka, S. and Y. Nojiri	
Trans Future 5	2014-01-25	2014-02-07	North Pacific, Tropical Pacific, Southern Ocean	1558	Nakaoka, S. and Y. Nojiri	
Trans Future 5	2014-03-12	2014-03-23	North Pacific, Tropical Pacific, Southern Ocean	1451	Nakaoka, S. and Y. Nojiri	
Trans Future 5	2014-04-24	2014-05-05	North Pacific, Tropical Pacific, Southern Ocean	1381	Nakaoka, S. and Y. Nojiri	
Trans Future 5	2014-06-03	2014-06-15	North Pacific, Tropical Pacific, Southern Ocean	1456	Nakaoka, S. and Y. Nojiri	

Table A1. Continued.

Vessel	Start date yyyy-mm-dd	End date yyyy-mm-dd	Regions	No. of samples	Principal Investigators	DOI (if available)/comment
Trans Future 5	2014-07-16	2014-07-27	North Pacific, Tropical Pacific, Southern Ocean	1415	Nakaoka, S. and Y. Nojiri	
Trans Future 5	2014-08-27	2014-09-07	North Pacific, Tropical Pacific, Southern Ocean	1405	Nakaoka, S. and Y. Nojiri	
Trans Future 5	2014-10-06	2014-10-19	North Pacific, Tropical Pacific, Southern Ocean	1422	Nakaoka, S. and Y. Nojiri	
Trans Future 5	2014-11-18	2014-11-29	North Pacific, Tropical Pacific, Southern Ocean	809	Nakaoka, S. and Y. Nojiri	
Trans Future 5	2014-09-23	2014-10-05	Southern Ocean	196	Nakaoka, S. and Y. Nojiri	
Trans Future 5	2013-10-09	2013-10-21	Tropical Pacific, Southern Ocean	880	Nakaoka, S. and Y. Nojiri	
Trans Future 5	2013-11-19	2013-12-01	Tropical Pacific, Southern Ocean	921	Nakaoka, S. and Y. Nojiri	
Trans Future 5	2014-01-02	2014-01-17	Tropical Pacific, Southern Ocean	1000	Nakaoka, S. and Y. Nojiri	
Trans Future 5	2014-02-25	2014-03-10	Tropical Pacific, Southern Ocean	909	Nakaoka, S. and Y. Nojiri	
Trans Future 5	2014-04-10	2014-04-23	Tropical Pacific, Southern Ocean	941	Nakaoka, S. and Y. Nojiri	
Trans Future 5	2014-05-20	2014-06-01	Tropical Pacific, Southern Ocean	910	Nakaoka, S. and Y. Nojiri	
Trans Future 5	2014-07-02	2014-07-15	Tropical Pacific, Southern Ocean	1027	Nakaoka, S. and Y. Nojiri	
Trans Future 5	2014-08-12	2014-08-25	Tropical Pacific, Southern Ocean	1040	Nakaoka, S. and Y. Nojiri	
Trans Future 5	2014-11-05	2014-11-17	Tropical Pacific, Southern Ocean	853	Nakaoka, S. and Y. Nojiri	
Trans Future 5	2014-12-16	2014-12-30	Tropical Pacific, Southern Ocean	939	Nakaoka, S. and Y. Nojiri	
Wakataka-maru	2014-05-10	2014-05-20	North Pacific	9360	Kuwata, A. and K. Tadokoro	
Wakataka-maru	2014-06-05	2014-06-11	North Pacific	9025	Kuwata, A. and K. Tadokoro	
Walton Smith	2013-03-31	2013-04-18	North Atlantic, Tropical Atlantic	8392	Millero, F.	
Walton Smith	2013-04-19	2013-04-28	North Atlantic, Tropical Atlantic	4890	Millero, F.	
Walton Smith	2014-04-28	2014-05-25	North Atlantic, Tropical Atlantic	12 666	Millero, F.	
Walton Smith	2013-05-25	2013-05-27	Tropical Atlantic	898	Millero, F.	
Walton Smith	2013-06-13	2013-06-15	Tropical Atlantic	1214	Millero, F.	
Walton Smith	2013-06-20	2013-06-27	Tropical Atlantic	2883	Millero, F.	
Walton Smith	2013-07-06	2013-07-18	Tropical Atlantic	5529	Millero, F.	
Walton Smith	2013-08-13	2013-08-28	Tropical Atlantic	7900	Millero, F.	
Walton Smith	2013-10-08	2013-10-09	Tropical Atlantic	509	Millero, F.	
Walton Smith	2013-10-17	2013-10-18	Tropical Atlantic	707	Millero, F.	
Walton Smith	2013-12-20	2013-12-21	Tropical Atlantic	748	Millero, F.	
Walton Smith	2014-04-22	2014-04-22	Tropical Atlantic	214	Millero, F.	
Walton Smith	2014-04-23	2014-04-24	Tropical Atlantic	657	Millero, F.	
Walton Smith	2014-04-26	2014-04-26	Tropical Atlantic	155	Millero, F.	

Data availability

The data presented here are made available in the belief that their wide dissemination will lead to greater understanding and new scientific insights of how the carbon cycle works, how humans are altering it, and how we can mitigate the resulting human-driven climate change. The free availability of these data does not constitute permission for publication of the data. For research projects, if the data are essential to the work, or if an important result or conclusion depends on the data, co-authorship may need to be considered. Full contact details and information on how to cite the data are given at the top of each page in the accompanying database, and summarised in Table 2.

The accompanying database includes two Excel files organised in the following spreadsheets (accessible with the free viewer http://www.microsoft.com/en-us/download/details.aspx?id=10):

The file Global_Carbon_Budget_2015.xlsx includes

1. a summary;
2. the global carbon budget (1959–2014);
3. global CO_2 emissions from fossil fuels and cement production by fuel type, and the per-capita emissions (1959–2014);
4. CO_2 emissions from land-use change from the individual methods and models (1959–2014);
5. ocean CO_2 sink from the individual ocean models and data products (1959–2014);
6. terrestrial residual CO_2 sink from the DGVMs (1959–2014);
7. additional information on the carbon balance prior to 1959 (1750–2014).

The file National_Carbon_Emissions_2015.xlsx includes

1. a summary;
2. territorial country CO_2 emissions from fossil fuels and industry (1959–2014) from CDIAC, extended to 2014 using BP data;
3. territorial country CO_2 emissions from fossil fuels and industry (1959–2014) from CDIAC with UNFCCC data overwritten where available, extended to 2014 using BP data;
4. consumption country CO_2 emissions from fossil fuels and industry and emissions transfer from the international trade of goods and services (1990–2013) using CDIAC/UNFCCC data (worksheet 3 above) as reference;
5. emissions transfers (consumption minus territorial emissions; 1990–2013);
6. country definitions.

National emissions data are also available from the Global Carbon Atlas (http://globalcarbonatlas.org).

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References

Achard, F. and House, J. I.: Reporting Carbon losses from tropical deforestation with Pan-tropical biomass maps, Environ. Res. Lett., 10, 101002, 2015.

Achard, F., Beuchle, R., Mayaux, P., Stibig, H. J., Bodart, C., Brink, A., Carboni, S., Desclée, B., Donnay, F., and Eva, H.: Determination of tropical deforestation rates and related carbon losses from 1990 to 2010, Glob. Change Biol., 20, 2540–2554, 2014.

Andres, R. J., Fielding, D. J., Marland, G., Boden, T. A., Kumar, N., and Kearney, A. T.: Carbon dioxide emissions from fossil fuel use, 1751–1950, Tellus, 51, 759–765, 1999.

Andres, R. J., Boden, T. A., Bréon, F.-M., Ciais, P., Davis, S., Erickson, D., Gregg, J. S., Jacobson, A., Marland, G., Miller, J., Oda, T., Olivier, J. G. J., Raupach, M. R., Rayner, P., and Treanton, K.: A synthesis of carbon dioxide emissions from fossil-fuel combustion, Biogeosciences, 9, 1845–1871, doi:10.5194/bg-9-1845-2012, 2012.

Andres, R. J., Boden, T., and Higdon, D.: A new evaluation of the uncertainty associated with CDIAC estimates of fossil fuel carbon dioxide emission, Tellus B, 66, 23616, doi:10.3402/tellusb.v66.23616, 2014.

Andrew, R. M. and Peters, G. P.: A multi-region input-output table based on the Global Trade Analysis Project Database (GTAP-MRIO), Economic Systems Research, 25, 99–121, 2013.

Archer, D., Eby, M., Brovkin, V., Ridgwell, A., Cao, L., Mikolajewicz, U., Caldeira, K., Munhoven, G., Montenegro, A., and Tokos, K.: Atmospheric Lifetime of Fossil Fuel Carbon Dioxide, Annu. Rev. Earth Pl. Sc., 37, 117–134, 2009.

Arora, V. and Boer, G.: A parameterization of leaf phenology for the terrestrialecosystem component of climate models, Glob. Change Biol., 11, 39–59, 2005.

Assmann, K. M., Bentsen, M., Segschneider, J., and Heinze, C.: An isopycnic ocean carbon cycle model, Geosci. Model Dev., 3, 143–167, doi:10.5194/gmd-3-143-2010, 2010.

Atlas, R., Hoffman, R. N., Ardizzone, J., Leidner, S. M., Jusem, J. C., Smith, D. K., and Gombos, D.: A cross-calibrated, multiplatform ocean surface wind velocity product for meteorological and oceanographic applications, B. Amer. Meteorol. Soc., 92, 157–174, 2011.

Aumont, O. and Bopp, L.: Globalizing results from ocean in situ iron fertilization studies, Global Biogeochem. Cy., 20, GB2017, doi:10.1029/2005GB002591, 2006.

Baccini, A., Goetz, S. J., Walker, W. S., Laporte, N. T., Sun, M., Sulla-Menashe, D., Hackler, J., Beck, P. S. A., Dubayah, R., Friedl, M. A., Samanta, S., and Houghton, R. A.: Estimated carbon dioxide emissions from tropical deforestation improved by carbon-density maps, Nature Clim. Change, 2, 182–186, 2012.

Bakker, D. C. E., Pfeil, B., Smith, K., Hankin, S., Olsen, A., Alin, S. R., Cosca, C., Harasawa, S., Kozyr, A., Nojiri, Y., O'Brien, K. M., Schuster, U., Telszewski, M., Tilbrook, B., Wada, C., Akl, J., Barbero, L., Bates, N. R., Boutin, J., Bozec, Y., Cai, W.-J., Castle, R. D., Chavez, F. P., Chen, L., Chierici, M., Currie, K., de Baar, H. J. W., Evans, W., Feely, R. A., Fransson, A., Gao, Z., Hales, B., Hardman-Mountford, N. J., Hoppema, M., Huang, W.-J., Hunt, C. W., Huss, B., Ichikawa, T., Johannessen, T., Jones, E. M., Jones, S. D., Jutterström, S., Kitidis, V., Körtzinger, A., Landschützer, P., Lauvset, S. K., Lefèvre, N., Manke, A. B., Mathis, J. T., Merlivat, L., Metzl, N., Murata, A., Newberger, T., Omar, A. M., Ono, T., Park, G.-H., Paterson, K., Pierrot, D., Ríos, A. F., Sabine, C. L., Saito, S., Salisbury, J., Sarma, V. V. S. S., Schlitzer, R., Sieger, R., Skjelvan, I., Steinhoff, T., Sullivan, K. F., Sun, H., Sutton, A. J., Suzuki, T., Sweeney, C., Takahashi, T., Tjiputra, J., Tsurushima, N., van Heuven, S. M. A. C., Vandemark, D., Vlahos, P., Wallace, D. W. R., Wanninkhof, R., and Watson, A. J.: An update to the Surface Ocean CO_2 Atlas (SOCAT version 2), Earth Syst. Sci. Data, 6, 69–90, doi:10.5194/essd-6-69-2014, 2014.

Bakker, D. C. E., Pfeil, B., Smith, K., Harasawa, S., Landa, C., Nakaoka, S., Nojiri, Y., Metzl, N., O'Brien, K. M., Olsen, A., Schuster, U., Tilbrook, B., Wanninkhof, R., Alin, S. R., Barbero, L., Bates, N. R., Bianchi, A. A., Bonou, F., Boutin, J., Bozec, Y., Burger, E., Cai, W.-J., Castle, R. D., Chen, L., Chierici, M., Cosca, C., Currie, K., Evans, W., Featherstone, C., Feely, R. A., Fransson, A., Greenwood, N., Gregor, L., Hankin, S., Hardman-Mountford, N. J., Harlay, J., Hauck, J., Hoppema, M., Humphreys, M., Hunt, C. W., Ibánhez, J. S. P., Johannessen, T., Jones, S. D., Keeling, R., Kitidis, V., Körtzinger, A., Kozyr, A., Krasakopolou, E., Kuwata, A., Landschtzer, P., Lauvset, S. K., Lefèvre, N., Lo Monaco, C., Manke, A. B., Mathis, J. T., Merlivat, L., Monteiro, P., Munro, D., Murata, A., Newberger, T., Omar, A. M., Ono, T., Paterson, K., Pierrot, D., Robbins, L. L., Sabine, C. L., Saito, S., Salisbury, J., Schneider, B., Schlitzer, R., Sieger, R., Skjelvan, I., Steinhoff, T., Sullivan, K. F., Sutherland, S. C., Sutton, A. J., Sweeney, C., Tadokoro, K., Takahashi, T., Telszewski, M., van Heuven, S. M. A. C., Vandemark, D., Wada, C., Ward, B., and Watson, A. J.: A 58-year record of high quality data in version 3 of the Surface Ocean CO_2 Atlas (SOCAT), Earth Syst. Sci. Data Discuss., in preparation, 2015.

Ballantyne, A. P., Alden, C. B., Miller, J. B., Tans, P. P., and White, J. W. C.: Increase in observed net carbon dioxide uptake by land and oceans during the last 50 years, Nature, 488, 70–72, 2012.

Ballantyne, A. P., Andres, R., Houghton, R., Stocker, B. D., Wanninkhof, R., Anderegg, W., Cooper, L. A., DeGrandpre, M., Tans, P. P., Miller, J. B., Alden, C., and White, J. W. C.: Audit of the global carbon budget: estimate errors and their impact on uptake uncertainty, Biogeosciences, 12, 2565–2584, doi:10.5194/bg-12-2565-2015, 2015.

Bauer, J. E., Cai, W.-J., Raymond, P. A., Bianchi, T. S., Hopkinson, C. S., and Regnier, P. A. G.: The changing carbon cycle of the coastal ocean, Nature, 504, 61–70, 2013.

Best, M. J., Pryor, M., Clark, D. B., Rooney, G. G., Essery, R .L. H., Ménard, C. B., Edwards, J. M., Hendry, M. A., Porson, A., Gedney, N., Mercado, L. M., Sitch, S., Blyth, E., Boucher, O., Cox, P. M., Grimmond, C. S. B., and Harding, R. J.: The Joint UK Land Environment Simulator (JULES), model description – Part 1: Energy and water fluxes, Geosci. Model Dev., 4, 677–699, doi:10.5194/gmd-4-677-2011, 2011.

Biemans, H., Haddeland, I., Kabat, P., Ludwig, F., Hutjes, R. W. A., Heinke, J., von Bloh, W., and Gerten, D.: Impact of reservoirs on river discharge and irrigation water supply during the 20th century, Water Resour. Res., 47, W03509, doi:10.1029/2009WR008929, 2011.

Boden, T. A., Marland, G., and Andres, R. J.: Global, Regional, and National Fossil-Fuel CO_2 Emissions, Oak Ridge National Laboratory, US Department of Energy, Oak Ridge, Tenn., USA, 2013.

Boden, T. A., Marland, G., and Andres, R. J.: Global, Regional, and National Fossil-Fuel CO_2 Emissions, Oak Ridge National Laboratory, US Department of Energy, Oak Ridge, Tenn., USA, 2015.

Bondeau, A., Smith, P., Zaehle, S., Schaphoff, S., Lucht, W., Cramer, W., Gerten, D., Lotze-Campen, H., Müller, C., Reichstein, M., and Smith, B.: Modelling the role of agriculture for the 20th century global terrestrial carbon balance, Glob. Change Biol., 13, 1–28, 2007.

BP: Statistical Review of World Energy 2015, available at: http://www.bp.com/en/global/corporate/about-bp/energy-economics/statistical-review-of-world-energy.html, last access: 5 October 2015.

Bruno, M. and Joos, F.: Terrestrial carbon storage during the past 200 years: A monte carlo analysis of CO_2 data from ice core and atmospheric measurements, Global Biogeochem. Cy., 11, 111–124, 1997.

Buitenhuis, E. T., Rivkin, R. B., Sailley, S., and Le Quéré, C.: Biogeochemical fluxes through microzooplankton, Global Biogeochem. Cy., 24, Gb4015, doi:10.1029/2009gb003601, 2010.

Canadell, J., Ciais, P., Sabine, C., and Joos, F. (Eds.): REgional Carbon Cycle Assessment and Processes (RECCAP), Biogeosciences, http://www.biogeosciences.net/special_issue107.html, 2012–2013.

Canadell, J. G., Le Quéré, C., Raupach, M. R., Field, C. B., Buitenhuis, E. T., Ciais, P., Conway, T. J., Gillett, N. P., Houghton, R. A., and Marland, G.: Contributions to accelerating atmospheric CO_2 growth from economic activity, carbon intensity, and efficiency of natural sinks, P. Natl. Acad. Sci. USA, 104, 18866–18870, 2007.

Chevallier, F.: On the statistical optimality of CO_2 atmospheric inversions assimilating CO_2 column retrievals, Atmos. Chem. Phys., 15, 11133–11145, doi:10.5194/acp-15-11133-2015, 2015.

Chevallier, F., Fisher, M., Peylin, P., Serrar, S., Bousquet, P., Bréon, F.-M., Chédin, A., and Ciais, P.: Inferring CO_2 sources and sinks from satellite observations: Method and application to TOVS data, J. Geophys. Res., D24309, doi:10.1029/2005JD006390, 2005.

China Coal Industry Association: Economic performance of coal in the first half of 2015, available at: http://www.coalchina.org.cn/detail/15/07/30/00000027/content.html, last access: July 2015 (in Chinese).

China Coal Resource: Economic performance of China's coal industry in the first 8 months of the year, available at: http://www.sxcoal.com/coal/4237319/articlenew.html (last access: 16 September 2015), 2015 (in Chinese).

Ciais, P., Sabine, C., Govindasamy, B., Bopp, L., Brovkin, V., Canadell, J., Chhabra, A., DeFries, R., Galloway, J., Heimann, M., Jones, C., Le Quéré, C., Myneni, R., Piao, S., and Thornton, P.: Chapter 6: Carbon and Other Biogeochemical Cycles, in: Climate Change 2013 The Physical Science Basis, edited by: Stocker, T., Qin, D., and Platner, G.-K., Cambridge University Press, Cambridge, 2013.

Clark, D. B., Mercado, L. M., Sitch, S., Jones, C. D., Gedney, N., Best, M. J., Pryor, M., Rooney, G. G., Essery, R. L. H., Blyth, E., Boucher, O., Harding, R. J., Huntingford, C., and Cox, P. M.: The Joint UK Land Environment Simulator (JULES), model description – Part 2: Carbon fluxes and vegetation dynamics, Geosci. Model Dev., 4, 701–722, doi:10.5194/gmd-4-701-2011, 2011.

Danabasoglu, G., Yeager, S. G., Bailey, D., Behrens, E., Bentsen, M., Bi, D., Biastoch, A., Böning, C., Bozec, A., Canuto, V. M., Cassou, C., Chassignet, E., Coward, A. C., Danilov, S., Diansky, N., Drange, H., Farneti, R., Fernandez, E., Fogli, P. G., Forget, G., Fujii, Y., Griffies, S. M., Gusev, A., Heimbach, P., Howard, A., Jung, T., Kelley, M., Large, W.G., Leboissetier, A., Lu, J., Madec, G., Marsland, S.J., Masina, S., Navarra, A., Nurser, A. J. G., Pirani, A., Salas y Mélia, D., Samuels, B. L., Scheinert, M., Sidorenko, D., Treguier, A.-M., Tsujino, H., Uotila, P., Valcke, S., Voldoire, A., and Wangi, Q.: North Atlantic simulations in Coordinated Ocean-ice Reference Experiments phase II (CORE-II). Part I: Mean states, Ocean Model., 73, 76–107, 2014.

Davis, S. J. and Caldeira, K.: Consumption-based accounting of CO_2 emissions, P. Natl. Acad. Sci., 107, 5687–5692, 2010.

Davis, S. J., Peters, G. P., and Caldeira, K.: The supply chain of CO_2 emissions, P. Natl. Acad. Sci., 108, 18554–18559, 2011.

Denman, K. L., Brasseur, G., Chidthaisong, A., Ciais, P., Cox, P. M., Dickinson, R. E., Hauglustaine, D., Heinze, C., Holland, E., Jacob, D., Lohmann, U., Ramachandran, S., Leite da Silva Dias, P., Wofsy, S. C., and Zhang, X.: Couplings Between Changes in the Climate System and Biogeochemistry, Intergovernmental Panel on Climate Change, 978-0-521-70596-7, 499–587, 2007.

Dietzenbacher, E., Pei, J., and Yang, C.: Trade, production fragmentation, and China's carbon dioxide emissions, J. Environ. Econ. Manag., 2012, 88–101, 2012.

Dlugokencky, E. and Tans, P.: Trends in atmospheric carbon dioxide, National Oceanic & Atmospheric Administration, Earth System Research Laboratory (NOAA/ESRL), available at: http://www.esrl.noaa.gov/gmd/ccgg/trends, last access: 8 August 2014.

Dlugokencky, E. and Tans, P.: Trends in atmospheric carbon dioxide, National Oceanic & Atmospheric Administration, Earth System Research Laboratory (NOAA/ESRL), available at: http://www.esrl.noaa.gov/gmd/ccgg/trends, last access: 7 October 2015.

Doney, S. C., Lima, I., Feely, R. A., Glover, D. M., Lindsay, K., Mahowald, N., Moore, J. K., and Wanninkhof, R.: Mechanisms governing interannual variability in upper-ocean inorganic carbon system and air–sea CO_2 fluxes: Physical climate and atmospheric dust, Deep-Sea Res. Pt. II, 56, 640-655, 2009.

Durant, A. J., Le Quéré, C., Hope, C., and Friend, A. D.: Economic value of improved quantification in global sources and sinks of carbon dioxide, Philos. T. R. Soc. A, 269, 1967–1979, 2010.

Earles, J. M., Yeh, S., and Skog, K. E.: Timing of carbon emissions from global forest clearance, Nature Clim. Change, 2, 682–685, 2012.

El-Masri, B., Barman, R., Meiyappan, P., Song, Y., Liang, M., and Jain, A. K.: Carbon dynamics in the Amazonian Basin: Integration of eddy covariance and ecophysiological data with a land surface model, Agr. Forest Meteorol., 182–183, 156–167, 2013.

Erb, K.-H., Kastner, T., Luyssaert, S., Houghton, R. A., Kuemmerle, T., Olofsson, P., and Haberl, H.: Bias in the attribution of forest carbon sinks, Nature Clim. Change, 3, 854–856, 2013.

Etheridge, D. M., Steele, L. P., Langenfelds, R. L., and Francey, R. J.: Natural and anthropogenic changes in atmospheric CO_2 over the last 1000 years from air in Antarctic ice and firn, J. Geophys. Res., 101, 4115–4128, 1996.

Fader, M., Rost, S., Müller, C., Bondeau, A., and Gerten, D.: Virtual water content of temperate cereals and maize: Present and potential future patterns, J. Hydrol., 384, 218–231, 2010.

FAO: Global Forest Resource Assessment 2010, 378 pp., 2010.

FAOSTAT: Food and Agriculture Organization Statistics Division, available at: http://faostat.fao.org/2010 (last access: October 2012), 2010.

Federici, S., Tubiello, F. N., Salvatore, M., Jacobs, H., and Schmidhuber, J.: New estimates of CO_2 forest emissions and removals: 1990–2015, Forest Ecol. Manag., 352, 89–98, 2015.

Francey, R. J., Trudinger, C. M., van der Schoot, M., Law, R. M., Krummel, P. B., Langenfelds, R. L., Steele, L. P., Allison, C. E., Stavert, A. R., Andres, R. J., and Rodenbeck, C.: Reply to "Anthropogenic CO_2 emissions", Nature Clim. Change, 3, 604–604, 2013.

Friedlingstein, P., Andrew, R. M., Rogelj, J., Peters, G. P., Canadell, J. G., Knutti, R., Luderer, G., Raupach, M. R., Schaeffer, M., van Vuuren, D. P., and Le Quéré, C.: Persistent growth of CO_2 emissions and implications for reaching climate targets, Nat. Geosci., 7, 709–715, doi:10.1038/ngeo2248, 2014.

Friedlingstein, P., Houghton, R. A., Marland, G., Hackler, J., Boden, T. A., Conway, T. J., Canadell, J. G., Raupach, M. R., Ciais, P., and Le Quéré, C.: Update on CO_2 emissions, Nat. Geosci., 3, 811–812, 2010.

Friend, A. D.: Terrestrial Plant Production and Climate Change, J. Exp. Bot., 61, 1293–1309, 2010.

Gasser, T. and Ciais, P.: A theoretical framework for the net land-to-atmosphere CO_2 flux and its implications in the definition of "emissions from land-use change", Earth Syst. Dynam., 4, 171–186, doi:10.5194/esd-4-171-2013, 2013.

GCP: The Global Carbon Budget 2007, available at: http://lgmacweb.env.uea.ac.uk/lequere/co2/2007/carbon_budget_2007.htm (last access: November 2013), 2007.

General Administration of Customs of the People's Republic of China: China's major exports by quantity and RMB value, August 2015, available at: http://www.customs.gov.cn/publish/portal0/tab49666/info772246.htm, last access: October 2015 (in Chinese).

General Administration of Customs of the People's Republic of China: China's major imports by quantity and RMB value, August 2015, available at: http://www.customs.gov.cn/publish/portal0/tab49666/info772245.htm, last access: October 2015 (in Chinese).

Giglio, L., Randerson, J., and van der Werf, G.: Analysis of daily, monthly, and annual burned area using the fourth-generation global fire emissions database (GFED4), J. Geophys. Res.-Biogeo., 118, 317–328, doi:10.1002/jgrg.20042, 2013.

Gitz, V. and Ciais, P.: Amplifying effects of land-use change on future atmospheric CO_2 levels, Global Biogeochem. Cy., 17, 1024, doi:10.1029/2002GB001963, 2003.

Goll, D. S., Brovkin, V., Liski, J., Raddatz, T., Thum, T., and Todd-Brown, K. E. O.: Strong dependence of CO_2 emissions from anthropogenic land cover change on initial land cover and soil carbon parametrization, Global Biogeochem. Cy., 29, 1511–1523, doi:10.1002/2014GB004988, 2015.

Green, F. and Stern, N.: China's "new normal": structural change, better growth, and peak emissions, Policy report, Centre for Climate Change Economics and Policy (CCCEP), University of Leeds, 2015.

Gregg, J. S., Andres, R. J., and Marland, G.: China: Emissions pattern of the world leader in CO_2 emissions from fossil fuel consumption and cement production, Geophys. Res. Lett., 35, L08806, doi:10.1029/2007GL032887, 2008.

Hansen, M., Potapov, P., and Moore, R.: High-resolution global maps of 21st century forest cover change, Science, 342, 850–853, 2013.

Hansis, E., Davis, S. J., and Pongratz, J.: Relevance of methodological choices for accounting of land use change carbon fluxes, Global Biogeochem. Cy., 29, 1230–1246, 2015.

Harris, I., Jones, P. D., Osborn, T. J., and Lister, D. H.: Updated high-resolution grids of monthly climatic observations – the CRU TS3.10 Dataset, Int. J. Climatol., 34, 623–642, 2015.

Harris, N., Brown, S., and Hagen, S. C.: Baseline map of carbon emissions from deforestation in tropical regions, Science, 336, 1573–1576, 2012.

Hauck, J., Völker, C., Wang, T., Hoppema, M., Losch, M., and Wolf-Gladrow, D. A.: Seasonally different carbon flux changes in the Southern Ocean in response to the southern annular mode, Global Biogeochem. Cy., 27, 1236–1245, 2013.

Hertwich, E. G. and Peters, G. P.: Carbon Footprint of Nations: A Global, Trade-Linked Analysis, Environ. Sci. Technol., 43, 6414–6420, 2009.

Houghton, R. A.: Revised estimates of the annual net flux of carbon to the atmosphere from changes in land use and land management 1850–2000, Tellus B, 55, 378–390, 2003.

Houghton, R. A., House, J. I., Pongratz, J., van der Werf, G. R., DeFries, R. S., Hansen, M. C., Le Quéré, C., and Ramankutty, N.: Carbon emissions from land use and land-cover change, Biogeosciences, 9, 5125–5142, doi:10.5194/bg-9-5125-2012, 2012.

Hourdin, F., Musat, I., Bony, S., Braconnot, P., Codron, F., Dufresne, J.-L., Fairhead, L., Filiberti, M.-A., Freidlingstein, P., Grandpeix, J.-Y., Krinner, G., LeVan, P., Li, Z.-X., and Lott, F.: The LMDZ4 general circulation model: climate performance and sensitivity to parametrized physics with emphasis on tropical convection, Clim. Dynam., 27, 787–813, 2006.

Hurtt, G. C., Chini, L. P., Frolking, S., Betts, R. A., Feddema, J., Fischer, G., Fisk, J. P., Hibbard, K., Houghton, R. A., Janetos, A., Jones, C. D., Kindermann, G., Kinoshita, T., Klein Goldewijk, K., Riahi, K., Shevliakova, E., Smith, S., Stehfest, E., Thomson, A., Thornton, P., van Vuuren, D. P., and Wang, Y. P.: Harmonization of land-use scenarios for the period 1500–2100: 600 years of global gridded annual land-use transitions, wood harvest, and resulting secondary lands, Climatic Change, 109, 117–161, 2011.

IEA/OECD: CO_2 emissions from fuel combustion highlights, Paris, International Energy Agency, 2014.

Ilyina, T., Six, K., Segschneider, J., Maier-Reimer, E., Li, H., and Núñez-Riboni, I.: The global ocean biogeochemistry model HAMOCC: Model architecture and performance as component of the MPI-Earth System Model in different CMIP5 experimental realizations, Journal of Advances in Modeling Earth Systems, 5, 287–315, 2013.

IMF: World Economic Outlook of the International Monetary Fund, available at: http://www.imf.org/external/ns/cs.aspx?id=_29, last access: 9 October 2015.

Inomata, S. and Owen, A.: COMPARATIVE EVALUATION OF MRIO DATABASES, Economic Systems Research, 26, 239–244, 2014.

Ito, A. and Inatomi, M.: Use of a process-based model for assessing the methane budgets of global terrestrial ecosystems and evaluation of uncertainty, Biogeosciences, 9, 759–773, doi:10.5194/bg-9-759-2012, 2012.

Jackson, R. B., Canadell, J. G., Le Quéré, C., Andrew, R. M., Korsbakken, J. I., Peters, G. P., and Nakicenovic, N.: Reaching Peak Emissions, Nature Clim. Change, doi:10.1038/nclimate2892, online first, 2015.

Jacobson, A. R., Mikaloff Fletcher, S. E., Gruber, N., Sarmiento, J. L., and Gloor, M.: A joint atmosphere-ocean inversion for surface fluxes of carbon dioxide: 1. Methods and global-scale fluxes, Global Biogeochem. Cy., 21, GB1019, doi:10.1029/2005GB002556, 2007.

Jain, A. K., West, T., Yang, X., and Post, W.: Assessing the Impact of Changes in Climate and CO_2 on Potential Carbon Sequestration in Agricultural Soils, Geophys. Res. Lett., 32, L19711, doi:10.1029/2005GL023922, 2005.

Jain, A. K., Meiyappan, P., Song, Y., and House, J. I.: CO_2 Emissions from Land-Use Change Affected More by Nitrogen Cycle, than by the Choice of Land Cover Data, Glob. Change Biol., 9, 2893–2906, 2013.

Joos, F. and Spahni, R.: Rates of change in natural and anthropogenic radiative forcing over the past 20,000 years, P. Natl. Acad. Sci., 105, 1425–1430, 2008.

Karstensen, J., Peters, G. P., and Andrew, R. M.: Uncertainty in temperature response of current consumption-based emissions estimates, Earth Syst. Dynam., 6, 287–309, doi:10.5194/esd-6-287-2015, 2015.

Kato, E., Kinoshita, T., Ito, A., Kawamiya, M., and Yamagata, Y.: Evaluation of spatially explicit emission scenario of land-use change and biomass burning using a process-based biogeochemical model, Journal of Land Use Science, 8, 104–122, 2013.

Keeling, C. D., Bacastow, R. B., Bainbridge, A. E., Ekdhal, C. A., Guenther, P. R., and Waterman, L. S.: Atmospheric carbon dioxide variations at Mauna Loa Observatory, Hawaii, Tellus, 28, 538–551, 1976.

Keeling, R. F., Manning, A. C., and Dubey, M. K.: The atmospheric signature of carbon capture and storage, Philos. T. R. Soc. A, 369, 2113–2132, 2011.

Khatiwala, S., Primeau, F., and Hall, T.: Reconstruction of the history of anthropogenic CO_2 concentrations in the ocean, Nature, 462, 346–350, 2009.

Khatiwala, S., Tanhua, T., Mikaloff Fletcher, S., Gerber, M., Doney, S. C., Graven, H. D., Gruber, N., McKinley, G. A., Murata, A., Ríos, A. F., and Sabine, C. L.: Global ocean storage of anthropogenic carbon, Biogeosciences, 10, 2169–2191, doi:10.5194/bg-10-2169-2013, 2013.

Kirschke, S., Bousquet, P., Ciais, P., Saunois, M., Canadell, J. G., Dlugokencky, E. J., Bergamaschi, P., Bergmann, D., Blake, D. R., Bruhwiler, L., Cameron Smith, P., Castaldi, S., Chevallier, F., Feng, L., Fraser, A., Heimann, M., Hodson, E. L., Houweling, S., Josse, B., Fraser, P. J., Krummel, P. B., Lamarque, J., Langenfelds, R. L., Le Quéré, C., Naik, V., O'Doherty, S., Palmer, P. I., Pison, I., Plummer, D., Poulter, B., Prinn, R. G., Rigby, M., Ringeval, B., Santini, M., Schmidt, M., Shindell, D. T., Simpson, I. J., Spahni, R., Steele, L. P., Strode, S. A., Sudo, K., Szopa, S., van der Werf, G. R., Voulgarakis, A., van Weele, M., Weiss, R. F., Williams, J. E., and Zeng, G.: Three decades of global methane sources and sinks, Nat. Geosci., 6, 813–823, 2013.

Klein Goldewijk, K., Beusen, A., van Drecht, G., and de Vos, M.: The HYDE 3.1 spatially explicit database of human-induced global land-use change over the past 12,000 years, Global Ecol. Biogeogr., 20, 73–86, 2011.

Krinner, G., Viovy, N., de Noblet, N., Ogée, J., Friedlingstein, P., Ciais, P., Sitch, S., Polcher, J., and Prentice, I. C.: A dynamic global vegetation model for studies of the coupled atmosphere-biosphere system, Global Biogeochem. Cy., 19, 1–33, 2005.

Lamarque, J.-F., Bond, T. C., Eyring, V., Granier, C., Heil, A., Klimont, Z., Lee, D., Liousse, C., Mieville, A., Owen, B., Schultz, M. G., Shindell, D., Smith, S. J., Stehfest, E., Van Aardenne, J., Cooper, O. R., Kainuma, M., Mahowald, N., McConnell, J. R., Naik, V., Riahi, K., and van Vuuren, D. P.: Historical (1850–2000) gridded anthropogenic and biomass burning emissions of reactive gases and aerosols: methodology and application, Atmos. Chem. Phys., 10, 7017–7039, doi:10.5194/acp-10-7017-2010, 2010.

Landschützer, P., Gruber, N., Bakker, D. C. E., and Schuster, U.: Recent variability of the global ocean carbon sink, Global Biogeochem. Cy., 28, 927–949, doi:10.1002/2014GB004853, 2014.

Landschützer, P., Gruber, N., Haumann, F. A., Rödenbeck, C., Bakker, D. C. E., van Heuven, S., Hoppema, M., Metzl, N., Sweeney, C., Takahashi, T., Tilbrook, B., and Wanninkhof, R.: The reinvigoration of the Southern Ocean carbon sink, Science, 349, 1221–1224, 2015.

Le Quéré, C.: Closing the global budget for CO_2, Global Change, 74, 28–31, 2009.

Le Quéré, C., Raupach, M. R., Canadell, J. G., Marland, G., Bopp, L., Ciais, P., Conway, T. J., Doney, S. C., Feely, R. A., Foster, P., Friedlingstein, P., Gurney, K., Houghton, R. A., House, J. I., Huntingford, C., Levy, P. E., Lomas, M. R., Majkut, J., Metzl, N., Ometto, J. P., Peters, G. P., Prentice, I. C., Randerson, J. T., Running, S. W., Sarmiento, J. L., Schuster, U., Sitch, S., Takahashi, T., Viovy, N., van der Werf, G. R., and Woodward, F. I.: Trends in the sources and sinks of carbon dioxide, Nat. Geosci., 2, 831–836, 2009.

Le Quéré, C., Andres, R. J., Boden, T., Conway, T., Houghton, R. A., House, J. I., Marland, G., Peters, G. P., van der Werf, G. R., Ahlström, A., Andrew, R. M., Bopp, L., Canadell, J. G., Ciais, P., Doney, S. C., Enright, C., Friedlingstein, P., Huntingford, C., Jain, A. K., Jourdain, C., Kato, E., Keeling, R. F., Klein Goldewijk, K., Levis, S., Levy, P., Lomas, M., Poulter, B., Raupach, M. R., Schwinger, J., Sitch, S., Stocker, B. D., Viovy, N., Zaehle, S., and Zeng, N.: The global carbon budget 1959–2011, Earth Syst. Sci. Data, 5, 165–185, doi:10.5194/essd-5-165-2013, 2013.

Le Quéré, C., Peters, G. P., Andres, R. J., Andrew, R. M., Boden, T. A., Ciais, P., Friedlingstein, P., Houghton, R. A., Marland, G., Moriarty, R., Sitch, S., Tans, P., Arneth, A., Arvanitis, A., Bakker, D. C. E., Bopp, L., Canadell, J. G., Chini, L. P., Doney, S. C., Harper, A., Harris, I., House, J. I., Jain, A. K., Jones, S. D., Kato, E., Keeling, R. F., Klein Goldewijk, K., Körtzinger, A., Koven, C., Lefèvre, N., Maignan, F., Omar, A., Ono, T., Park, G.-H., Pfeil, B., Poulter, B., Raupach, M. R., Regnier, P., Rödenbeck, C., Saito, S., Schwinger, J., Segschneider, J., Stocker, B. D., Takahashi, T., Tilbrook, B., van Heuven, S., Viovy, N., Wanninkhof, R., Wiltshire, A., and Zaehle, S.: Global carbon budget 2013, Earth Syst. Sci. Data, 6, 235–263, doi:10.5194/essd-6-235-2014, 2014.

Le Quéré, C., Moriarty, R., Andrew, R. M., Peters, G. P., Ciais, P., Friedlingstein, P., Jones, S. D., Sitch, S., Tans, P., Arneth, A., Boden, T. A., Bopp, L., Bozec, Y., Canadell, J. G., Chini, L. P., Chevallier, F., Cosca, C. E., Harris, I., Hoppema, M., Houghton, R. A., House, J. I., Jain, A. K., Johannessen, T., Kato, E., Keeling, R. F., Kitidis, V., Klein Goldewijk, K., Koven, C., Landa, C. S., Landschützer, P., Lenton, A., Lima, I. D., Marland, G., Mathis, J. T., Metzl, N., Nojiri, Y., Olsen, A., Ono, T., Peng, S., Peters, W., Pfeil, B., Poulter, B., Raupach, M. R., Regnier, P., Rödenbeck, C., Saito, S., Salisbury, J. E., Schuster, U., Schwinger, J., Séférian, R., Segschneider, J., Steinhoff, T., Stocker, B. D., Sutton, A. J., Takahashi, T., Tilbrook, B., van der Werf, G. R., Viovy, N., Wang, Y.-P., Wanninkhof, R., Wiltshire, A., and Zeng, N.: Global carbon budget 2014, Earth Syst. Sci. Data, 7, 47–85, doi:10.5194/essd-7-47-2015, 2015.

Liu, Z., Guan, D., Wei, W., Davis, S. J., Ciais, P., Bai, J., Peng, S., Zhang, Q., Hubacek, K., Marland, G., Andres, R. J., Crawford-Brown, D., Lin, J., Zhao, H., Hong, C., Boden, T. A., Feng, K., Peters, G. P., Xi, F., Liu, J., Li, Y., Zhao, Y., Zeng, N., and He, K.: Reduced carbon emission estimates from fossil fuel combustion and cement production in China, Nature, 524, 335–338, 2015.

MacDicken, K. G.: Global Forest Resources Assessment 2015: What, why and how?, Forest Ecol.Manage., 352, 3–8, 2015.

Manning, A. C. and Keeling, R. F.: Global oceanic and land biotic carbon sinks from the Scripps atmospheric oxygen flask sampling network, Tellus B, 58, 95–116, 2006.

Marland, G.: Uncertainties in accounting for CO_2 from fossil fuels, J. Ind. Ecol., 12, 136–139, 2008.

Marland, G., Andres, R. J., Blasing, T. J., Boden, T. A., Broniak, C. T., Gregg, J. S., Losey, L. M., and Treanton, K.: Energy, industry and waste management activities: An introduction to CO_2 emissions from fossil fuels, in: A report by the US Climate Change Science Program and the Subcommittee on Global Change Research, in: The First State of the Carbon Cycle Report (SOCCR): The North American Carbon Budget and Implications for the Global Carbon Cycle, edited by: King, A. W., Dilling, L., Zimmerman, G. P., Fairman, D. M., Houghton, R. A., Marland, G., Rose, A. Z., and Wilbanks, T. J., Asheville, NC, 2007.

Marland, G., Hamal, K., and Jonas, M.: How Uncertain Are Estimates of CO_2 Emissions?, J. Ind. Ecol., 13, 4–7, 2009.

Masarie, K. A. and Tans, P. P.: Extension and integratino of atmospheric carbon dioxide data into a globally consistent measurement record, J. Geophys. Res.-Atmos., 100, 11593–11610, 1995.

McNeil, B. I., Matear, R. J., Key, R. M., Bullister, J. L., and Sarmiento, J. L.: Anthropogenic CO_2 uptake by the ocean based on the global chlorofluorocarbon data set, Science, 299, 235–239, 2003.

Mikaloff Fletcher, S. E., Gruber, N., Jacobson, A. R., Doney, S. C., Dutkiewicz, S., Gerber, M., Follows, M., Joos, F., Lindsay, K., Menemenlis, D., Mouchet, A., Müller, S. A., and Sarmiento, J. L.: Inverse estimates of anthropogenic CO_2 uptake, transport, and storage by the oceans, Global Biogeochem. Cy., 20, GB2002, doi:10.1029/2005GB002530, 2006.

Moran, D. and Wood, R.: CONVERGENCE BETWEEN THE EORA, WIOD, EXIOBASE, AND OPENEU'S CONSUMPTION-BASED CARBON ACCOUNTS, Economic Systems Research, 26, 245–261, 2014.

Myhre, G., Alterskjær, K., and Lowe, D.: A fast method for updating global fossil fuel carbon dioxide emissions, Environ. Res. Lett., 4, 034012, doi:10.1088/1748-9326/4/3/034012, 2009.

Narayanan, B., Aguiar, A., and McDougall, R.: Global Trade, Assistance, and Production: The GTAP 9 Data Base, available at: www.gtap.agecon.purdue.edu/databases/v9/default.asp, last access: September 2015.

National Bureau of Statistics of China: China Energy Statistical Yearbook 2014, China Statistics Press, Beijing, 2015a.

National Bureau of Statistics of China: Industrial Production Operation in August 2015, available at: http://www.stats.gov.cn/english/PressRelease/201509/t20150915_1245026.html, last access: September 2015b.

National Energy Administration: Conference on energy trends for the first half of 2015, available at: http://www.nea.gov.cn/2015-07/27/c_134450600.htm, last access: July 2015.

NOAA/ESRL: NOAA/ESRL calculation of global means, available at: http://www.esrl.noaa.gov/gmd/ccgg/about/global_means.html, last access: 7 October 2015a.

NOAA/ESRL: Multi-laboratory compilation of atmospheric carbon dioxide data for the period 1968–2014, obspack_co2_1_GLOBALVIEWplus_v1.0_2015-07-30, Project, C. G. A. D. I., 2015b.

Oke, P. R., Griffin, D. A., Schiller, A., Matear, R. J., Fiedler, R., Mansbridge, J., Lenton, A., Cahill, M., Chamberlain, M. A., and Ridgway, K.: Evaluation of a near-global eddy-resolving ocean model, Geosci. Model Dev., 6, 591–615, doi:10.5194/gmd-6-591-2013, 2013.

Oleson, K., Lawrence, D., Bonan, G., Drewniak, B., Huang, M., Koven, C., Levis, S., Li, F., Riley, W., Subin, Z., Swenson, S., Thornton, P., Bozbiyik, A., Fisher, R., Heald, C., Kluzek, E., Lamarque, J., Lawrence, P., Leung, L., Lipscomb, W., Muszala, S., Ricciuto, D., Sacks, W., Tang, J., and Yang, Z.: Technical Description of version 4.5 of the Community Land Model (CLM), NCAR, 2013.

Peters, G. P. and Hertwich, E. G.: Post-Kyoto Greenhouse Gas Inventories: Production versus Consumption, Climatic Change, 86, 51–66, 2008.

Peters, G. P., Andrew, R., and Lennos, J.: Constructing a multiregional input-output table using the GTAP database, Economic Systems Research, 23, 131–152, 2011a.

Peters, G. P., Minx, J. C., Weber, C. L., and Edenhofer, O.: Growth in emission transfers via international trade from 1990 to 2008, P. Natl. Acad. Sci. USA, 108, 8903–8908, 2011b.

Peters, G. P., Davis, S. J., and Andrew, R.: A synthesis of carbon in international trade, Biogeosciences, 9, 3247–3276, doi:10.5194/bg-9-3247-2012, 2012a.

Peters, G. P., Marland, G., Le Quéré, C., Boden, T. A., Canadell, J. G., and Raupach, M. R.: Correspondence: Rapid growth in CO_2 emissions after the 2008–2009 global financial crisis, Nature Clim. Change, 2, 2–4, 2012b.

Peters, G. P., Andrew, R. M., Boden, T., Canadell, J. G., Ciais, P., Le Quéré, C., Marland, G., Raupach, M. R., and Wilson, C.: The challenge to keep global warming below 2 °C, Nature Clim. Change, 3, 4–6, 2013.

Peters, W., Krol, M. C., van der Werf, G. R., Houweling, S., Jones, C. D., Hughes, J., Schaefer, K., Masarie, K. A., Jacobson, A. R., Miller, J. B., Cho, C. H., Ramonet, M., Schmidt, M., Giattaglia, L., Apadula, F., Heltai, D., Meinhardt, F., Di Sarra, A. G., Piacentino, S., Sferlazzo, D., Aalto, T., Hatakka, J., Ström, J., Haszpra, L., Meijer, H. A. J., Van Der Laan, S., Neubert, R. E. M., Jordan, A., Rodó, X., Morguí, J.-A., Vermeulen, A. T., Popa, E., Rozanski, K., Zimnoch, M., Manning, A. C., Leuenberger, M., Uglietti, C., Dolman, A. J., Ciais, P., Heimann, M., and Tans, P. P.: Seven years of recent European net terrestrial carbon dioxide exchange constrained by atmospheric observations, Glob. Change Biol., 16, 1317–1337, 2010.

Pfeil, B., Olsen, A., Bakker, D. C. E., Hankin, S., Koyuk, H., Kozyr, A., Malczyk, J., Manke, A., Metzl, N., Sabine, C. L., Akl, J., Alin, S. R., Bates, N., Bellerby, R. G. J., Borges, A., Boutin, J., Brown, P. J., Cai, W.-J., Chavez, F. P., Chen, A., Cosca, C., Fassbender, A. J., Feely, R. A., González-Dávila, M., Goyet, C., Hales, B., Hardman-Mountford, N., Heinze, C., Hood, M., Hoppema, M., Hunt, C. W., Hydes, D., Ishii, M., Johannessen, T., Jones, S. D., Key, R. M., Körtzinger, A., Landschützer, P., Lauvset, S. K., Lefèvre, N., Lenton, A., Lourantou, A., Merlivat, L., Midorikawa, T., Mintrop, L., Miyazaki, C., Murata, A., Nakadate, A., Nakano, Y., Nakaoka, S., Nojiri, Y., Omar, A. M., Padin, X. A., Park, G.-H., Paterson, K., Perez, F. F., Pierrot, D., Poisson, A., Ríos, A. F., Santana-Casiano, J. M., Salisbury, J., Sarma, V. V. S. S., Schlitzer, R., Schneider, B., Schuster, U., Sieger, R., Skjelvan, I., Steinhoff, T., Suzuki, T., Takahashi, T., Tedesco, K., Telszewski, M., Thomas, H., Tilbrook, B., Tjiputra, J., Vandemark, D., Veness, T., Wanninkhof, R., Watson, A. J., Weiss, R., Wong, C. S., and Yoshikawa-Inoue, H.: A uniform, quality controlled Surface Ocean CO_2 Atlas (SOCAT), Earth Syst. Sci. Data, 5, 125–143, doi:10.5194/essd-5-125-2013, 2013.

Pongratz, J., Reick, C. H., Raddatz, T., and Claussen, M.: Effects of anthropogenic land cover change on the carbon cycle of the last millennium, Global Biogeochem. Cy., 23, Gb4001, doi:10.1029/2009gb003488, 2009.

Pongratz, J., Reick, C. H., Houghton, R. A., and House, J. I.: Terminology as a key uncertainty in net land use and land cover change carbon flux estimates, Earth Syst. Dynam., 5, 177–195, doi:10.5194/esd-5-177-2014, 2014.

Poulter, B., Frank, D., Ciais, P., Myneni, R. B., Andela, N., Bi, J., Broquet, G., Canadell, J. G., Chevallier, F., Liu, Y. Y., Running, S. W., Sitch, S., and van der Werf, G. R.: Contribution of semi-arid ecosystems to interannual variability of the global carbon cycle, Nature, 509, 600–603, 2014.

Prather, M. J., Holmes, C. D., and Hsu, J.: Reactive greenhouse gas scenarios: Systematic exploration of uncertainties and the role of atmospheric chemistry, Geophys. Res. Lett., 39, L09803, doi:10.1029/2012GL051440, 2012.

Prentice, I. C., Farquhar, G. D., Fasham, M. J. R., Goulden, M. L., Heimann, M., Jaramillo, V. J., Kheshgi, H. S., Le Quéré, C., Scholes, R. J., and Wallace, D. W. R.: The Carbon Cycle and Atmospheric Carbon Dioxide, in: Climate Change 2001: The Scientific Basis. Contribution of Working Group I to the Third Assessment Report of the Intergovernmental Panel on Climate Change, edited by: Houghton, J. T., Ding, Y., Griggs, D. J., Noguer, M., van der Linden, P. J., Dai, X., Maskell, K., and Johnson, C. A., Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 2001.

Randerson, J., Chen, Y., van der Werf, G. R., Rogers, B. M., and Morton, D. C.: Global burned area and biomass burning emissions from small fires, J. Geophys. Res.-Biogeo., 117, G04012, doi:10.1029/2012JG002128, 2012.

Raupach, M. R., Marland, G., Ciais, P., Le Quéré, C., Canadell, J. G., Klepper, G., and Field, C. B.: Global and regional drivers of accelerating CO_2 emissions, P. Natl. Acad. Sci. USA, 104, 10288–10293, 2007.

Regnier, P., Friedlingstein, P., Ciais, P., Mackenzie, F. T., Gruber, N., Janssens, I. A., Laruelle, G. G., Lauerwald, R., Luyssaert, S., Andersson, A. J., Arndt, S., Arnosti, C., Borges, A. V., Dale, A. W., Gallego-Sala, A., Goddéris, Y., Goossens, N., Hartmann, J., Heinze, C., Ilyina, T., Joos, F., La Rowe, D. E., Leifeld, J., Meysman, F. J. R., Munhoven, G., Raymond, P. A., Spahni, R., Suntharalingam, P., and Thullner M.: Anthropogenic perturbation of the carbon fluxes from land to ocean, Nat. Geosci., 6, 597–607, 2013.

Reick, C. H., Raddatz, T., Brovkin, V., and Gayler, V.: The representation of natural and anthropogenic land cover change in MPI-ESM, Journal of Advances in Modeling Earth Systems, 5, 459–482, 2013.

Rhein, M., Rintoul, S. R., Aoki, S., Campos, E., Chambers, D., Feely, R. A., Gulev, S., Johnson, G. C., Josey, S. A., Kostianoy, A., Mauritzen, C., Roemmich, D., Talley, L. D., and Wang, F.: Chapter 3: Observations: Ocean, in: Climate Change 2013 The Physical Science Basis, Cambridge University Press, Cambridge, United Kingdom, 2013.

Rödenbeck, C.: Estimating CO_2 sources and sinks from atmospheric mixing ratio measurements using a global inversion of atmospheric transport, Max Planck Institute, MPI-BGC, 2005.

Rödenbeck, C., Houweling, S., Gloor, M., and Heimann, M.: CO_2 flux history 1982–2001 inferred from atmospheric data using a global inversion of atmospheric transport, Atmos. Chem. Phys., 3, 1919–1964, doi:10.5194/acp-3-1919-2003, 2003.

Rödenbeck, C., Keeling, R. F., Bakker, D. C. E., Metzl, N., Olsen, A., Sabine, C., and Heimann, M.: Global surface-ocean pCO_2 and sea-air CO_2 flux variability from an observation-driven ocean mixed-layer scheme, Ocean Sci., 9, 193–216, doi:10.5194/os-9-193-2013, 2013.

Rödenbeck, C., Bakker, D. C. E., Metzl, N., Olsen, A., Sabine, C., Cassar, N., Reum, F., Keeling, R. F., and Heimann, M.: Interannual sea-air CO_2 flux variability from an observation-driven ocean mixed-layer scheme, Biogeosciences, 11, 4599–4613, doi:10.5194/bg-11-4599-2014, 2014.

Rödenbeck, C., Bakker, D. C. E., Gruber, N., Iida, Y., Jacobson, A. R., Jones, S., Landschützer, P., Metzl, N., Nakaoka, S., Olsen, A., Park, G.-H., Peylin, P., Rodgers, K. B., Sasse, T. P., Schuster, U., Shutler, J. D., Valsala, V., Wanninkhof, R., and Zeng, J.: Data-based estimates of the ocean carbon sink variability – first results of the Surface Ocean pCO_2 Mapping intercomparison (SOCOM), Biogeosciences Discuss., 12, 14049–14104, doi:10.5194/bgd-12-14049-2015, 2015.

Rost, S., Gerten, D., Bondeau, A., Lucht, W., Rohwer, J., and Schaphoff, S.: Agricultural green and blue water consumption and its influence on the global water system, Water Resour. Res., W09405, doi:10.1029/2007WR006331, 2008.

Rypdal, K., Paciomik, N., Eggleston, S., Goodwin, J., Irving, W., Penman, J., and Woodfield, M.: Chapter 1 Introduction to the 2006 Guidelines, in: 2006 IPCC Guidelines for National Greenhouse Gas Inventories, edited by: Eggleston, S., Buendia, L., Miwa, K., Ngara, T., and Tanabe, K., Institute for Global Environmental Strategies (IGES), Hayama, Kanagawa, Japan, 2006.

Saatchi, S. S., Harris, N. L., and Brown, S.: Benchmark map of forest carbon stocks in tropical regions across three continents, P. Natl. Acad. Sci., 108, 9899–9904, 2011.

Schaphoff, S., Heyder, U., Ostberg, S., Gerten, D., Heinke, J., and Lucht, W.: Contribution of permafrost soils to the global carbon budget., Environ. Res. Lett., 8, 014026, doi:10.1088/1748-9326/8/1/014026, 2013.

Schimel, D., Alves, D., Enting, I., Heimann, M., Joos, F., Raynaud, D., Wigley, T., Prater, M., Derwent, R., Ehhalt, D., Fraser, P., Sanhueza, E., Zhou, X., Jonas, P., Charlson, R., Rodhe, H., Sadasivan, S., Shine, K. P., Fouquart, Y., Ramaswamy, V., Solomon, S., Srinivasan, J., Albritton, D., Derwent, R., Isaksen, I., Lal, M., and Wuebbles, D.: Radiative Forcing of Climate Change, in: Climate Change 1995 The Science of Climate Change. Contribution of Working Group I to the Second Assessment Report of the Intergovernmental Panel on Climate Change, edited by: Houghton, J. T., Meira Rilho, L. G., Callander, B. A., Harris, N., Kattenberg, A., and Maskell, K., Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 1995.

Scripps: The Keeling Curve, available at: http://keelingcurve.ucsd.edu/, last access: 7 November 2013.

Séférian, R., Bopp, L., Gehlen, M., Orr, J., Ethé, C., Cadule, P., Aumont, O., Salas y Mélia, D., Voldoire, A., and Madec, G.: Skill assessment of three earth system models with common marine biogeochemistry, Clim. Dynam., 40, 2549–2573, 2013.

Shevliakova, E., Pacala, S., Malyshev, S., Hurtt, G., Milly, P., Caspersen, J., Sentman, L., Fisk, J., Wirth, C., and Crevoisier, C.: Carbon cycling under 300 years of land use change: Importance of the secondary vegetation sink, Global Biogeochem. Cy., 23, GB2022, doi:10.1029/2007GB003176, 2009.

Sitch, S., Smith, B., Prentice, I. C., Arneth, A., Bondeau, A., Cramer, W., Kaplan, J. O., Levis, S., Lucht, W., Sykes, M. T., Thonicke, K., and Venevsky, S.: Evaluation of ecosystem dynamics, plant geography and terrestrial carbon cycling in the LPJ dynamic global vegetation model, Glob. Change Biol., 9, 161–185, 2003.

Sitch, S., Friedlingstein, P., Gruber, N., Jones, S. D., Murray-Tortarolo, G., Ahlström, A., Doney, S. C., Graven, H., Heinze, C., Huntingford, C., Levis, S., Levy, P. E., Lomas, M., Poulter, B., Viovy, N., Zaehle, S., Zeng, N., Arneth, A., Bonan, G., Bopp, L., Canadell, J. G., Chevallier, F., Ciais, P., Ellis, R., Gloor, M., Peylin, P., Piao, S. L., Le Quéré, C., Smith, B., Zhu, Z., and Myneni, R.: Recent trends and drivers of regional sources and sinks of carbon dioxide, Biogeosciences, 12, 653–679, doi:10.5194/bg-12-653-2015, 2015.

Smith, B., Wårlind, D., Arneth, A., Hickler, T., Leadley, P., Siltberg, J., and Zaehle, S.: Implications of incorporating N cycling and N limitations on primary production in an individual-based dynamic vegetation model, Biogeosciences, 11, 2027–2054, doi:10.5194/bg-11-2027-2014, 2014.

Smith, P., Bustamante, M., Clark, H., Dong, H., Elsiddig, E. A., Haberl, H., Harper, R., House, J. I., Jafari, M., Masera, O., Mbow, C., Ravindranath, N. H., Rice, C. W., Robledo Abad, C., Romanovskaya, A., Sperling, F., and Tubiello, F. N.: Agriculture, Forestry and Other Land Use (AFOLU), in: Chapter 11 in Climate Change 2014: Mitigation of Climate Change. Contribution of Working Group III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change, edited by: Edenhofer, O., Pichs-Madruga, R., Sokona, Y., Farahani, E., Kadner, S., Seyboth, K., Adler, A., Baum, I., Brunner, S., Eickemeier, P., Kriemann, B., Savolainen, J., Schlömer, S., von Stechow, C., Zwickel, T., and Minx, J. C., Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 2014.

Stephens, B. B., Gurney, K. R., Tans, P. P., Sweeney, C., Peters, W., Bruhwiler, L., Ciais, P., Ramonet, M., Bousquet, P., Nakazawa, T., Aoki, S., Machida, T., Inoue, G., Vinnichenko, N., Lloyd, J., Jordan, A., Heimann, M., Shibistova, O., Langenfelds, R. L., Steele, L. P., Francey, R. J., and Denning, A. S.: Weak Northern and Strong Tropical Land Carbon Uptake from Vertical Profiles of Atmospheric CO_2, Science, 316, 1732–1735, 2007.

Stocker, T., Qin, D., and Platner, G.-K.: Climate Change 2013 The Physical Science Basis, Cambridge University Press, Cambridge, United Kingdom, 2013.

Sweeney, C., Gloor, E., Jacobson, A. R., Key, R. M., McKinley, G., Sarmiento, J. L., and Wanninkhof, R.: Constraining global air-sea gas exchange for CO_2 with recent bomb ^{14}C measurements, Global Biogeochem. Cy., 21, GB2015, doi:10.1029/2006GB002784, 2007.

Tans, P. and Keeling, R. F.: Trends in atmospheric carbon dioxide, National Oceanic & Atmospheric Administration, Earth System Research Laboratory (NOAA/ESRL) & Scripps Institution of Oceanography, available at: http://www.esrl.noaa.gov/gmd/ccgg/trends/ and http://scrippsco2.ucsd.edu/, last access: 8 August 2014.

Tjiputra, J. F., Roelandt, C., Bentsen, M., Lawrence, D. M., Lorentzen, T., Schwinger, J., Seland, Ø., and Heinze, C.: Evaluation of the carbon cycle components in the Norwegian Earth System Model (NorESM), Geosci. Model Dev., 6, 301–325, doi:10.5194/gmd-6-301-2013, 2013.

Tubiello, F. N., Salvatore, M., Ferrara, A. F., House, J., Federici, S., Rossi, S., Biancalani, R., Condor Golec, R. D., Jacobs, H., Flammini, A., Prosperi, P., Cardenas-Galindo, P., Schmidhuber, J., Sanz Sanchez, M. J., Srivastava, N., and Smith, P.: The contribution of agriculture, forestry and other land use activities to global warming 1990–2012, Glob. Change Biol., 21, 2655–2660, doi:10.1111/gcb.12865, 2015.

Tyukavina, A., Baccini, A., Hansen, M. C., Potapov, P. V., Stehman, S. V., Houghton, R. A., Krylov, A. M., Turubanova, S., and Goetz, S. J.: Aboveground carbon loss in natural and managed tropical forests from 2000 to 2012, Environ. Res. Lett., 10, 074002, doi:10.1088/1748-9326/10/7/074002, 2015.

UN: United Nations Statistics Division: Energy Statistics, United Nations Statistics Division: Energy Statistics, available at: http://unstats.un.org/unsd/energy/ (last access: October 2015), 2014a.

UN: United Nations Statistics Division: Industry Statistics, United Nations Statistics Division: Industry Statistics, available at: http://unstats.un.org/unsd/industry/default.asp (last access: October 2015), 2014b.

UN: United Nations Statistics Division: National Accounts Main Aggregates Database, United Nations Statistics Division: National Accounts Main Aggregates Database, available at: http://unstats.un.org/unsd/snaama/Introduction.asp (last access: February 2015), 2014c.

UNFCCC: GHG Data – UNFCCC, available at: http://unfccc.int/ghg_data/ghg_data_unfccc/time_series_annex_i/items/3814.php, last access: May 2015.

USGS: Mineral Commodities Summaries: Cement, USGS, 2015.

van der Werf, G. R., Dempewolf, J., Trigg, S. N., Randerson, J. T., Kasibhatla, P., Giglio, L., Murdiyarso, D., Peters, W., Morton, D. C., Collatz, G. J., Dolman, A. J., and DeFries, R. S.: Climate regulation of fire emissions and deforestation in equatorial Asia, P. Natl. Acad. Sci., 15, 20350–20355, 2008.

van der Werf, G. R., Randerson, J. T., Giglio, L., Collatz, G. J., Mu, M., Kasibhatla, P. S., Morton, D. C., DeFries, R. S., Jin, Y., and van Leeuwen, T. T.: Global fire emissions and the contribution of deforestation, savanna, forest, agricultural, and peat fires (1997–2009), Atmos. Chem. Phys., 10, 11707–11735, doi:10.5194/acp-10-11707-2010, 2010.

van Minnen, J. G., Goldewijk, K. K., Stehfest, E., Eickhout, B., van Drecht, G., and Leemans, R.: The importance of three centuries of land-use change for the global and regional terrestrial carbon cycle, Climatic Change, 97, 123–144, 2009.

van Oss, H. G.: Cement, US Geological Survey, June, 2013.

van Oss, H. G.: Cement, US Geological Survey, 2015.

Waha, K., van Bussel, L. G. J., Müller, C., and Bondeau, A.: Climate-driven simulation of global crop sowing dates, Global Ecol. Biogeogr., 12, 247–259, 2012.

Wanninkhof, R., Park, G.-H., Takahashi, T., Sweeney, C., Feely, R., Nojiri, Y., Gruber, N., Doney, S. C., McKinley, G. A., Lenton, A., Le Quéré, C., Heinze, C., Schwinger, J., Graven, H., and Khatiwala, S.: Global ocean carbon uptake: magnitude, variability and trends, Biogeosciences, 10, 1983–2000, doi:10.5194/bg-10-1983-2013, 2013.

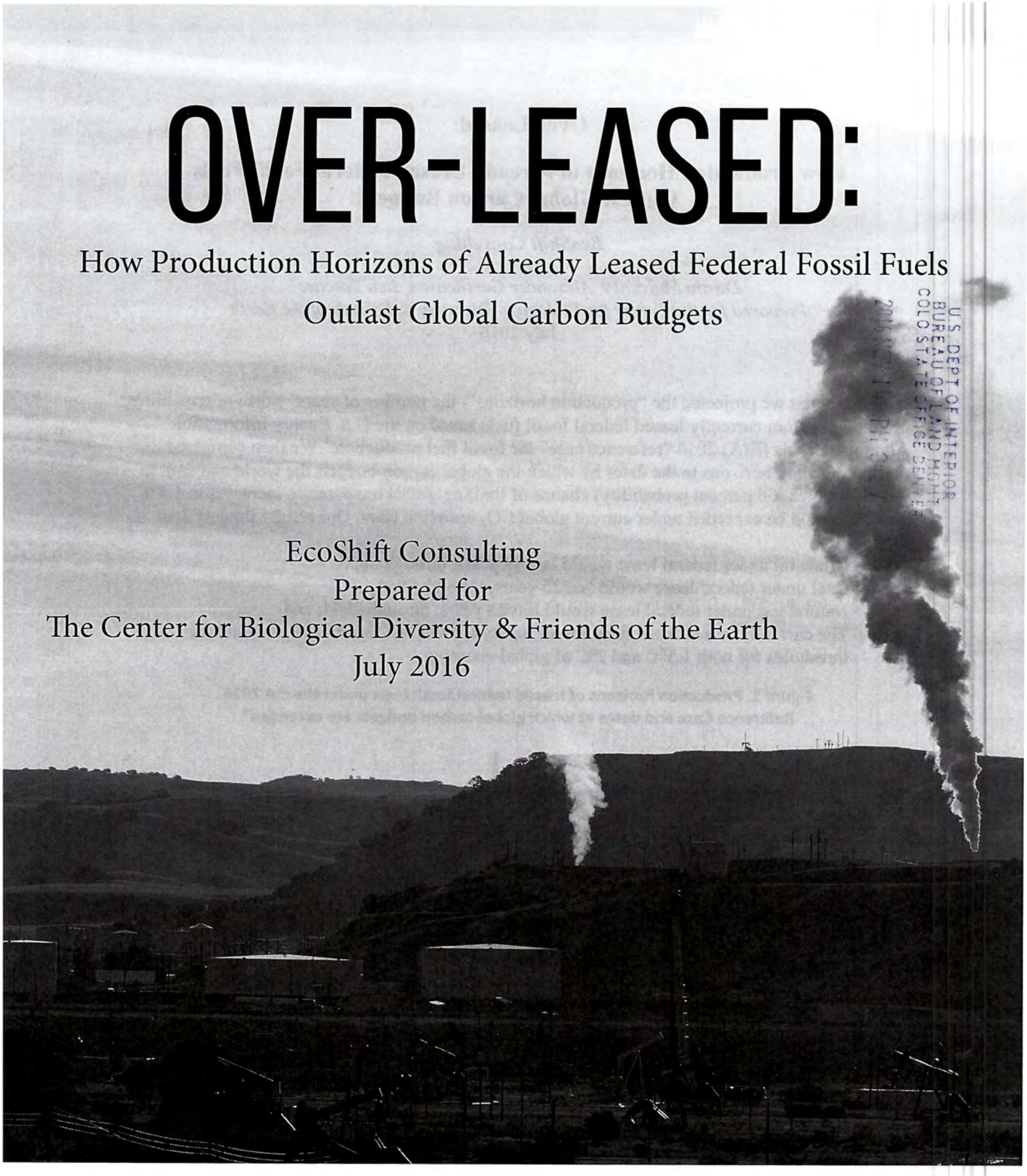
Watson, R. T., Rodhe, H., Oeschger, H., and Siegenthaler, U.: Greenhouse Gases and Aerosols, in: Climate Change: The IPCC Scientific Assessment. Intergovernmental Panel on Climate Change (IPCC), edited by: Houghton, J. T., Jenkins, G.

J., and Ephraums, J. J., Cambridge University Press, Cambridge, United Kingdom, 1990.

Zaehle, S., Friend, A. D., Friedlingstein, P., Dentener, F., Peylin, P., and Schulz, M.: Carbon and Nitrogen Cycle Dynamics in the O-CN Land Surface Model: 2. Role of the Nitrogen Cycle in the Historical Terrestrial Carbon Balance, Global Biogeochem. Cy., 24, GB1006, doi:10.1029/2009GB003522, 2010.

Zaehle, S., Ciais, P., Friend, A. D., and Prieur, V.: Carbon benefits of anthropogenic reactive nitrogen offset by nitrous oxide emissions, Nat. Geosci., 4, 601–605, 2011.

Exhibit 21



OVER-LEASED:

How Production Horizons of Already Leased Federal Fossil Fuels Outlast Global Carbon Budgets

EcoShift Consulting
Prepared for
The Center for Biological Diversity & Friends of the Earth
July 2016

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CENTER for BIOLOGICAL DIVERSITY

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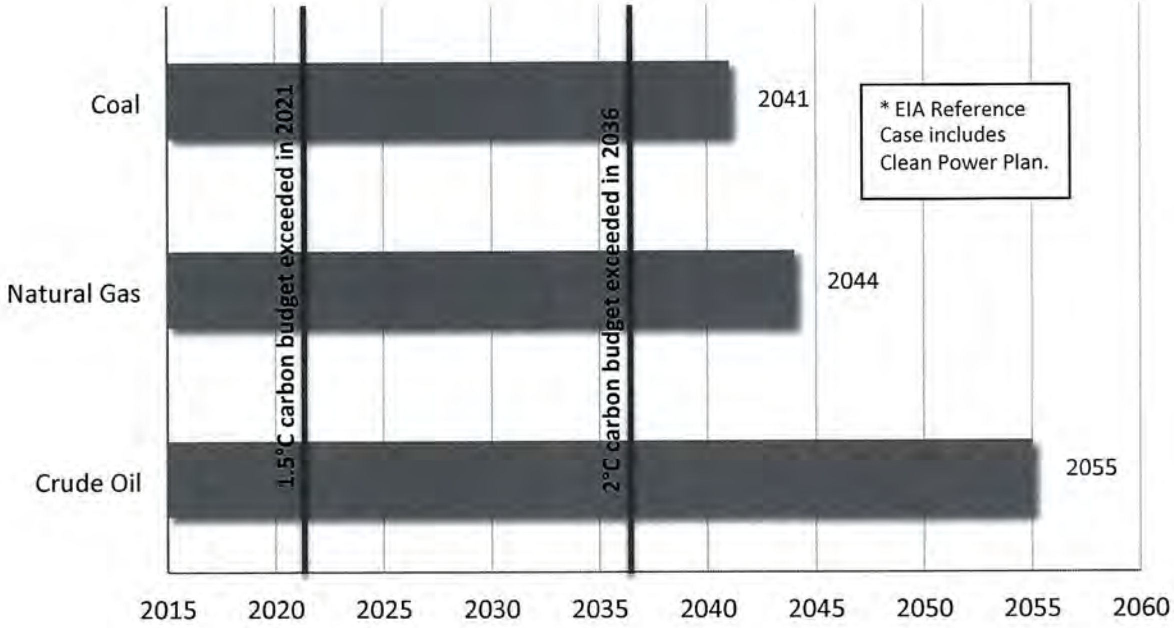
Overview

In this analysis we projected the "production horizons"- the number of years' worth of remaining production - from currently leased federal fossil fuels based on the U.S. Energy Information Administration's (EIA) 2016 "reference case" for fossil fuel production.[1] We then compared these production horizons to the dates by which the global carbon budgets the world can emit to have a "likely" (66 percent probability) chance of limiting global temperature increases to 1.5°C and 2°C would be exceeded under current global CO_2 emission rates. Our results suggest that:

- Crude oil under federal lease would last 39 years, through 2055;
- Coal under federal lease would last 25 years, through 2041;
- Natural gas under federal lease would last 28 years, through 2044; and
- The currently leased fossil fuels for all fuel types will last significantly beyond the thresholds for both 1.5°C and 2°C of global warming.

Figure 1. Production horizons of leased federal fossil fuels under the EIA 2016 Reference Case and dates at which global carbon budgets are exceeded*



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[1] Energy Information Agency. 2016. Annual Energy Outlook. https://www.eia.gov/forecasts/aeo/index.cfm

Assuming current global CO_2 emissions continue at 2014 rates, and U.S. fossil fuel production continues as estimated by the EIA, we project that existing federal leases will still be producing fossil fuels long after global carbon budgets have been exhausted. Our analysis found that for all fossil fuels, production from lands and waters already leased to industry would outlast the 1.5°C carbon budget by several decades, and the 2°C budget by years to decades. Importantly, every new lease would extend production horizons even further into the future. As previous studies suggest, federal fossil fuel leasing policy should be aligned with U.S. climate policy goals. The analysis strongly suggests that staying within the global carbon budgets will likely require not only ending new federal leases, but also keeping significant amounts of *already leased* federal fossil fuels in the ground.

Introduction

Climate change is already affecting ecosystems, the food supply and public health, and further increases in warming will have even more significant impacts on human health and the environment. The 2015 Paris Agreement reached by 195 countries around the globe aims to hold global warming "well below 2°C above pre-industrial levels" and commits parties to "pursu[e] efforts to limit the temperature increase to 1.5°C above pre-industrial levels."[2] Immediate and aggressive greenhouse gas emissions reductions are vital to achieving both of these goals.

According to the IPCC, to maintain just a "likely" (66 percent probability) of limiting global warming to 1.5°C requires adherence to a stringent carbon budget of only 400 $GtCO_2$ beginning in 2011, of which about 240 $GtCO_2$ remained at the start of 2015.[3] Further, to maintain a 66 percent chance of keeping global temperatures under 2°C, a threshold that countries agreed to stay "well below" in the Paris Agreement, the global carbon budget was 1,000 $GtCO_2$ in 2011, of which only 850 $GtCO_2$ remained as of 2015. With global annual emissions amounting to 36 $GtCO_2$ in 2015,[4] scientists predict that at current rates global emissions will exceed the carbon budgets necessary to stay under the 1.5°C target by 2021 and the 2°C target by 2036.[5]

Even considering the emissions reductions that can be accomplished under the Clean Power Plan and other federal and state climate policies, the EIA projects that U.S. energy production will continue to grow at a rate of 1 percent per year through 2040.[6] The U.S. was the top global oil and natural gas producer in 2014, and only China extracts more coal.[7] The EIA projections assume the U.S. continues to be a major fossil fuel exporter into the future in competition for an increasing share of overall global production. As a result, even as the U.S. commits to consume

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[2] Paris Agreement, article 2, § 1(a), at http://unfccc.int/paris_agreement/items/9485.php.

[3] Rogelj, J. et al. (2016) report that the global carbon budget was reduced by ~160 $GtCO_2$ between 2011 and 2015. *See* Table 2 in Rogelj, J. et al. (2016). Differences between carbon budget estimates unraveled. Nature Climate Change 6: 245-252.

[4] Oak Ridge National Laboratories. 2015. Carbon Dioxide Information Analysis Center. http://cdiac.ornl.gov/GCP/

[5] Carbon Brief. 2016. Data Dashboard: Climate, the IPCC's carbon budgets. http://www.carbonbrief.org/data-dashboard-climate-change

[6] Energy Information Agency. 2016. Annual Energy Outlook, Total Energy Supply, Disposition, and Price Summary. https://www.eia.gov/forecasts/aeo/data/browser/#/?id=1-AEO2016&region=0-0&cases=ref2016~ref_no_cpp&start=2013&end=2040&f=A&linechart=~~ref2016-d032416a.12-1-AEO2016~ref_no_cpp-d032316a.12-1-AEO2016&ctype=linechart&sourcekey=0

[7] BP. 2015. BP Statistical Review of World Energy. 64th Edition. http://www.bp.com/content/dam/bp/pdf/energy-economics/statistical-review-2015/bp-statistical-review-of-world-energy-2015-coal-section.pdf

less fossil fuels domestically, the EIA projects increased domestic fossil fuel production. Federal lands accounted for 23.7 percent of fossil fuel production in the U.S. 2014.[8]

Objective

In order to evaluate how federal mineral leasing policy aligns with U.S. climate change goals and global carbon budgets, this research estimated the production horizons — how long federal fossil fuels that have already been leased to industry will last — for crude oil, natural gas and coal. Our objectives are twofold: 1) Model how long already leased federal fossil fuel deposits will produce into the future under the EIA reference scenario;[9] and 2) Compare those production horizons with dates by which global CO_2 emissions (if they continue at 2014 levels) will exceed global carbon budgets for maintaining a "likely" (66 percent) chance of limiting global warming to 1.5ºC and 2ºC above pre-industrial levels.

Methodology

We analyzed federal fossil fuels— coal, oil and natural gas— that are currently under lease for production on federal lands and offshore areas (hereafter, "federal lands"). To estimate the production horizons for already leased federal fossil fuels, we calculated an annual rate of energy production on federal lands. Our methodology is as follows:

Step 1: We compiled U.S. energy production data reported in quads (quadrillion British thermal units or Btu) of energy from the EIA's 2016 *Annual Energy Outlook* that reports on 2014 production and makes projections for every year through 2040 for each of coal, natural gas and oil. We used the overall growth rate for each fossil fuel from 2014-2040 to extrapolate annual production for 2041 and each year beyond. To calculate annual federal production from existing leases, we assumed annual federal coal, oil (combined with condensate), and natural gas extraction will be a function of overall U.S. production multiplied by the proportions of production that occur on federal lands.

To calculate the rate of annual federal production from existing leases, we assumed the rate of federal coal, oil (combined with condensate), and natural gas extraction will be a function of overall U.S. production multiplied by the proportions of production that occur on federal lands. The proportion of federal coal, oil, and natural gas production is based on data collected by the Department of Interior and published by the EIA.[10] These data show that federal lands supplied 21.4 percent of oil, 14.1 percent of natural gas, and 40.7 percent of coal produced in the U.S. in 2014. We assumed these proportions would stay consistent throughout the production horizon. Multiplying overall U.S. coal, oil, and natural gas production projected by the EIA by these percentages gave us the annual rates of federal coal, oil, and natural gas production.

Step 2: The total energy content of already leased federal crude oil, coal, and natural gas was estimated using energy inventories from the Energy Policy and Conservation Act (EPCA Phase 3) and leasing data from the Office of Natural Resource Revenue (ONRR), Bureau of Land

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[8] Energy Information Agency. 2015. Sales of Fossil Fuels Produced from Federal and Indian Lands, FY 2003 through FY 2014. http://www.eia.gov/analysis/requests/federallands/pdf/eia-federallandsales.pdf

[9] EIA "reference case" for U.S. fossil fuel production reflects production under current federal, state and local laws and regulations and includes implementation of the Clean Power Plan (CPP) rules and regulations.

[10] Energy Information Agency. 2015. Sales of Fossil Fuels Produced from Federal and Indian Lands, FY 2003 through FY 2014. http://www.eia.gov/analysis/requests/federallands/pdf/eia-federallandsales.pdf

Management (BLM), Bureau of Ocean Energy Management (BOEM), and Government Accountability Office (GAO). The equations and steps used to calculate "already leased" federal resources are described in Appendix 1 of *the Potential Greenhouse Gas Emissions of U.S. Federal Fossil Fuels*.[11] The EPCA Phase 3 inventory estimates the total energy in federal crude oil and natural gas.[12] The portion of onshore crude oil ad natural gas already leased is calculated using BLM data.[13] Offshore crude oil and natural gas already leased is based on statistics from BOEM for the Gulf of Mexico, Southern California, and Alaska.[14] The amount of federal coal under lease is not available, so the calculation is based on data from GAO,[15] BLM,[16] and the percentage of leased and unmined federal coal reserves remaining in the Powder River Basin.[17] This total amount of energy in leases for federal crude oil, coal, and natural gas was divided by the 2014 rates of federal crude oil, coal, and natural gas production. The result is the production horizon for federal coal, oil and natural gas leases.

Figure 2a. Step 1 calculated the annual rate of federal oil, coal, and natural gas production

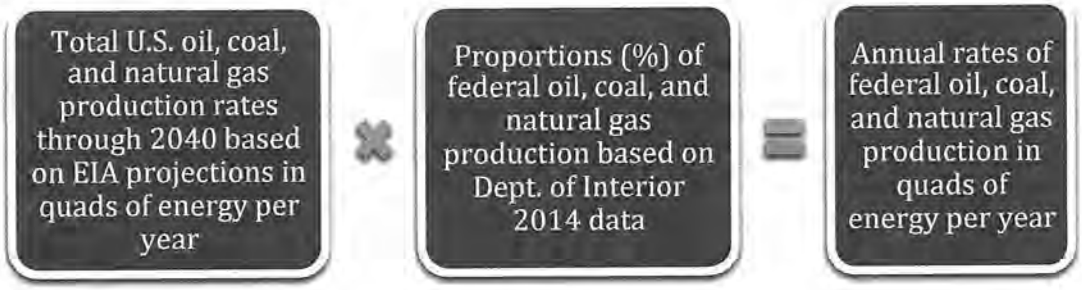

Figure 2b. Step 2 compiled the total inventory of federal oil, coal, and natural gas leases and divided this by the annual rates of federal production to get the production horizons

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[11] Appendix 1, pages 26–28, EcoShift Consulting. 2015. The Potential Greenhouse Gas Emissions from U.S. Federal Fossil Fuels. Report for the Center for Biological Diversity and Friends of the Earth. http://www.ecoshiftconsulting.com/wp- content/uploads/Potential-Greenhouse-Gas-Emissions-U-S-Federal-Fossil-Fuels.pdf

[12] Bureau of Land Management. 2008. Energy Policy and Conservation Act. Phase 3 Inventory. http://www.blm.gov/wo/st/en/prog/energy/oil_and_gas/EPCA_III.html

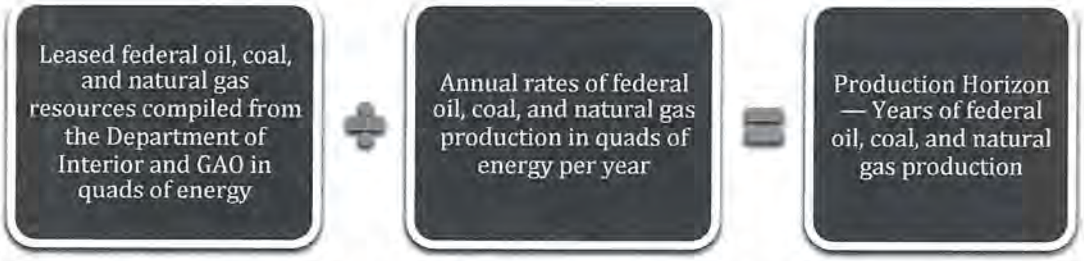
[13] BLM 2014a. United States Department of the Interior, Bureau of Land Management. "Oil and Gas Statistics." http:// www.blm.gov/wo/st/en/prog/energy/oil_and_gas/statistics.html

[14] BOEM 2015. United States Bureau of Ocean Energy Management. "Combined Leasing Report as of February 2, 2015." http://www.boem.gov/Combined-Leasing-Report-February-2015/

[15] GAO 2013. "Coal Leasing - BLM Could Enhance Appraisal Process, More Explicitly Consider Coal Exports, and Provide More Public Information." http://www.gao.gov/assets/660/659801.pdf

[16] BLM 2014b. United States Department of the Interior, Bureau of Land Management. "Total Federal Coal Leases in Effect, Total Acres Under Lease, and Lease Sales by Fiscal Year Since 1990." http://www.blm.gov/wo/st/en/prog/energy/ coal and_non-energy/coal_lease_table.html

[17] Wright, S. 2015. Electronic mail correspondence with Steven S. Wright, P.E., MBA, Assistant District Manager, Solid Minerals, BLM Wyoming High Plains District dated Friday May 15, 2015.



Finally, we used an analysis conducted by Carbon Brief that estimates the number of years until global carbon budgets for 1.5°C and 2°C temperature thresholds are exceeded. Carbon Brief used the remaining quota of global CO_2 emissions that can be emitted to maintain a "likely" chance (66 percent) of limiting global temperature increases to 1.5°C or 2°C above pre-industrial levels (the remaining "carbon budget") and divided this by annual global CO_2 emissions as of 2014. These results projected what year the carbon budgets for 1.5°C and 2°C would be exceeded if 2014 emissions levels continue. The global quota used by Carbon Brief is based on climate science compiled by the Intergovernmental Panel on Climate Change (IPCC).[18]

Since the IPCC produced this budget in 2011, Carbon Brief updated the carbon budget to reflect the remaining quota in 2016 by subtracting annual CO_2 emissions that have occurred since 2011. Oak Ridge National Laboratories compiled the annual emissions data underlying Carbon Brief's analysis, which used annual CO_2 emissions from 2011–2014, and applied 2014 emissions rates for each year into the future.[19] The results of Carbon Brief's analysis show that global emissions will exceed the global carbon budget to likely stay below 1.5°C by 2021, and the global carbon budget to likely stay below 2°C by 2036, if the 2014 pace of emissions continues.

Results

The production horizon for leased crude oil extends the furthest into the future, lasting 39 years until 2055. Natural gas production on federal lands will last 28 years, through 2044. The production horizon for coal extends 25 years to 2041. In the EIA's reference scenario, the CPP lowers demand for coal-powered electricity, creating lower domestic demand for coal.

Comparing these production horizons to dates at which carbon budgets would be exceeded if current emissions level continue:

- Federal crude oil already leased will continue producing 34 years beyond the 1.5°C threshold and 19 years beyond 2°C;
- Federal natural gas already leased will continue producing 23 years beyond the 1.5°C threshold and 8 years beyond 2°C;
- Federal coal already leased will continue producing 20 years beyond the 1.5°C threshold and 5 years beyond 2°C.

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[18] Intergovernmental Panel on Climate Change. 2014: Climate Change 2014: Synthesis Report. Contribution of Working Groups I, II and III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change [Core Writing Team, R.K. Pachauri and L.A. Meyer (eds.)]. IPCC, Geneva, Switzerland. http://www.ipcc.ch/pdf/assessment-report/ar5/syr/SYR_AR5_FINAL_full_wcover.pdf

[19] Oak Ridge National Laboratories. 2015. Carbon Dioxide Information Analysis Center. http://cdiac.ornl.gov/GCP/

Conclusion

Production horizons from already leased federal fossil fuels calculated in this report will last for decades into the future and extend beyond projected dates by which the global carbon budgets necessary to maintain a likely chance of limiting global warming to 1.5ºC (2021) and 2ºC (2036) will be exceeded if current global emission levels continue. Further, the federal government continues to offer new leases that will extend production horizons even further into the future.[20]

These findings add to prior research estimating that ceasing federal fossil fuel leasing would remove up to 450 $GtCO_2e$ from the threat of development and prevent 100 million tons in annual CO_2 emissions through 2030.[21, 22]

Our analysis is not meant to suggest that current emissions rates must or will continue into the foreseeable future or that carbon budgets will be exceeded in a fixed number of years. Indeed, if we are to avoid the worst effects of climate change, emissions rates must decline steeply, and immediately. Success in significantly lowering emissions rates would also extend production horizons. Changes in emissions rates, either upward or downward, would necessarily affect the dates by which the 1.5°C and 2°C carbon budgets are exhausted. Nor do we intend to suggest that if all federal fossil fuels remain in the ground, no further climate action would be necessary. Preserving a likely chance of meeting the goals of the Paris Agreement will require additional, concerted efforts in the U.S. and around the world.

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[20] The Department of the Interior has put in place a moratorium on most new coal leasing while it conducts a Programmatic Environmental Impact Statement of the federal coal-leasing program.

[21] EcoShift Consulting. 2015. The Potential Greenhouse Gas Emissions from U.S. Federal Fossil Fuels. Report for the Center for Biological Diversity and Friends of the Earth. http://www.ecoshiftconsulting.com/wp-content/uploads/Potential-Greenhouse-Gas-Emissions-U-S-Federal-Fossil-Fuels.pdf

[22] Stockholm Environment Institute. 2016. How would phasing out U.S. federal leases for fossil fuel extraction affect CO2 emissions and 2°C goals? Working Paper No. 2016-02.

Exhibit 22

Title:

Differences between carbon budget estimates unravelled

Authors:

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Preface:

Several methods exist to estimate the cumulative carbon emissions which would keep global warming to below a given temperature limit. We here review estimates reported by the IPCC and the recent literature, and discuss the reasons underlying their differences. The most scientifically robust number – the carbon budget for CO_2-induced warming only – is also the least relevant for real-world policy. Including all greenhouse gases and using methods based on scenarios that avoid instead of exceed a given temperature limit results in lower carbon budgets. To limit warming below the internationally agreed temperature limit of 2°C relative to preindustrial levels with >66% chance, the most appropriate carbon budget estimate is 590-1240 $GtCO_2$ from 2015 onward. Variations within this range depend on the probability of staying below 2°C and on end-of-century non-CO_2 warming. Current annual CO_2 emissions are about 40 $GtCO_2$/yr, and global CO_2 emissions thus have to be reduced urgently to keep within a 2°C-compatible budget.

Main text:

The ultimate objective of the international climate negotiations is to prevent dangerous anthropogenic interference with the climate system[1]. Since 2010, this objective has been interpreted as limiting global-mean temperature increase to below 2°C relative to preindustrial levels[2], although discussion remains whether it needs to be strengthened to 1.5°C (for example, see Ref. 3).

Over the past decade, a large body of literature has appeared which shows that the maximum global-mean temperature increase as a result of carbon dioxide emissions is nearly linearly proportional to the total cumulative carbon (CO_2) emissions[4-11]. Maximum warming is also influenced by the amount of non-CO_2 forcing leading up to the time of the peak[12-14]. This has culminated in the most recent assessment of the Intergovernmental Panel on Climate Change (IPCC) in the form of several estimates of emission budgets compatible with limiting warming to below specific temperature limits. Here, we first explain the underlying scientific rationale for such budgets and then continue with a detailed account of the strengths and limitations of the various budgets reported in both the IPCC Fifth Assessment Report (AR5) and the recent literature, and of the differences between them.

The purpose of budgets

The IPCC AR5 Working Group I (WGI) Report[15] indicated that the total net cumulative emission of anthropogenic CO_2 is the principal driver of long-term warming since preindustrial times. Therefore, to limit the warming caused by CO_2 emissions to below a given temperature threshold, cumulative CO_2 emissions from all anthropogenic sources need to be capped to a specific amount, sometimes referred to as carbon budget or quota (which, in the context of this paper, refers to global values and not to emission allowances of single countries).

The near-linearity between peak global-mean temperature rise and cumulative CO_2 emissions is the result of an incidental interplay of several compensating feedback processes in both the carbon cycle and the climate: the logarithmic relationship between atmospheric CO_2 concentrations and radiative forcing, the decline of ocean-heat-uptake efficiency over time, as well as the change of the airborne fraction of anthropogenic CO_2 emissions[15]. This compensating relationship is robust over a range of CO_2 emissions and over timescales of up to a few centuries, with very few exceptions[16]. Such a relationship is not generally available for other anthropogenic radiatively active species. An approximate proportionality exists for other long-lived greenhouse gases (GHG) for warming during this century[12], while for short-lived climate forcers the rate of emissions leading up to the time of peak warming is important[12-14].

The unique characteristics of the Earth system's response to anthropogenic carbon emissions allow the definition of a quantity called the transient climate response to cumulative emissions of carbon

(TCRE). TCRE is defined as global average surface temperature change per unit of total cumulative anthropogenic CO_2 emissions, typically 1000 PgC. The IPCC AR5 assessed TCRE to fall 'likely' (i.e. with greater than 66% probability[17]) between 0.8 to 2.5°C per 1000 PgC for cumulative CO_2 emissions less than about 2000 PgC and until the time at which temperature peaks.

The constancy of TCRE means that it can also be assessed for the real world by dividing an estimate of CO_2-induced warming to date by an estimate of anthropogenic CO_2 emissions[5,10]. Such an approach relies on a calculation of GHG-attributable warming using a regression of observed warming onto the simulated response to GHG and other forcings, and an estimate of the ratio of CO_2 to total GHG radiative forcing or temperature response. Alternatively TCRE may be assessed from observations by applying observational constraints to the parameters of a simple carbon-cycle climate model[7,8], and evaluating the ratio of warming to emissions for the constrained model.

For a carbon budget approach to make sense, TCRE must be reasonably independent of the pathway of emissions. Earlier studies have indeed shown that this is the case[7,8,18,19], at least for peak warming and monotonously increasing cumulative carbon emissions. If a set carbon budget limit is exceeded, CO_2 needs to be removed actively from the atmosphere afterwards[20-22] to bring emissions back to within the budget. Figure 1 illustrates this path independency (even for moderate amounts of net negative CO_2 emissions), and shows with the simple carbon-cycle and climate model MAGICC[7,23,24] that even with large variations in the pathway of CO_2 emissions during the 21st century, the transient temperature paths as a function of cumulative CO_2 emissions are very similar – a characteristic also found in other models[18,25]. Once all pathways achieve the same end-of-century cumulative CO_2 emissions, the temperature projections are virtually identical (Figure 1b).

Given these considerations, carbon budgets are a useful guide for defining and characterizing emissions pathways which limit warming to certain levels, such as 2°C relative to preindustrial.

An abundance of carbon budgets

Budget for CO_2-induced warming only

The most direct application of TCRE is to derive cumulative carbon budgets consistent with limiting CO_2-induced warming to below a specific temperature threshold. For instance, IPCC WGI indicates[26] that limiting anthropogenic CO_2-induced warming to below 2°C relative to 1861-1880 with an assessed probability of greater than 50% will require cumulative CO_2 emissions from all anthropogenic sources since that period to stay approximately below 4440 $GtCO_2$. Alternatively, doing so with a greater than 66% probability would imply a 3670 $GtCO_2$ budget. These values assume a normal distribution of which the standard-deviation (1-sigma) range is given by the assessed 'likely'

TCRE range of 0.8 to 2.5°C per 1000 PgC (i.e., about 3670 $GtCO_2$), and make use of the near-linearity of the ratio of CO_2-induced warming and cumulative CO_2 emissions[15].

While being the most robust translation of the TCRE concept into a cumulative carbon budget, it is at the same time also the least directly useful to policy-making. In the real world, non-CO_2 forcing also plays a role, and its global-mean temperature effect is superimposed on the CO_2-induced warming. A carbon budget derived from a TCRE-based estimate should thus not be used in isolation.

The near-linear relationship of TCRE does hence not necessarily apply to the ratio of total human-induced warming to cumulative carbon emissions (as might be suggested by Figure SPM.10 in Ref. 26). The latter relationship is scenario dependent, because, for example, the percentage contribution of non-CO_2 climate drivers to total anthropogenic warming increases in the future in many scenarios. Therefore, to take into account the influence of non-CO_2 forcing on carbon budgets, the TCRE-based approach can be extended using multi-gas emission scenarios. Multi-gas emission scenarios provide an internally consistent evolution over time of all radiatively active species of anthropogenic origin. They are often created with "integrated assessment models" (IAMs) which represent interactions within the global energy-economy-land system (for examples, see Refs. 27-29).

Threshold exceedance budgets

A first, straight-forward methodology to extend TCRE-based carbon budgets for CO_2-induced warming to budgets that also take into account non-CO_2 warming is here defined as *threshold exceedance budgets* (TEB) for multi-gas warming (see Table 1).

This approach uses multiple realisations of the simulated response to a multi-gas emission scenario. These realisations can either be multi-model ensembles or perturbed parameter ensembles. An example of the former would be simulations of the Representative Concentration Pathways[30,31] (RCP) by Earth-System Models (ESMs) that were contributed to the Fifth Phase of the Coupled Model Intercomparison Project[32] (CMIP5). An example of the latter would be the use of a simple climate model in a probabilistic setup[7,23,24], as used in the assessments of the IPCC[33-35] as well as in other recent studies[36-38]. From such multi-model or perturbed parameter ensembles, the carbon budget is estimated at the time a specified share (for example, 50% or one third) of realisations exceeds a given temperature limit (i.e., 50% or two thirds of the ensemble members remain below the limit, see orange scenario in Figure 2).

The TEB approach was used by IPCC WGI for determining carbon budgets that account for non-CO_2 forcing[15]. Applying this methodology to the CMIP5 RCP8.5 (Ref. 39) simulations of ESMs[10,40] and Earth-System Models of Intermediate Complexity[41] (EMICs), they found that compatible CO_2

emissions since 1870 are about 3010 $GtCO_2$ and 2900 $GtCO_2$ to limit warming to less than 2°C since the period 1861–1880 in more than 50% and 66% of the available model runs, respectively. Other recent studies[36] have used an extended version of this approach which computes TEBs based on perturbed parameter ensembles of a subset of scenarios from the IPCC AR5 Scenario Database (hosted at the International Institute for Applied Systems Analysis – IIASA, and available at https://secure.iiasa.ac.at/web-apps/ene/AR5DB/).

The results of a TEB approach are most useful if the warming due to non-CO_2 forcing as a function of cumulative CO_2 emissions is similar across scenarios, meaning that the conclusions are not strongly dependent on the scenario chosen. However, Figure 3a shows that there is quite a large variation in non-CO_2 forcing for a given level of cumulative CO_2 emissions when looking at all scenarios available in the IPCC AR5 Scenario Database. Caution is therefore advised when deriving carbon budgets based on one single multi-gas scenario (see more below). Finally, the use of TEBs for limiting warming to below a given temperature limit, assumes that non-CO_2 warming never increases beyond the level it reached at the time the TEB was computed (see Figure 2). Also non-CO_2 forcing thus needs to be kept within limits over time.

Threshold avoidance budgets

Carbon budgets defined in the previous section are derived at the time a given scenario exceeds a specific temperature threshold or limit. A complementary approach is to consider multiple emission scenarios and evaluate carbon budgets for the subset of scenarios that avoid crossing such a threshold with a given probability. We name these budgets *threshold avoidance budgets* (TAB, see Table 1). Because, by definition, such scenarios do not exceed the limit of interest at any specific point in time (with a given probability), a time horizon needs to be defined until when a budget is computed. This time horizon can either be a predefined period, for example the 2011-2050 or the 2011-2100 period, or more variable in nature, for example the time period until peak warming (see yellow scenario in Figure 2). Both of these approaches were used in the IPCC AR5, and more sophisticated approaches based on the TAB methodology have been used in the literature[7].

IPCC Working Group III (WGIII) computed TABs for the periods 2011-2050 and 2011-2100, by assessing the probabilistic temperature projections in 2100[34,35]. For this, WGIII categorized a large number of scenarios based on end-of-century CO_2-equivalent concentrations. The reported TAB values – for example, in Table 6.3 in the WGIII Report[35] or Table SPM.1 in the Synthesis Report[33,34] (SYR) – are therefore the result of an assessment of the exceedance probability outcomes found in each of the CO_2-equivalent concentration categories. Alternatively, scenarios could have been categorised on the basis of median temperature, probabilities to limit warming to below a specific temperature limit, or even carbon budgets. For scenarios that limit end-of-century warming to below

2°C with a 'likely' probability (greater than 66% chance), the IPCC AR5 WGIII assessment[34] reports that the TABs in terms of cumulative CO_2 emissions in the periods 2011-2050 and 2011-2100 are 150-1300 $GtCO_2$ and 630-1180 $GtCO_2$, respectively.

In the IPCC SYR[33] TABs are also computed based on the scenarios available in the IPCC AR5 Scenario Database – see Table 2.2 in Ref. 33. However, the SYR categorizes scenarios directly based on their probability of keeping peak warming to below a specific temperature threshold (1.5°C, 2°C, or 3°C) during the 21st century. For example, the IPCC SYR reports TABs for limiting warming to below 2°C with at least 66% chance of 2550-3150 $GtCO_2$ from 1870 until peak warming.

The numbers compared

To understand what the different approaches mean in terms of the actual values of carbon budgets, we compare the available budgets related to the 2°C limit. Table 2 provides an overview for all the numbers discussed in this section, relative to two common base years (2011 and 2015). Taking into account that about 2050 $GtCO_2$ (ca. 560 PgC) of CO_2 had already been emitted by the end of 2014 (Ref. 36), a CO_2-only budget approach would indicate that 1620 $GtCO_2$ (or 440 PgC) remain to have a >66% probability of limiting warming to below 2°C relative to preindustrial levels (here defined as the 1861-1880 period[26]). Using a TEB approach and assuming non-CO_2 forcing as in RCP8.5, this amount is reduced to 850 $GtCO_2$ (or 230 PgC). When assessed with the latter approach, a 1620 $GtCO_2$ budget would limit warming to below 2°C in less than 33% of the available models (Ref. 42).

It is worth noting that the IPCC assessment of the CO_2-only budget is based on an assessed uncertainty range of TCRE, drawing upon many lines of evidence. The IPCC WGI numbers including non-CO_2 forcing are based on CMIP5 simulations of the response to RCPs, which – although being a valid approach – provide a narrower scientific basis. At least for the four RCPs used by WGI, a similar warming as a function of cumulative CO_2 emissions is found (see Figure TFE.8 in Ref. 42), despite having different non-CO_2 evolutions (see Figure 3a). This counterintuitive result is explained further below.

When extensively varying the non-CO_2 assumptions for TEBs using a subset of baseline and weak mitigation scenarios from the IPCC AR5 Scenario Database (which all exceed the 2°C limit), a range of 850-1550 $GtCO_2$ (5th-95th percentile range across all TEB scenarios, from 2015 onward) is associated with limiting warming to below 2°C with 66% probability[36]. The difference between this range and the 850 $GtCO_2$ number quoted above is, on the one hand, caused by the different modelling frameworks and, on the other hand, by the fact that the non-CO_2 forcing evolution of RCP8.5 is situated amongst the highest percentiles of the non-CO_2 forcing in other high emission scenarios that exceed the 2°C threshold (see Figure 3).

When considering TAB until peak warming, based on the stringent mitigation scenarios of the IPCC AR5 Scenario Database, a range of 590-1240 $GtCO_2$ is found for limiting warming to below 2°C with >66% probability[33] (10th-90th percentile range, as reported by IPCC WGIII, from 2015 onward). Finally, for TAB calculated over the 2015-2100 period, an assessment of the stringent mitigation scenarios available in the IPCC AR5 Scenario Database and their temperature outcomes results in a range of 470-1020 $GtCO_2$ (10th-90th percentile range) for limiting warming to below 2°C with a 'likely' (greater than 66%) chance[35].

In conclusion, moving from a CO_2-only budget[42] to a multi-gas multi-scenario TEB budget[36] removes around 420 $GtCO_2$ (i.e., the average of the 70-770 $GtCO_2$ range) from the CO_2 budget from 2015 onward for limiting warming to below 2°C with 66% chance. Subsequently moving to a TAB budget until peak warming[33] or over the 2015-2100 period[35] and a >66% chance would additionally remove about 260-310 $GtCO_2$ and 380-530 $GtCO_2$, respectively. (Note that these values are illustrative as they are obtained by comparing ranges which are defined in different ways.)

In conclusion, the TAB range for limiting warming to below 2°C with greater than 66% probability of 470-1020 $GtCO_2$ for the 2015-2100 period is thus 35 to 70% below what would have been inferred from a CO_2-only budget with a TEB approach.

Strengths and limitations

The various approaches to computing carbon budgets each come with their respective strengths and limitations. Understanding what can lead to possible differences in budget estimates is critical to avoid misinterpretation of the numbers.

The budget type definition, the underlying data and modelling, the scenario selection, temperature response timescales and the accompanying pathway of CO_2 and non-CO_2 emissions are identified as possible key drivers of the difference between the various budget options discussed above.

That the **budget type definition** will have an influence on the resulting numbers is almost trivial. For example, when defining TABs from 2011 to 2100 instead of until peak warming, the cumulated net negative emissions which can be achieved until the end of the century will lead to consistently lower 2015-2100 TABs compared to TABs defined until peak-warming levels. Negative emissions occur when carbon dioxide is actively removed from instead of emitted into the atmosphere by human activities. For instance, for TABs compatible with limiting warming to below 2°C with >66% chance, the difference between TABs defined until peak warming and over the 2015-2100 period would be of the order of 120-220 $GtCO_2$. Furthermore, the budget type definition also influences other factors, like scenario selection, whose impact on the carbon budget is explained in more detail below.

Underlying data and modelling

Some of the differences between the quantitative budgets estimates are simply driven by differences in the underlying data and models. In general, these differences apply to TEB and TAB alike. For example, while the WGI CO_2-only budget is based on the interpretation of an assessed uncertainty range, the other TEB and TAB budgets were computed either from CMIP5 RCP results (in the WGI Report and the SYR) or from a simple climate model (MAGICC) in a probabilistic setup[7,23,24] (in the WGIII Report and the SYR).

Budget estimates can differ depending on whether a single-scenario multi-model ensemble is used (for example, all CMIP5 runs for RCP8.5) or alternatively a single-model multi-scenario perturbed parameter ensemble is used (for example, the IPCC AR5 WGIII approach which uses MAGICC). The former approach allows us to use information from a wide range of the most sophisticated models and incorporate state-of-the-art Earth-system interactions in the budget assessment. However, this approach comes at a high computational cost, resulting in only a limited ensemble of opportunity of model runs being available for any assessment. The latter method, on the other hand, uses a much simpler model, and hence comes with great computational efficiency which allows for hundreds if not thousands of realisations per scenario. This allows variations in scenario assumptions on the pathways and evolution of non-CO_2 forcing over time to be explored in more detail.

These differences in the underlying data and modelling can result in changes in the budget estimates. However, while a simple climate model does not provide the detail of ESMs, it can closely emulate their global-mean behaviour[43] and can represent the uncertainties in carbon-cycle and climate response in line with the assessment of the IPCC AR5 (Refs. 7,24,44). Of importance here is that the MAGICC setup applied in WGIII and the SYR is consistent with the CMIP5 ensemble for temperature projections and TCRE (Figure 12.8 in Ref. 15, and Figure 6.12 in Ref. 35). It is therefore expected that these differences are limited.

A final aspect related to the data and modelling is the interpretation of the nature of the uncertainties that accompany the various data. Uncertainty ranges can be the expression of a variety of underlying uncertainty sources[45], and they can be interpreted in different ways. In the context of the quantification of carbon budgets, at least three kinds of uncertainty ranges can be distinguished: (1) an uncertainty range resulting from an in-depth assessment of multiple lines of evidence (a so-called assessed uncertainty range); (2) an uncertainty range emerging from a sophisticated statistical sampling of the parameter space or; (3) an uncertainty range which represents the spread across an arbitrary collection of model results (a so-called ensemble of opportunity). Each of these uncertainty ranges can be interpreted in different ways, and they decline in robustness going from an assessed uncertainty range over targeted statistical approaches to ensembles of opportunities. These aspects thus also influence the robustness of any carbon budget estimates based on them. For example, the budget for CO_2-induced warming from WGI is derived from an assessed uncertainty range, while the WGI budgets that additionally take into account non-CO_2 forcing are based on an ensemble of opportunity, which makes them much less robust (see also Technical Focus Element 8 in Ref. 42).

Scenario selection

Applying the definition of TEB and TAB budgets to a large scenario ensemble for the assessment of CO_2 budgets in line with a particular temperature limit results in the selection of two disjoint subsets of emission scenarios: a subset of baseline and weak mitigation scenarios that exceed the temperature limit with a given probability in case of TEB budgets, and a disjoint subset of more stringent to very stringent mitigation scenarios that all keep warming to below the specified temperature limit with a given probability in case of TAB budgets.

A first implication of the use of these disjoint scenario sets results from only very few scenarios being available that have, for example, precisely a 66% probability for limiting warming to below a given temperature threshold. While TEBs are consistently computed for each scenario at the time a scenario exceeds a temperature limit with a given probability, the value of TABs is further driven by the choice of the range of probabilities that is used to select appropriate TAB scenarios. For example, the IPCC SYR selected all scenarios that have a 66 to 100% probability of limiting warming to below a given threshold (compared to exactly 66% for TEB). This resulted in an average probability of staying below 2°C across the subset of TAB scenarios that comply with the abovementioned selection criterion of about 75%. This can explain about one third to half of the 260-310 $GtCO_2$ difference between the TEB estimates from Friedlingstein *et al.* (Ref. 36) and the IPCC SYR TAB estimates. Moreover, for some temperature levels, for example around 3°C, the scenarios available in the IPCC AR5 Scenario Database do not sample the possible range extensively, which can lead to additional biases in the numbers obtained.

Temperature response timescales

A second aspect that is different in the disjoint scenario subsets are the CO_2 emission pathways and hence the annual CO_2 emissions at the time the compatible carbon budget is derived. In the TAB subset, CO_2 emissions will typically approach zero or become negative in order to stabilize global temperatures, and will thus be very low at the time of maximum warming during the 21st century. In the TEB subset this is not the case. Because of the timescales of CO_2-induced warming[46,47] this leads to differences in the carbon budget estimates.

Recent research indicates that, at current emission rates, maximum CO_2-induced warming only occurs about a decade after a CO_2 emission[46,47]. Thus, even in a CO_2-only world, TABs and TEBs with complementary probabilities (for example, a 66% probability to limit warming below 2°C and a 34% probability to exceed 2°C) would not be entirely identical. In case of the TEB approach, the maximum warming of the CO_2 emissions of the last decade before the temperature limit was exceeded has possibly not yet fully occurred. In a TAB approach the emissions in the last decade would be significantly lower, if not zero, and this would allow a much larger fraction of the warming to already be realized. The TEB approach thus leads to a consistent overestimate of the CO_2 budget compatible with a given temperature limit, while this is not the case with the TAB approach. At least one third of the approximately 260-310 $GtCO_2$ difference between the TEB estimates from Ref. 36 and the IPCC SYR TAB estimates can be explained by accounting for the approximately one decade delay between CO_2 emissions and their maximum warming.

Non-CO_2 warming contribution

A third and last aspect that differs between the two disjoint TEB and TAB scenario subsets is the mixture of CO_2 and non-CO_2 forcers. This mixture differs over time and therefore, depending on when the compatible carbon budget is determined, the TAB and TEB are derived under possibly very different non-CO_2 forcing (see Figure 3b). The relationship between CO_2 emissions and non-CO_2 forcing is complex, as it covers the total non-CO_2 forcing which results from both positive and negative climate forcers. Climate policy influences these non-CO_2 forcers both directly (via abatement measures) and indirectly (via changes induced in the energy system), which is captured in different ways in IAMs. For example, stabilizing and peaking global temperatures requires global CO_2 emissions to be reduced to close to net zero. Such very low CO_2 emissions are achieved through a fundamental transformation of the global energy-economy-land system[35], which in turn leads to changes in non-CO_2 emissions because of the phase-out of common sources of CO_2 and non-CO_2 emissions[14,48]. This can lead to important differences in non-CO_2 forcing as a function of total cumulative CO_2 emissions (Figure 3a). Figure 3b shows that median non-CO_2 forcing at the time which is of importance for deriving the carbon budget (i.e., the time of exceedance for TEBs, and peak warming for TABs) is about 0.2 W/m^2 higher in the subset of scenarios used for TEBs compared to the subset used for TABs.

However, the non-CO_2 forcing at either peak warming or the time of exceeding a given temperature threshold does not tell the entire story. When estimating the actual non-CO_2-induced warming at these time points of interest (see Box 1 on 'Non-CO_2 temperature contributions'), very little difference can be found between the TEB and TAB scenario subsets (Figure 3c). This thus suggests that, when a sufficiently large scenario sample is available, variations in non-CO_2 forcing cannot be used to explain the variations between TEB and TAB estimates for limiting warming to below 2°C. The precise influence of this difference on the carbon budgets has not been quantified.

Incidentally, this feature is not obviously visible when looking at the four RCPs only, because both the lowest, RCP2.6, and the highest, RCP8.5, are outliers in terms of non-CO_2 warming, at opposite sides of the scenario distribution (Figures 3b-c).

Finally, while non-CO_2 forcing does not provide a strong explanation for the variations between TEB and TAB estimates, it plays an important role for the variation within the TEB and TAB subsets. Figure 3d shows that respectively 70% and 50% of the variance within the TEB and TAB subsets can be explained by non-CO_2 warming at the time of determining the carbon budget.

Future non-CO_2 warming under stringent mitigation remains nonetheless very uncertain at present. Its magnitude will depend on the extent to which society will be successful in bringing about assumed future improvements in agricultural yields and practices or dietary changes[49], amongst many other factors. These are very uncertain. Furthermore, how much non-CO_2 forcing is reduced compared to CO_2 depends on the relative weight that is given to CO_2 and non-CO_2 emissions in mitigation scenarios, and also on other mitigation choices[50]. These weights are mostly constant in IAMs (for example, by using global warming potentials as a fixed exchange rate), but can also change over time and depend on the question posed.

Air pollution controls can influence the rate of near-term warming and, depending on the precise mix of air pollutants that is reduced by air pollution controls, non-CO_2 warming can be increased, decreased or stay constant[14]. The estimated effect of air pollution controls on carbon budgets, in particular on TABs, is very small[51]. This is important information for policy-making, as it can be used to consider trade-offs between the uncertainty in non-CO_2 mitigation, possibly larger CO_2 budgets, and a larger amount of committed warming at the multi-century scale due to larger cumulative CO_2 emissions.

Applicability

Earlier we indicated that budgets that only take into account CO_2-induced warming are scientifically best understood as – per definition – they do not depend on additional uncertainties associated with other forcings. However, at the same they are impractical and largely irrelevant for use in the real world, because of their obvious limitation of neglecting any contribution that is different from CO_2. The other approaches that go beyond this CO_2-only approach, might therefore be more practical. Using a CO_2-only approach estimate for real-word decision-making would lead to an overestimation of the allowable carbon budget, i.e. a very high risk of exceeding a given climate target when emitting that particular carbon budget.

The strength of TEBs is that they are easily comparable to TCRE-based budgets for CO_2-induced warming only. Hence the influence of non-CO_2 forcing on the size of carbon budgets can be assessed.

However, because of the limitations related to scenario selection (TEBs are derived from scenarios that fail in limiting warming to the temperature level of interest) and the timescales of the temperature response, TABs are preferred over TEBs. The strength of TABs lies exactly in their use of scenarios that represent our best understanding of how CO_2 and other radiatively active species would evolve over time when CO_2 emissions are stringently reduced.

Conclusions

Several possibilities are available to compute cumulative carbon budgets consistent with a particular temperature limit. We have shown that each of the CO_2 budget approaches has strengths but also comes with important limitations. The devil is in the detail here. The most scientifically robust number – the budget for CO_2-induced warming – is also the least practical in the real world. Selecting budgets based on multi-gas emission scenarios that actually restrict warming to below a given temperature threshold, results in the lowest, but most relevant CO_2 emission budgets in a real-world multi-gas setting. Any practical implementation of a carbon budget mitigation strategy would require parallel mitigation efforts for non-CO_2 agents.

At the time of the IPCC AR5, no established methodologies were available to ensure easy comparability of carbon budget estimates across working groups. In hindsight and anticipating future assessments, three recommendations can be formulated. First, insofar important topics can already be identified, coordinated model simulations, intercomparisons, and methods could be initiated at an early stage to ensure consistency and traceability. Second, consistency across – and collaboration and integration between – the IPCC working groups could be improved by setting up stronger ties between them. And third, IPCC reports should be clearer about the policy-applicability of the numbers they provide, without being policy prescriptive.

For limiting warming to below 2°C relative to preindustrial levels with greater than 66% probability, the remaining CO_2 budget from 2015 onwards for CO_2-induced warming only is 1620 $GtCO_2$. The corresponding TAB budget would be 590-1240 $GtCO_2$. The latter is equivalent to about 15 to 30 years of CO_2 emission at current (2014) levels (about 40 $GtCO_2$/yr, Ref. 52). No matter which approach is taken, the CO_2 budget for keeping warming to below 2°C always implies stringent emission reductions over the coming decades and net zero CO_2 emissions in the long term. For policymaking in the context of the UNFCCC, we suggest using the 590-1240 $GtCO_2$ estimate from 2015 onward, as this is derived from an assessment of scenarios that effectively limit warming to below the 2°C limit.

BOX 1: Non-CO_2 temperature contributions

The estimated temperature contributions of non-CO_2 forcing, shown in Figure 3c, are derived by the following equation, as described in the Supplementary Material to the IPCC AR5 Working Group I Chapter on 'Anthropogenic and Natural Radiative Forcing'[53] (equation 8.SM.13).

$$R_T(t) = \sum_{j=1}^{M} \frac{c_j}{d_j} exp\left(-\frac{t}{d_j}\right)$$

Where R_T is the climate response to a unit of forcing, c_j the component of the climate sensitivity, d_j the response times, and t the time. For the two-term approximation ($M=2$) presented by Ref. 54, values of c_1, c_2, d_1, and d_2 are taken from Table 8.SM.9 in Ref. 53. This estimate is to be considered an illustrative approximation of the non-CO_2 forcing's temperature effect.

END BOX 1

Figure captions:

Figure 1 | Proportionality of global-mean temperature increase to cumulative emissions of CO_2. Four CO_2 emission pathways with identical cumulative carbon emissions over the 21st century (panel **a**) and their corresponding temperature projections (panel **b**). The grey area in panel **b** shows the central 66 percent uncertainty range of temperature projections around the thick purple line. Panels are adapted from Figure 12.46 in Ref. 15.

Figure 2 | Illustration of the approach to compute threshold exceedance budgets (TEB) versus threshold avoidance budgets (TAB). In a first step (arrows labelled "1"), temperature outcomes are computed from multi-gas emission scenarios which either exceed (orange) or avoid (yellow) a given temperature threshold. Based on either the timing of exceeding the chosen threshold or the timing of peak warming, carbon budgets compatible with the chosen temperature threshold are computed in a second step (arrow labelled "2") by summing the carbon emissions of the underlying scenarios until the timing of exceeding the threshold or peak warming for TEB or TAB (arrow labelled "3"), respectively.

Figure 3 | Non-CO_2 forcing and cumulative CO_2 emissions. a, Non-CO_2 forcing as a function of cumulative CO_2 emissions from 2015 onwards for scenarios of the IPCC AR5 Scenario Database. Scenarios are split up into two subsets: (1) scenarios that limit warming to below 2°C relative to preindustrial with at least 66% probability (yellow-mustard, used for TAB) and (2) scenarios that lead to global-mean temperatures exceeding the 2°C relative to preindustrial limit with at least 34% (orange, used for TEB). **b**, Distribution of non-CO_2 forcing at the time point critical for deriving TEB (orange) and TAB (yellow-mustard) budgets, i.e., the moment the 2°C limit is exceeded for TEBs and peak warming for TABs. **c**, Distribution of the estimated temperature contribution from non-CO_2 forcing at the same time point as in panel **b** (see Box 1 on 'Non-CO_2 temperature contributions'). The four RCPs are also included for comparison. **d**, Variation within the TEB and TAB budget subsets as a function of the estimated temperature contribution from non-CO_2 forcing as in panel **c**. Numerical values in panel **d** are R^2 values for the two linear fits.

Tables:

Table 1 | Three different types of carbon budgets and their definition

Carbon budget type	Abbreviation	Definition and description
Budget for CO_2-induced warming	CO_2-only budget	Amount of cumulative carbon emissions that are compatible with limiting warming to below a specific temperature threshold with a given probability in the hypothetical case that CO_2 is the only source of anthropogenic radiative forcing. This budget can be inferred from the assessed range of TCRE.
Threshold Exceedance Budget	TEB	Amount of cumulative carbon emissions at the time a specific temperature threshold is exceeded with a given probability in a particular multi-gas emission scenarios. This budget thus takes into account the impact of non-CO_2 warming at the time of exceeding the threshold of interest.
Threshold Avoidance Budget	TAB	Amount of cumulative carbon emissions over a given time period of a multi-gas emission scenario that limits global-mean temperature increase to below a specific threshold with a given probability. This budget thus takes into account the impact of non-CO_2 warming at peak global-mean warming, which is approximately the time global CO_2 emissions become zero and global-mean temperature is stabilized.

Table 2 | Selection of carbon emission budgets related to a global temperature limit of 2°C relative to preindustrial levels from various sources. 1890 GtCO$_2$ were already emitted by 2011, and about 2050 GtCO$_2$ by 2015. All values are in GtCO$_2$, reported from 2011 and 2015 onwards, and rounded to the nearest 10. Budget types are defined in Table 1.

Source	Type	Specification	Value since 2011	Value since 2015
IPCC AR5 WGI	*CO_2-only budget*	To limit warming to less than 2°C since the period 1861-1880 with greater than 66% (or 50%) probability	1780 (or 2550)	1620 (or 2390)
IPCC AR5 WGI	*TEB*	To limit warming to less than 2°C since the period 1861-1880 in more than 66% (or 50%) of the model runs when accounting for the non-CO_2 forcing as in the RCP scenarios	1010 (or 1120)	850 (or 960)
IPCC AR5 WGIII	*TAB*	To limit warming in 2100 to below 2°C since 1850-1900 with a 'likely' (>66%) probability, accounting for the non-CO_2 forcing as spanned by the subset of stringent mitigation scenarios in the IPCC AR5 Scenario Database*. (10%-90% range over scenarios in IPCC WGIII scenario category 1)	630 to 1180	470 to 1020
IPCC AR5 WGIII	*TAB*	To limit warming in 2100 to below 2°C since 1850-1900 with a 'more likely than not' (>50%) probability, accounting for the non-CO_2 forcing as spanned by the subset of stringent mitigation scenarios in the IPCC AR5 Scenario Database*. (10%-90% range over scenarios in IPCC AR5 scenario category II without overshoot)	960 to 1430	800 to 1270
IPCC AR5 SYR	*TEB*	To limit warming to less than 2°C since the period 1861-1880 in more than 66% (or 50% or 33%) of the model runs of the CMIP5 RCP8.5 ESM and EMIC simulations. (These correspond to the IPCC AR5 WGI TEB budgets reported above)	1010 (1110 or 1410)	850 (960 or 1250)
IPCC AR5 SYR	*TAB*	To limit warming to below 2°C since 1861-1880 with 66-100% probability, accounting for the non-CO_2 forcing as spanned by the subset of stringent mitigation scenarios in the IPCC AR5 Scenario Database. (10%-90% range)	750 to 1400	590 to 1240
IPCC AR5 SYR	*TAB*	To limit warming to below 2°C since 1861-1880 with 50-66% probability, accounting for the non-CO_2 forcing as spanned by the subset of stringent mitigation scenarios in the IPCC AR5 Scenario Database. (10%-90% range)	1150 to 1400	990 to 1240
Friedlingstein et al. (2014)	*TEB*	To limit warming to less than 2°C since 1850-1900 with a 66% probability, accounting for the non-CO_2 forcing as spanned by the subset of baseline and weak mitigation scenarios in the IPCC AR5 Scenario Database*. (5%-95% range)	1310 (1010 to 1710)	1150 (850 to 1550)
Friedlingstein et al. (2014)	*TEB*	To limit warming to less than 2°C since 1850-1900 with a 50% probability, accounting for the non-CO_2 forcing as spanned by the subset of baseline and weak mitigation scenarios in the IPCC AR5 Scenario Database*. (5%-95% range)	1610 (1210 to 2010)	1450 (1050 to 1850)

*: The temperature difference between the 1861-1880 and 1850-1900 is 0.02°C, based on Ref. 55

References:

1. UNFCCC. United Nations Framework Convention on Climate Change. 1992: 1-25.
2. UNFCCC. 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. 2010: 31.
3. UNFCCC. FCCC/CP/2012/8/Add.1 - Report of the Conference of the Parties on its eighteenth session, held in Doha from 26 November to 8 December 2012 - Addendum - Part Two: Action taken by the Conference of the Parties at its eighteenth session. Doha, Qatar: UNFCCC; 2012. pp. 1-37.
4. Matthews HD, Caldeira K. Stabilizing climate requires near-zero emissions. *Geophysical Research Letters* 2008, **35**(4).
5. Matthews HD, Gillett NP, Stott PA, Zickfeld K. The proportionality of global warming to cumulative carbon emissions. *Nature* 2009, **459**(7248): 829-832.
6. Zickfeld K, Eby M, Matthews HD, Weaver AJ. Setting cumulative emissions targets to reduce the risk of dangerous climate change. *Proceedings of the National Academy of Sciences* 2009, **106**(38): 16129-16134.
7. Meinshausen M, Meinshausen N, Hare W, Raper SCB, Frieler K, Knutti R, *et al.* Greenhouse-gas emission targets for limiting global warming to 2°C. *Nature* 2009, **458**(7242): 1158-1162.
8. Allen MR, Frame DJ, Huntingford C, Jones CD, Lowe JA, Meinshausen M, *et al.* Warming caused by cumulative carbon emissions towards the trillionth tonne. *Nature* 2009, **458**(7242): 1163-1166.
9. Gillett NP, Arora VK, Zickfeld K, Marshall SJ, Merryfield WJ. Ongoing climate change following a complete cessation of carbon dioxide emissions. *Nature Geosci* 2011, **4**(2): 83-87.
10. Gillett NP, Arora VK, Matthews D, Allen MR. Constraining the Ratio of Global Warming to Cumulative CO2 Emissions Using CMIP5 Simulations. *Journal of Climate* 2013, **26**(18): 6844-6858.
11. Knutti R, Rogelj J. The legacy of our CO2 emissions: a clash of scientific facts, politics and ethics. *Climatic Change* 2015: 1-13.
12. Smith SM, Lowe JA, Bowerman NHA, Gohar LK, Huntingford C, Allen MR. Equivalence of greenhouse-gas emissions for peak temperature limits. *Nature Clim Change* 2012, **2**(7): 535-538.
13. Bowerman NHA, Frame DJ, Huntingford C, Lowe JA, Smith SM, Allen MR. The role of short-lived climate pollutants in meeting temperature goals. *Nature Clim Change* 2013, **3**(12): 1021-1024.
14. Rogelj J, Schaeffer M, Meinshausen M, Shindell DT, Hare W, Klimont Z, *et al.* Disentangling the effects of CO2 and short-lived climate forcer mitigation. *Proc Natl Acad Sci U S A* 2014, **111**(46): 16325-16330.
15. Collins M, R. Knutti, J. Arblaster, J.-L. Dufresne, T. Fichefet, P. Friedlingstein, *et al.* Long-term Climate Change: Projections, Commitments and Irreversibility. In: Stocker TF, D. Qin, G.-K. Plattner, M. Tignor, S.K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex and P.M. Midgley (ed). *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, United Kingdom and New York, NY, USA, 2013, pp 1029-1136.
16. Frolicher TL, Winton M, Sarmiento JL. Continued global warming after CO2 emissions stoppage. *Nature Clim Change* 2014, **4**(1): 40-44.
17. Mastrandrea MD, Field CB, Stocker TF, Edenhofer O, Ebi KL, Frame DJ, *et al.* Guidance Notes for Lead Authors of the IPCC Fifth Assessment Report on Consistent Treatment of Uncertainties. IPCC; 2010. p. 5.
18. Zickfeld K, Arora VK, Gillett NP. Is the climate response to CO2 emissions path dependent? *Geophysical Research Letters* 2012, **39**(5): L05703.

19. Van Vuuren DP, Meinshausen M, Plattner GK, Joos F, Strassmann KM, Smith SJ, *et al.* Temperature increase of 21st century mitigation scenarios. *Proceedings of the National Academy of Sciences* 2008, **105**(40): 15258-15262.
20. Obersteiner M, Azar C, Kauppi P, Mollersten K, Moreira J, Nilsson S, *et al.* Managing climate risk. *Science* 2001, **294**(5543): 786-787.
21. Azar C, Lindgren K, Obersteiner M, Riahi K, van Vuuren D, den Elzen K, *et al.* The feasibility of low CO2 concentration targets and the role of bio-energy with carbon capture and storage (BECCS). *Climatic Change* 2010, **100**(1): 195-202.
22. Tavoni M, Socolow R. Modeling meets science and technology: an introduction to a special issue on negative emissions. *Climatic Change* 2013, **118**(1): 1-14.
23. Meinshausen M, Raper SCB, Wigley TML. Emulating coupled atmosphere-ocean and carbon cycle models with a simpler model, MAGICC6 – Part 1: Model description and calibration. *Atmos Chem Phys* 2011, **11**(4): 1417-1456.
24. Rogelj J, Meinshausen M, Knutti R. Global warming under old and new scenarios using IPCC climate sensitivity range estimates. *Nature Clim Change* 2012, **2**(4): 248-253.
25. Matthews HD, Solomon S, Pierrehumbert R. Cumulative carbon as a policy framework for achieving climate stabilization. *Philosophical Transactions of the Royal Society of London A: Mathematical, Physical and Engineering Sciences* 2012, **370**(1974): 4365-4379.
26. IPCC. Summary for Policymakers. In: Stocker TF, D. Qin, G.-K. Plattner, M. Tignor, S.K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex and P.M. Midgley (ed). *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, United Kingdom and New York, NY, USA, 2013, pp 1-29.
27. Clarke L, Edmonds J, Krey V, Richels R, Rose S, Tavoni M. International climate policy architectures: Overview of the EMF 22 International Scenarios. *Energy Econ* 2009, **31**(Supplement 2): S64-S81.
28. Riahi K, Dentener F, Gielen D, Grubler A, Jewell J, Klimont Z, *et al.* Chapter 17 - Energy Pathways for Sustainable Development. *Global Energy Assessment - Toward a Sustainable Future*. Cambridge University Press, Cambridge, UK and New York, NY, USA and the International Institute for Applied Systems Analysis, Laxenburg, Austria, 2012, pp 1203-1306.
29. Kriegler E, Weyant J, Blanford G, Krey V, Clarke L, Edmonds J, *et al.* The role of technology for achieving climate policy objectives: overview of the EMF 27 study on global technology and climate policy strategies. *Climatic Change* 2014, **123**(3-4): 353-367.
30. Moss RH, Edmonds JA, Hibbard KA, Manning MR, Rose SK, van Vuuren DP, *et al.* The next generation of scenarios for climate change research and assessment. *Nature* 2010, **463**(7282): 747-756.
31. van Vuuren D, Edmonds J, Kainuma M, Riahi K, Thomson A, Hibbard K, *et al.* The representative concentration pathways: an overview. *Climatic Change* 2011, **109**(1-2): 5-31.
32. Taylor KE, Stouffer RJ, Meehl GA. An Overview of CMIP5 and the Experiment Design. *Bulletin of the American Meteorological Society* 2011, **93:** 485–498.
33. IPCC. Summary for Policymakers. *Climate Change 2014: Synthesis Report of the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*. Cambridge University Press: Cambridge, United Kingdom, and New York, NY, USA, 2014, pp 1-32.
34. IPCC. Summary for Policymakers. In: Edenhofer O, Pichs-Madruga R, Sokona Y, Farahani E, Kadner S, Seyboth K, *et al.* (eds). *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, United Kingdom, and New York, NY, USA, 2014, pp 1-33.
35. Clarke L, Jiang K, Akimoto K, Babiker M, Blanford G, Fisher-Vanden K, *et al.* Assessing Transformation Pathways. In: Edenhofer O, Pichs-Madruga R, Sokona Y, Farahani E, Kadner S, Seyboth K, *et al.* (eds). *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, United Kingdom and New York, NY, USA, 2014, pp 413-510.

36. Friedlingstein P, Andrew RM, Rogelj J, Peters GP, Canadell JG, Knutti R, *et al.* Persistent growth of CO2 emissions and implications for reaching climate targets. *Nature Geoscience* 2014, **7**(10)**:** 709-715.

37. Schaeffer M, Gohar L, Kriegler E, Lowe J, Riahi K, van Vuuren D. Mid- and long-term climate projections for fragmented and delayed-action scenarios. *Technological Forecasting and Social Change* 2015, **90, Part A**(0)**:** 257-268.

38. Rogelj J, Luderer G, Pietzcker RC, Kriegler E, Schaeffer M, Krey V, *et al.* Energy system transformations for limiting end-of-century warming to below 1.5°C. *Nature Clim Change* in press.

39. Riahi K, Rao S, Krey V, Cho C, Chirkov V, Fischer G, *et al.* RCP 8.5—A scenario of comparatively high greenhouse gas emissions. *Climatic Change* 2011, **109**(1)**:** 33-57.

40. Jones C, Robertson E, Arora V, Friedlingstein P, Shevliakova E, Bopp L, *et al.* Twenty-First-Century Compatible CO2 Emissions and Airborne Fraction Simulated by CMIP5 Earth System Models under Four Representative Concentration Pathways. *Journal of Climate* 2013, **26**(13)**:** 4398-4413.

41. Zickfeld K, Eby M, Weaver AJ, Alexander K, Crespin E, Edwards NR, *et al.* Long-Term Climate Change Commitment and Reversibility: An EMIC Intercomparison. *Journal of Climate* 2013, **26**(16)**:** 5782-5809.

42. Stocker TF, Qin D, Plattner G-K, Alexander LV, Allen SK, Bindoff NL, *et al.* Technical Summary. In: Stocker TF, D. Qin, G.-K. Plattner, M. Tignor, S.K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex and P.M. Midgley (ed). *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, United Kingdom and New York, NY, USA, 2013, pp 33-115.

43. Meinshausen M, Wigley TML, Raper SCB. Emulating atmosphere-ocean and carbon cycle models with a simpler model, MAGICC6 – Part 2: Applications. *Atmos Chem Phys* 2011, **11**(4)**:** 1457-1471.

44. Rogelj J, Meinshausen M, Sedláček J, Knutti R. Implications of potentially lower climate sensitivity on climate projections and policy. *Environmental Research Letters* 2014, **9**(3)**:** 031003.

45. Smith LA, Stern N. Uncertainty in science and its role in climate policy. *Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences* 2011, **369**(1956)**:** 4818-4841.

46. Ricke KL, Caldeira K. Maximum warming occurs about one decade after a carbon dioxide emission. *Environmental Research Letters* 2014, **9**(12)**:** 124002.

47. Zickfeld K, Herrington T. The time lag between a carbon dioxide emission and maximum warming increases with the size of the emission. *Environmental Research Letters* 2015, **10**(3)**:** 031001.

48. Rogelj J, Rao S, McCollum DL, Pachauri S, Klimont Z, Krey V, *et al.* Air-pollution emission ranges consistent with the representative concentration pathways. *Nature Clim Change* 2014, **4**(6)**:** 446-450.

49. Gernaat DEHJ, Calvin K, Lucas PL, Luderer G, Otto SAC, Rao S, *et al.* Understanding the contribution of non-carbon dioxide gases in deep mitigation scenarios. *Global Environmental Change* 2015, **33**(0)**:** 142-153.

50. Rogelj J, Reisinger A, McCollum DL, Knutti R, Riahi K, Meinshausen M. Mitigation choices impact carbon budget size compatible with low temperature goals. *Environmental Research Letters* 2015, **10**(7)**:** 075003.

51. Rogelj J, Meinshausen M, Schaeffer M, Knutti R, Riahi K. Impact of short-lived non-CO2 mitigation on carbon budgets for stabilizing global warming. *Environmental Research Letters* 2015, **10**(7)**:** 075001.

52. Le Quéré C, Moriarty R, Andrew RM, Peters GP, Ciais P, Friedlingstein P*, et al.* Global carbon budget 2014. *Earth Syst Sci Data Discuss* 2014, **7**(2)**:** 521-610.

53. Myhre G, D. Shindell, F.-M. Bréon, W. Collins, J. Fuglestvedt, J. Huang*, et al.* Anthropogenic and Natural Radiative Forcing. In: Stocker TF, D. Qin, G.-K. Plattner, M. Tignor, S.K. Allen, J. Boschung*, et al.* (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, United Kingdom and New York, NY, USA, 2013, pp 659-740.

54. Boucher O, Reddy MS. Climate trade-off between black carbon and carbon dioxide emissions. *Energy Policy* 2008, **36**(1)**:** 193-200.

55. Brohan P, Kennedy JJ, Harris I, Tett SFB, Jones PD. Uncertainty estimates in regional and global observed temperature changes: A new data set from 1850. *Journal of Geophysical Research-Atmospheres* 2006, **111:** D12106.

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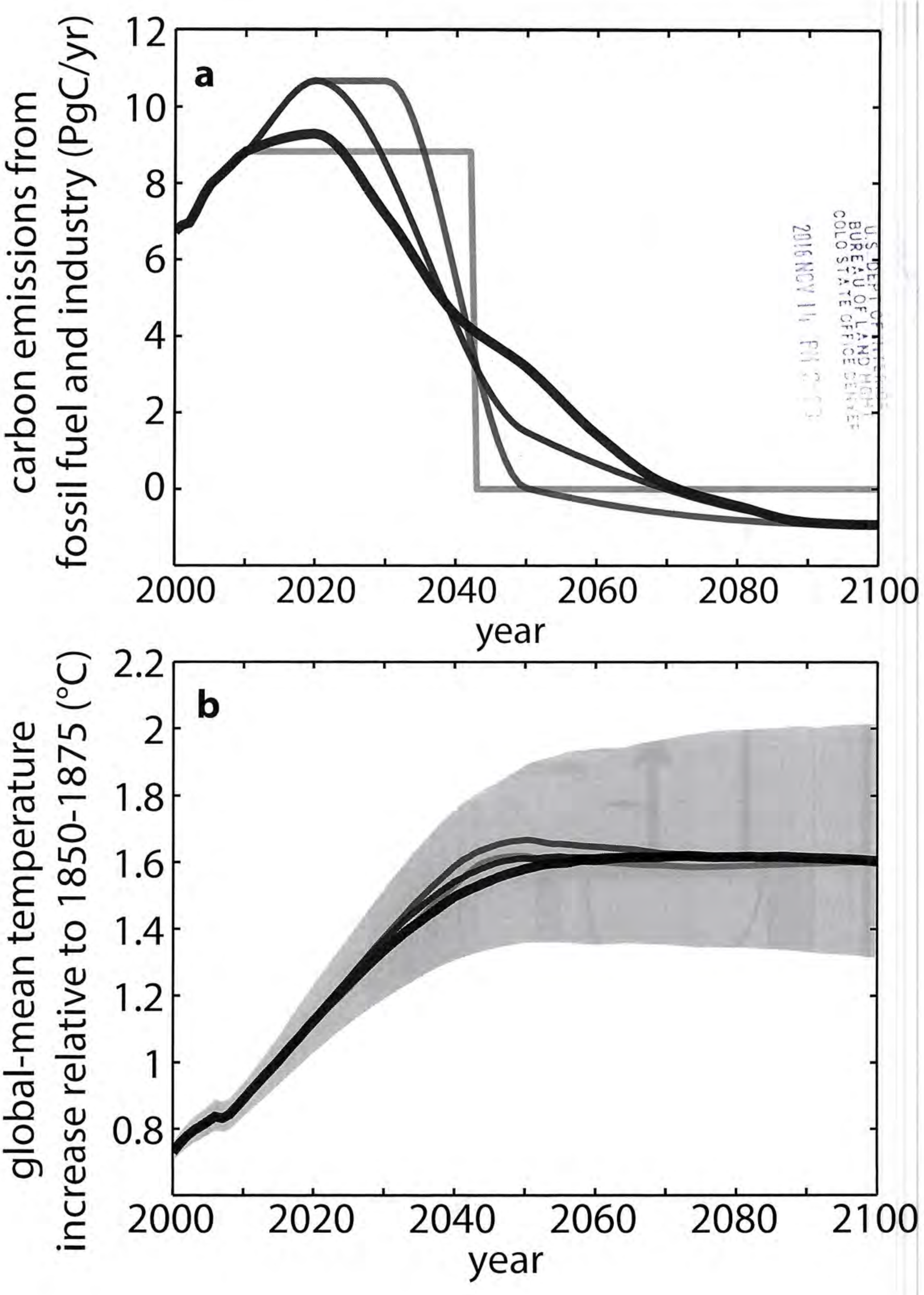
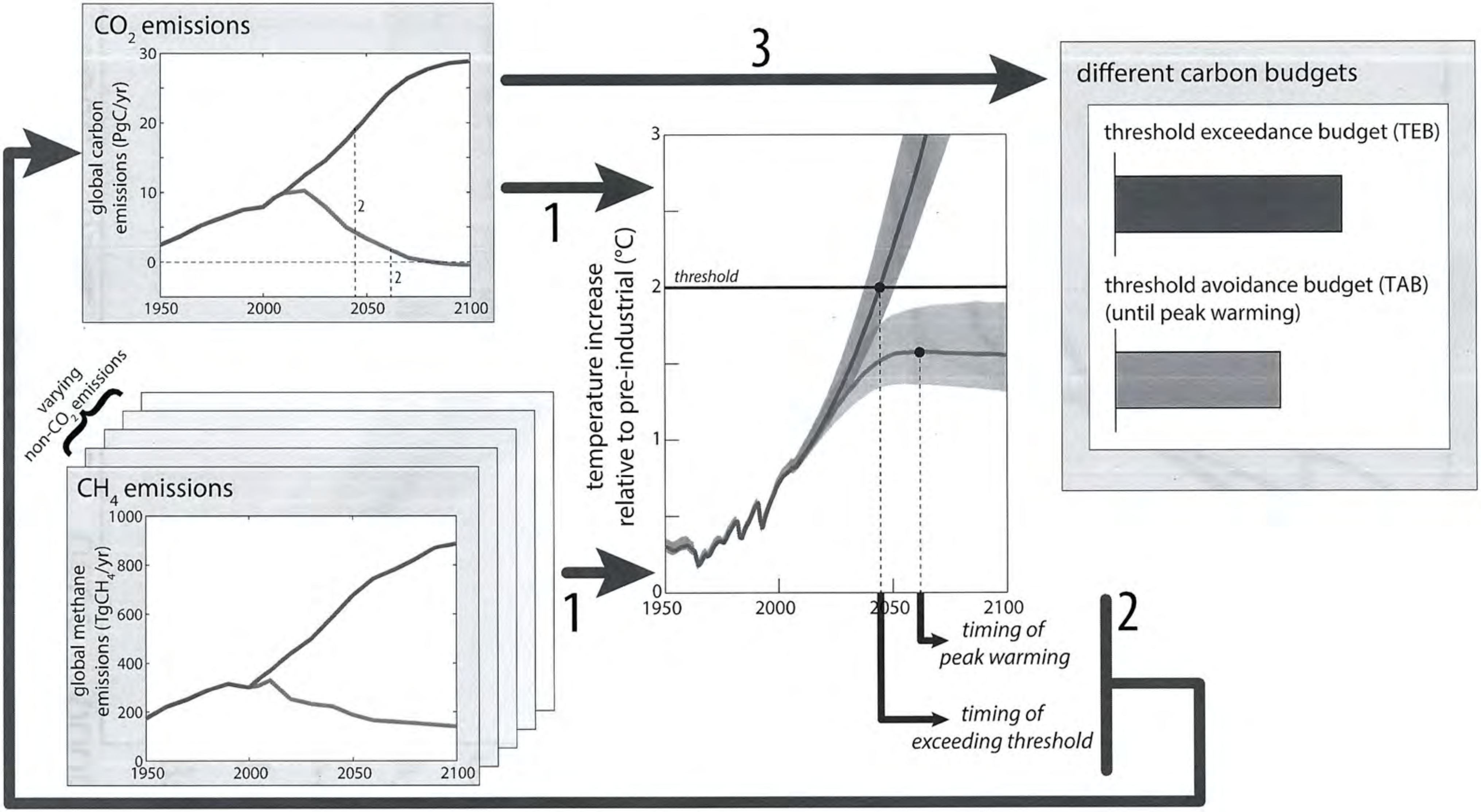
Author Contributions

All authors contributed to the underlying research during the writing process of the IPCC AR5. JR coordinated the conception and the writing of the paper. JR carried out the research with significant contributions from MS, and developed the TEB and TAB conceptual framework. JR produced the figures and wrote the first draft of the manuscript. All authors contributed to interpreting and discussing the results, and writing the paper.


a
carbon emissions from fossil fuel and industry (PgC/yr)
12
10
8
6
4
2
0
2000
2020
2040
2060
2080
2100
year
b
global-mean temperature increase relative to 1850-1875 (°C)
2.2
2
1.8
1.6
1.4
1.2
1
0.8
2000
2020
2040
2060
2080
2100
year


CO$_2$ emissions
global carbon emissions (PgC/yr)
30
20
10
0
1950
2000
2050
2100
2
2
3
different carbon budgets
threshold exceedance budget (TEB)
threshold avoidance budget (TAB) (until peak warming)
1
1
temperature increase relative to pre-industrial (°C)
3
2
1
0
threshold
1950
2000
2050
2100
timing of peak warming
timing of exceeding threshold
2
varying non-CO$_2$ emissions
CH$_4$ emissions
global methane emissions (TgCH$_4$/yr)
1000
800
600
400
200
0
1950
2000
2050
2100

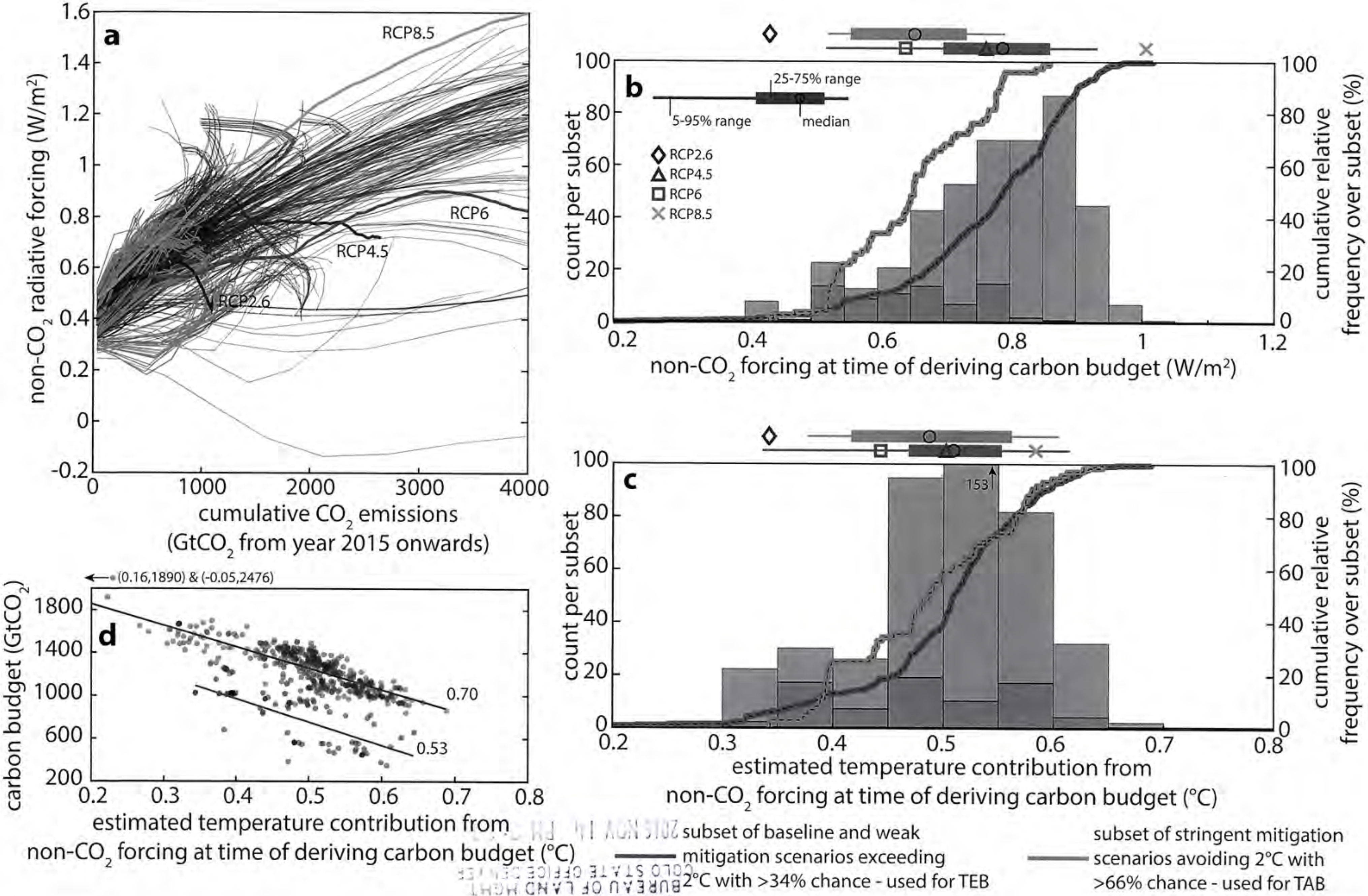

a
1.6
1.4
1.2
1
0.8
0.6
0.4
0.2
0
-0.2
non-CO₂ radiative forcing (W/m²)
RCP8.5
RCP6
RCP4.5
RCP2.6
0
1000
2000
3000
4000
cumulative CO₂ emissions
(GtCO₂ from year 2015 onwards)
b
25-75% range
5-95% range
median
RCP2.6
RCP4.5
RCP6
RCP8.5
count per subset
100
80
60
40
20
0
0.2
0.4
0.6
0.8
1
1.2
non-CO₂ forcing at time of deriving carbon budget (W/m²)
cumulative relative frequency over subset (%)
c
153
0.2
0.3
0.4
0.5
0.6
0.7
0.8
estimated temperature contribution from non-CO₂ forcing at time of deriving carbon budget (°C)
d
(0.16,1890) & (-0.05,2476)
carbon budget (GtCO₂)
1800
1400
1000
600
200
0.70
0.53
estimated temperature contribution from non-CO₂ forcing at time of deriving carbon budget (°C)
subset of baseline and weak mitigation scenarios exceeding 2°C with >34% chance - used for TEB
subset of stringent mitigation scenarios avoiding 2°C with >66% chance - used for TAB

Exhibit 23

doi:10.1038/nature14016

The geographical distribution of fossil fuels unused when limiting global warming to 2 °C

Christophe McGlade[1] & Paul Ekins[1]

Policy makers have generally agreed that the average global temperature rise caused by greenhouse gas emissions should not exceed 2 °C above the average global temperature of pre-industrial times[1]. It has been estimated that to have at least a 50 per cent chance of keeping warming below 2 °C throughout the twenty-first century, the cumulative carbon emissions between 2011 and 2050 need to be limited to around 1,100 gigatonnes of carbon dioxide (Gt CO_2)[2,3]. However, the greenhouse gas emissions contained in present estimates of global fossil fuel reserves are around three times higher than this[2,4], and so the unabated use of all current fossil fuel reserves is incompatible with a warming limit of 2 °C. Here we use a single integrated assessment model that contains estimates of the quantities, locations and nature of the world's oil, gas and coal reserves and resources, and which is shown to be consistent with a wide variety of modelling approaches with different assumptions[5], to explore the implications of this emissions limit for fossil fuel production in different regions. Our results suggest that, globally, a third of oil reserves, half of gas reserves and over 80 per cent of current coal reserves should remain unused from 2010 to 2050 in order to meet the target of 2 °C. We show that development of resources in the Arctic and any increase in unconventional oil production are incommensurate with efforts to limit average global warming to 2 °C. Our results show that policy makers' instincts to exploit rapidly and completely their territorial fossil fuels are, in aggregate, inconsistent with their commitments to this temperature limit. Implementation of this policy commitment would also render unnecessary continued substantial expenditure on fossil fuel exploration, because any new discoveries could not lead to increased aggregate production.

Recent climate studies have demonstrated that average global temperature rises are closely related to cumulative emissions of greenhouse gases emitted over a given timeframe[2,6,7]. This has resulted in the concept of the remaining global 'carbon budget' associated with the probability of successfully keeping the global temperature rise below a certain level[4,8,9]. The Intergovernmental Panel on Climate Change (IPCC)[3] recently suggested that to have a better-than-even chance of avoiding more than a 2 °C temperature rise, the carbon budget between 2011 and 2050 is around 870–1,240 Gt CO_2.

Such a carbon budget will have profound implications for the future utilization of oil, gas and coal. However, to understand the quantities that are required, and are not required, under different scenarios, we first

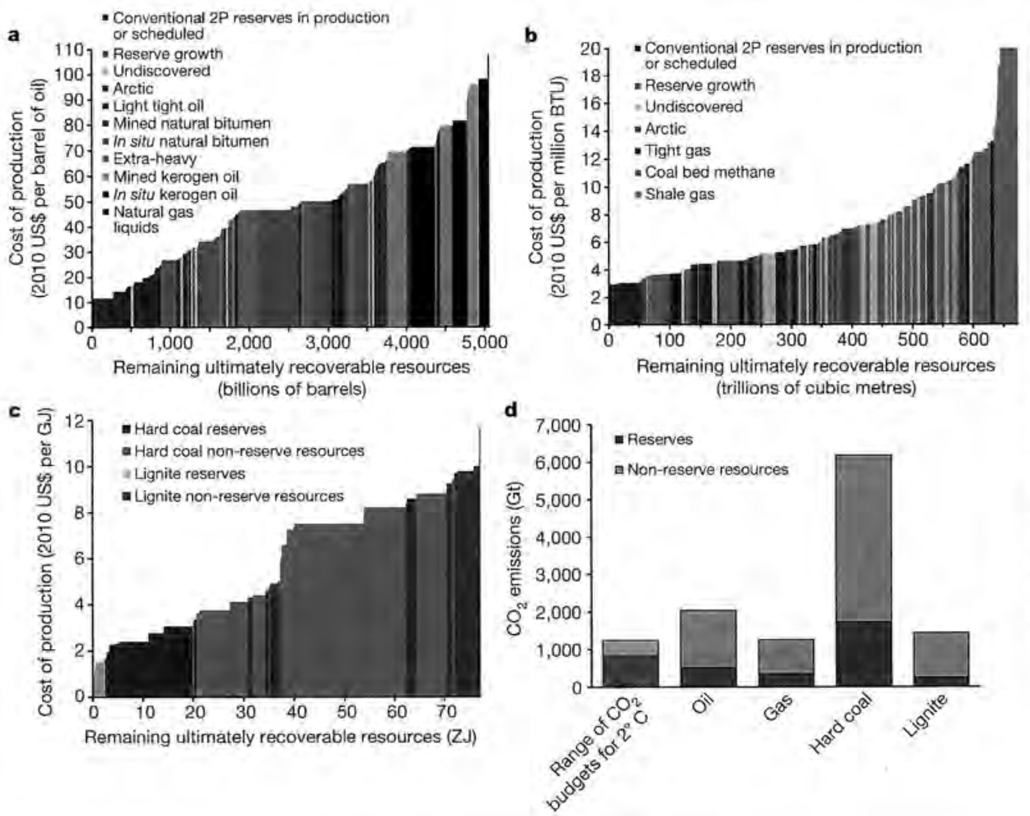


Figure 1 | Supply cost curves for oil, gas and coal and the combustion CO_2 emissions for these resources. **a–c**, Supply cost curves for oil (**a**), gas (**b**) and coal (**c**). **d**, The combustion CO_2 emissions for these resources. Within these resource estimates, 1,294 billion barrels of oil, 192 trillion cubic metres of gas, 728 Gt of hard coal, and 276 Gt of lignite are classified as reserves globally. These reserves would result in 2,900 Gt of CO_2 if combusted unabated. The range of carbon budgets between 2011 and 2050 that are approximately commensurate with limiting the temperature rise to 2 °C (870–1,240 Gt of CO_2) is also shown. 2P, 'proved plus probable' reserves; BTU, British thermal units (one BTU is equal to 1,055 J). One zettajoule (ZJ) is equal to one sextillion (10^{21}) joules. Annual global primary energy production is approximately 0.5 ZJ.

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need to establish the quantities and location of those currently estimated to exist. A variety of metrics with disparate nomenclature are relied upon to report the availability of fossil fuels[10,11], but the two most common are 'resources' and 'reserves'. In this work 'resources' are taken to be the remaining ultimately recoverable resources (RURR)—the quantity of oil, gas or coal remaining that is recoverable over all time with both current and future technology, irrespective of current economic conditions. 'Reserves' are a subset of resources that are defined to be recoverable under current economic conditions and have a specific probability of being produced[11]. Our best estimates of the reserves and resources are presented in Fig. 1 and, at the regional level, in Extended Data Table 1.

Figure 1 also compares the above carbon budget with the CO_2 emissions that would result from the combustion of our estimate of remaining fossil fuel resources (nearly 11,000 Gt CO_2). With the combustion emissions of the remaining reserves alone totalling nearly 2,900 Gt CO_2, the disparity between what resources and reserves exist and what can be emitted while avoiding a temperature rise greater than the agreed 2 °C limit is therefore stark.

Although previous research[12] has examined the implications that emissions mitigation might have on the rents collected by fossil fuel resource owners, more pertinent to policy and industry are the quantities of fossil fuel that are not used before 2050 in scenarios that limit the average global surface temperature rise to 2 °C. Such geographically disaggregated estimates of 'unburnable' reserves and resources are provided here using the linear optimization, integrated assessment model TIAM-UCL[13].

To provide context to the issue of unburnable fossil fuels and our results, it is useful to examine scenarios provided by other models that quantify separately the volumes of oil, gas and coal produced globally under a range of future emissions trajectories[5]. Cumulative production between 2010 and 2050 from these are presented in Fig. 2. Since they have very different future greenhouse gas emissions profiles, we have converted them to approximate temperature rise trajectories. These have been calculated using the climate model MAGICC[14], which generates a probability distribution over temperature rise trajectories for a given emissions profile. We use the 60th percentile temperature trajectory (to correspond with assumptions within TIAM-UCL) and then group the scenarios by the final temperature rise in 2100: below 2 °C, between 2 °C and 3 °C, or exceeding 3 °C.

In this work we have constructed three core scenarios that are constrained to limit the average surface temperature rise in all time periods to 2 °C, to 3 °C, and to 5 °C. Cumulative production of each fossil fuel between 2010 and 2050 in each of these scenarios can be identified within each of the three temperature groupings in Fig. 2.

The global reserves of oil, gas and coal included in Fig. 1 total approximately 7.4 ZJ, 7.1 ZJ and 20 ZJ, respectively. With narrow inter-quartile ranges, relative to the level of reserves available, Fig. 2 shows good agreement on the levels of fossil fuels produced within the temperature groups, despite the range of modelling methodologies and assumptions included.

Since assumptions in modelling the energy system are subject to wide bands of uncertainty[15], we further constructed a number of sensitivity scenarios using TIAM-UCL that remain within a 2 °C temperature rise. These span a broad range of assumptions on production costs, the availability of bio-energy, oil and gas, demand projections, and technology availability (one with no negative emissions technologies, and one with no carbon capture and storage (CCS)) (Extended Data Table 2). The availability of CCS has the largest effect on cumulative production levels (Extended Data Fig. 1); however, there is little variability in the total production of fossil fuels if the world is to have a good chance of staying within the agreed 2 °C limit.

Global production of oil, gas and coal over time in our main 2 °C scenario is given in Fig. 3. This separates production by category, that is, by the individual kinds of oil and gas that make up the global resource base, and compares total production with the projections from the 2 °C scenarios in Fig. 2. The results generated using TIAM-UCL are a product of the economically-optimal solution, and other regional distributions of unburnable reserves are possible while still remaining within the 2 °C limit (even though these would have a lower social welfare). A future multi-model analysis could therefore usefully build on and extend the work that is presented here, but results at the aggregate level can be seen to lie within range of the ensemble of models and scenarios that also give no more than a 2 °C temperature rise.

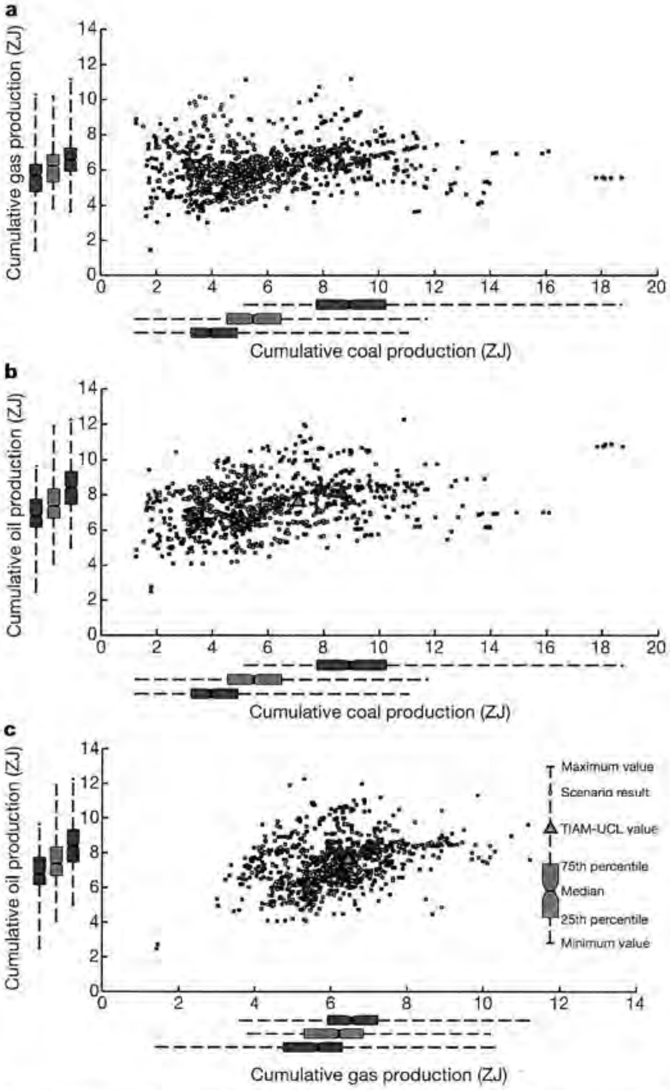

Figure 2 | Cumulative production between 2010 and 2050 from a range of long-term energy scenarios. Panels refer to coal and gas (**a**), coal and oil (**b**), and gas and oil (**c**). Scenarios[5] are coloured according to their approximate resultant 2100 temperature rise above pre-industrial levels. 379 individual scenarios result in a temperature rise of less than 2 °C (green), 366 of between 2 °C and 3 °C (orange), and 284 of more than 3 °C (red). Triangles are the values from the 2 °C (with CCS), 3 °C and 5 °C TIAM-UCL scenarios. Ranges and symbols are as shown in the key in **c**.

In the TIAM-UCL scenarios, production of reserves and non-reserve resources occurs contemporaneously. It is therefore important to recognize that it would be inappropriate simply to compare the cumulative production figures in Fig. 2 with the reserve estimates from Fig. 1 and declare any reserves not used as 'unburnable'. Although there may be sufficient reserves to cover cumulative production between 2010 and 2050, it does not follow that only reserves should be developed and all other resources should remain unused. For oil and gas, resources that are not currently reserves may turn out to be cheaper to produce than some reserves, while new resources will also be developed to maintain

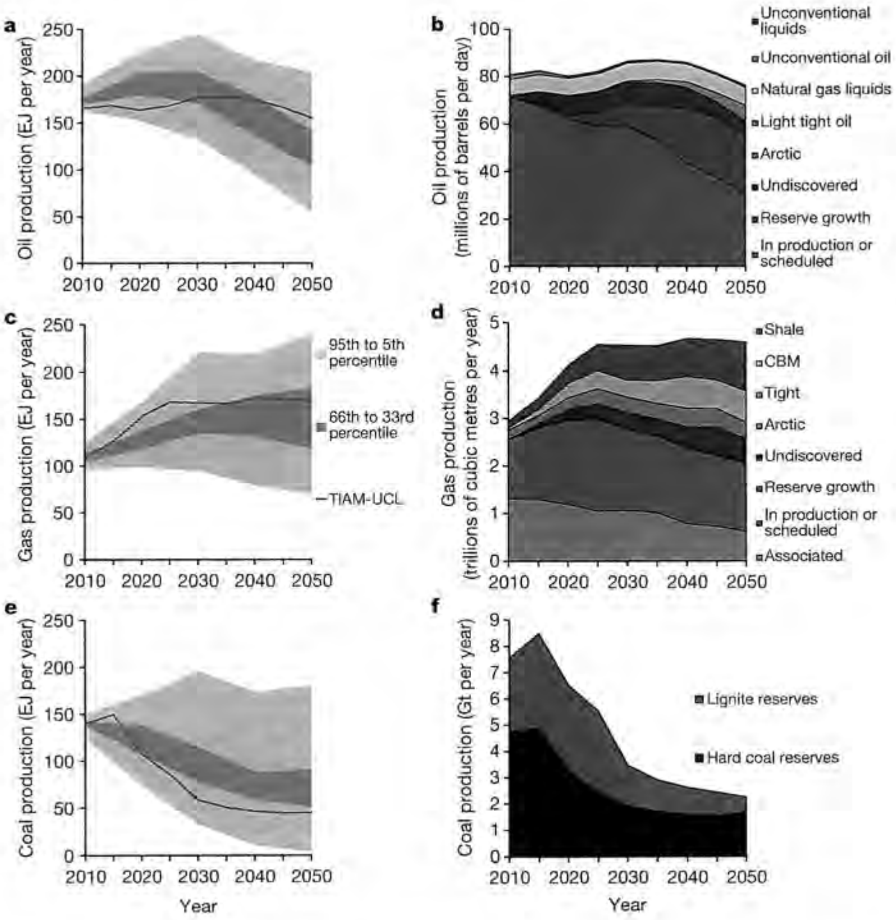

Figure 3 | Oil, gas and coal production in the TIAM-UCL 2 °C scenario (with CCS) and comparison with all other 2 °C scenarios in the Intergovernmental Panel on Climate Change Fifth Assessment Report (AR5) database[5]. **a**, **c** and **e** compare total production by oil, gas and coal with the AR5 database; **b**, **d** and **f** provide a disaggregated view of production for the TIAM-UCL 2 °C scenario separated by category. Associated gas is gas produced alongside crude oil from oil fields. One exajoule (EJ) is equal to one quintillion (10^{18}) joules.

the flow rates demanded by end-use sectors. However, if resources that are currently non-reserves are produced, a greater proportion of reserves must not be produced to stay within the carbon budget.

The reserves of oil, gas and coal that should be classified as unburnable within each region, and the percentage of current reserves that remain unused, are set out in Table 1. Since total production is most sensitive to assumptions on CCS, and since it has been suggested that the deployment of CCS will permit wider exploitation of the fossil fuel resource base[16], Table 1 includes the unburnable reserves from two alternative 2 °C scenarios. One scenario permits the widespread deployment of CCS from 2025 onwards, and the other assumes that CCS is unavailable in any time period.

Globally, when CCS is permitted, over 430 billion barrels of oil and 95 trillion cubic metres of gas currently classified as reserves should remain unburned by 2050. The Middle East, although using over 60% of its oil reserves, carries over half of the unburnable oil globally, leaving over 260 billions of barrels in the ground. Canada has the lowest utilization of its oil reserves (25%), as its natural bitumen[17] deposits remain largely undeveloped (see below) while the United States has the highest, given the proximity of supply and demand centres. The Middle East also holds half of unburnable global gas reserves, with Former Soviet Union countries accounting for another third, meaning that they can use only half their current reserves.

Coal reserves are by far the least-used fossil fuel, with a global total of 82% remaining unburned before 2050. The United States and the Former Soviet Union countries each use less than 10% of their current reserves, meaning that they should leave over 200 billion tonnes (Gt) coal (both hard and lignite) reserves unburned. Coal reserve utilization

Table 1 | Regional distribution of reserves unburnable before 2050 for the 2 °C scenarios with and without CCS

	2 °C with CCS						2 °C without CCS					
	Oil		Gas		Coal		Oil		Gas		Coal	
Country or region	Billions of barrels	%	Trillions of cubic metres	%	Gt	%	Billions of barrels	%	Trillions of cubic metres	%	Gt	%
Africa	23	21%	4.4	33%	28	85%	28	26%	4.4	34%	30	90%
Canada	39	74%	0.3	24%	5.0	75%	40	75%	0.3	24%	5.4	82%
China and India	9	25%	2.9	63%	180	66%	9	25%	2.5	53%	207	77%
FSU	27	18%	31	50%	203	94%	28	19%	36	59%	209	97%
CSA	58	39%	4.8	53%	8	51%	63	42%	5.0	56%	11	73%
Europe	5.0	20%	0.6	11%	65	78%	5.3	21%	0.3	6%	74	89%
Middle East	263	38%	46	61%	3.4	99%	264	38%	47	61%	3.4	99%
OECD Pacific	2.1	37%	2.2	56%	83	93%	2.7	46%	2.0	51%	85	95%
ODA	2.0	9%	2.2	24%	10	34%	2.8	12%	2.1	22%	17	60%
United States of America	2.8	6%	0.3	4%	235	92%	4.6	9%	0.5	6%	245	95%
Global	431	33%	95	49%	819	82%	449	35%	100	52%	887	88%

FSU, the former Soviet Union countries; CSA, Central and South America; ODA, Other developing Asian countries; OECD, the Organisation for Economic Co-operation and Development. A barrel of oil is 0.159 m^3; %, Reserves unburnable before 2050 as a percentage of current reserves.

is twenty-five percentage points higher in China and India, but still they should also leave nearly 200 Gt of their current coal reserves unburned.

The utilization of current reserves is lower in nearly all regions for all of the fossil fuels when CCS is not available, although there is a slight increase in gas production in some regions to offset some of the larger drop in coal production. Nevertheless, Table 1 demonstrates that the reserves of coal that can be burned are only six percentage points higher when CCS is allowed, with the utilization of gas and oil increasing by an even smaller fraction (around two percentage points). Because of the expense of CCS, its relatively late date of introduction (2025), and the assumed maximum rate at which it can be built, CCS has a relatively modest effect on the overall levels of fossil fuel that can be produced before 2050 in a 2 °C scenario.

As shown in Fig. 3, there is substantial production of many of the non-reserve resource categories of oil and gas. Extended Data Table 3 sets out the regional unburnable resources of all coal, gas and oil in the scenario that allows CCS by comparing cumulative production of all fossil fuel resources with the resource estimates in Fig. 1.

The RURR of both types of coal and unconventional oil vastly exceed cumulative production between 2010 and 2050, with the overwhelming majority remaining unburned. Resources of conventional oil are used to the greatest extent, with just under 350 billion barrels of non-reserve resources produced over the model timeframe. The Middle East again holds the largest share of the unburnable resources of conventional oil, but there is a much wider geographical distribution of these unburnable resources than was the case for oil reserves.

Regarding the production of unconventional oil, open-pit mining of natural bitumen in Canada soon drops to negligible levels after 2020 in all scenarios because it is considerably less economic than other methods of production. Production by *in situ* technologies continues in the 2 °C scenario that allows CCS, but this is accompanied by a rapid and total decarbonization of the auxiliary energy inputs required (Extended Data Fig. 2). Although such a decarbonization would be extremely challenging in reality, cumulative production of Canadian bitumen between 2010 and 2050 is still only 7.5 billion barrels. 85% of its 48 billion of barrels of bitumen reserves thus remain unburnable if the 2 °C limit is not to be exceeded. When CCS is not available, all bitumen production ceases by 2040. In both cases, the RURR of Canadian bitumen dwarfs cumulative production, so that around 99% of our estimate of its resources (640 billion barrels), remains unburnable. Similar results are seen for extra-heavy oil in Venezuela. Cumulative production is 3 billion barrels, meaning that almost 95% of its extra-heavy reserves and 99% of the RURR are unburnable, even when CCS is available.

The utilization of unconventional gas resources is considerably higher than unconventional oil. Under the 2 °C scenario, gas plays an important part in displacing coal from the electrical and industrial sectors and so there is over 50 trillion cubic metres unconventional gas production globally, over half of which occurs in North America. Nevertheless, there is a low level of utilization of the large potential unconventional gas resources held by China and India, Africa and the Middle East, and so over 80% of unconventional gas resources (247 trillion cubic metres) are unburnable before 2050. Production of these unconventional gas resources is, however, only possible if the levels of coal reserves identified in Table 1 are not developed: that is, it is not possible for unconventional gas to be additional to current levels of coal production.

Finally, we estimate there to be 100 billion barrels of oil (including natural gas liquids) and 35 trillion cubic metres of gas in fields within the Arctic Circle that are not being produced as of 2010. However, none is produced in any region in either of the 2 °C scenarios before 2050. These results indicate to us that all Arctic resources should be classified as unburnable.

To conclude, these results demonstrate that a stark transformation in our understanding of fossil fuel availability is necessary. Although there have previously been fears over the scarcity of fossil fuels[18], in a climate-constrained world this is no longer a relevant concern: large portions of the reserve base and an even greater proportion of the resource base should not be produced if the temperature rise is to remain below 2 °C.

Online Content Methods, along with any additional Extended Data display items and Source Data, are available in the online version of the paper; references unique to these sections appear only in the online paper.

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1. United Nations Framework Convention on Climate Change (UNFCC). *Report of the Conference of the Parties on its Fifteenth Session, held in Copenhagen from 7 to 19 December 2009. Part Two: Action taken by the Conference of the Parties at its Fifteenth Session.* United Nations Climate Change Conf. Report 43 http://unfccc.int/resource/docs/2009/cop15/eng/11a01.pdf (UNFCC, 2009).
2. Meinshausen, M. *et al.* Greenhouse gas emission targets for limiting global warming to 2 °C. *Nature* **458,** 1158–1162 (2009).
3. Clarke, L. *et al.* in *Climate Change 2014: Mitigation of Climate Change* (Edenhofer, O. *et al.*) Ch. 6 (Cambridge Univ. Press, 2014).
4. Raupach, M. R. *et al.* Sharing a quota on cumulative carbon emissions. *Nature Clim. Chang.* **4,** 873–879 (2014).
5. IPCC Working Group III. *Integrated Assessment Modelling Consortium (IAMC) AR5 Scenario Database* https://secure.iiasa.ac.at/web-apps/ene/AR5DB/ (International Institute for Applied Systems Analysis, 2014).
6. Allen, M. R. *et al.* Warming caused by cumulative carbon emissions towards the trillionth tonne. *Nature* **458,** 1163–1166 (2009).
7. Matthews, H. D., Gillett, N. P., Stott, P. A. & Zickfeld, K. The proportionality of global warming to cumulative carbon emissions. *Nature* **459,** 829–832 (2009).
8. Friedlingstein, P. *et al.* Persistent growth of CO_2 emissions and implications for reaching climate targets. *Nature Geosci.* **7,** 709–715 (2014).
9. Leaton, J. *Unburnable Carbon—Are the World's Financial Markets Carrying a Carbon Bubble?* http://www.carbontracker.org/wp-content/uploads/2014/09/Unburnable-Carbon-Full-rev2-1.pdf (Investor Watch, 2011).
10. McGlade, C. E. A review of the uncertainties in estimates of global oil resources. *Energy* **47,** 262–270 (2012).
11. Society of Petroleum Engineers (SPE). *Petroleum Resources Management System.* www.spe.org/industry/docs/Petroleum_Resources_Management_System_2007.pdf (SPE, 2008).
12. Bauer, N. *et al.* Global fossil energy markets and climate change mitigation—an analysis with REMIND. *Clim. Change* http://dx.doi.org/10.1007/s10584-013-0901-6 (2013).
13. Anandarajah, G., Pye, S., Usher, W., Kesicki, F. & McGlade, C. E. *TIAM-UCL Global Model Documentation.* http://www.ucl.ac.uk/energy-models/models/tiam-ucl/tiam-ucl-manual (University College London, 2011).
14. Meinshausen, M., Raper, S. C. B. & Wigley, T. M. L. Emulating atmosphere–ocean and carbon cycle models with a simpler model, MAGICC6—Part 1: Model description and calibration. *Atmos. Chem. Phys.* **11,** 1417–1456 (2011).
15. Usher, W. & Strachan, N. Critical mid-term uncertainties in long-term decarbonisation pathways. *Energy Policy* **41,** 433–444 (2012).
16. IEA. *Resources to Reserves* Ch. 8 (International Energy Agency, 2013).
17. Alberta Energy Regulator (AER). *Alberta's Energy Reserves 2013 and Supply/Demand Outlook 2014–2023.* www.aer.ca/documents/sts/ST98/ST98-2014.pdf (AER, 2014).
18. Yergin, D. *The Prize: the Epic Quest for Oil, Money and Power* Epilogue (Simon and Schuster, 2009).

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METHODS

Fossil fuel definitions. A 'McKelvey' box[19] is often used to provide an overview of the relationship between different resource and reserve estimates[20]. The best estimates of current oil and gas reserves in Extended Data Table 1 were of the 'proved plus probable' or '2P' quantities. Since 2P reserve estimates are rare for coal and none are in the public domain, the best estimates shown for coal were of the 'proved' or '1P' reserves. Broadly speaking, 1P estimates are more conservative, often corresponding to an estimate with a 90% probability of being exceeded, while 2P estimates are the median estimate of the reserves for a given field or region[11].

Oil and gas can be further separated into 'conventional' and 'unconventional' reserves and resources. Again, there is no single definition of these terms, but here we define oil with density greater than water (often standardized as '10°API') to be unconventional and all other quantities as conventional. We therefore categorize the 'light tight oil' extracted from impermeable shale formations using hydraulic fracturing as conventional oil.

For gas, tight gas (gas trapped in relatively impermeable hard rock, limestone or sandstone), coal-bed methane (gas trapped in coal seams that is adsorbed in the solid matrix of the coal), and shale gas (gas trapped in fine-grained shale) are considered as the three 'unconventional gases'; all other quantities are considered to be conventional.

Coal is distinguished by its energy density following the definitions used by the Federal Institute for Geosciences and Natural Resources (BGR)[21]. Hard coal has an energy density greater than 16.5 MJ kg^{-1}; any quantities with energy density less than this are classified as lignite.

Derivation of reserve and resource estimates. The estimated oil and gas reserves and resources shown in Extended Data Table 1 were derived in the following manner[22]. We first identified the individual elements or categories of oil and gas that make up the global resource base. For oil these are: current conventional 2P reserves in fields that are in production or are scheduled to be developed, reserve growth, undiscovered oil, Arctic oil, light tight oil, natural gas liquids, natural bitumen, extra-heavy oil, and kerogen oil. The latter three of these are the unconventional oil categories.

Reserve growth is defined to be 'the commonly observed increase in recoverable resources in previously discovered fields through time'[23]. Quantities in this category here include any contributions from reserves in fields that have been discovered but are not scheduled to be developed ('fallow fields'), the new implementation of advanced production technologies such as enhanced oil recovery, changes in geological understanding, and changes in regional definitions.

There are eight categories of conventional and unconventional gas: current conventional 2P reserves that are in fields in production or are scheduled to be developed, reserve growth, undiscovered gas, Arctic gas, associated gas, tight gas, coal-bed methane, and shale gas. As noted above, the latter three of these are collectively referred to as unconventional gas.

We then selected the most robust data sources that provide estimates of the resource potential of each individual category within each country; these sources are set out in Extended Data Table 4. Taken together, differences between these sources provide a spread of discrete quantitative resource estimates for each category within each country. We also differentiated between the quantities of conventional oil that are natural gas liquids, and the quantities of natural gas that are associated with oil fields; these distinctions are important for modelling purposes but are rarely made in the literature.

For unconventional oil, we first generated a range of estimates for the in-place resources of natural bitumen, extra-heavy oil, and kerogen oil, and a range of potential recovery factors for different extraction technologies. We separately characterized the natural bitumen and kerogen oil resources that are extractable using mining technologies and those resources that are extractable using *in situ* technologies because the resource potential, costs, and energy requirements of these technologies are very different.

Continuous distributions were next constructed across these data ranges. Since there is no empirical basis for the choice of a suitable shape or form for such distributions, we used both the triangular and the beta distributions, chosen because they can be skewed both positively and negatively, and because they allow identical distributions to be used across all of the ranges derived. With equal weighting for each distribution, we combined these into a single individual resource distribution for each category within each country.

We then estimated the production costs of each of the oil and gas resource categories. Taking account of the resource uncertainty, these were used to develop supply cost curves for each category of oil and gas within each country.

We finally used a Monte Carlo selection process to combine these country-level supply cost curves. Regional supply cost curves were thus formed from aggregated supply cost curves for individual countries, and similarly supply cost curves formed for multiple categories of oil or gas within one or more countries. Data in Fig. 1 are the median values from these aggregate distributions with Extended Data Table 4 giving high (95th percentile), median, and low (5th percentile) estimates for each category at the global level.

In most industry databases of oil and gas reserves (for example, the database produced by the consultancy IHS CERA[24,25]), some of the quantities classified as reserves lie in fields that were discovered over ten years ago, yet these fields have not been developed and there are no plans at present to do so. These are sometimes referred to as 'fallow fields'. For gas these quantities can also be called 'stranded gas', and they can be quite substantial; for example ref. 24 suggests that 50% gas reserves outside of North America are in stranded fields. Strictly, oil and gas in such fields should not be classified as reserves (for example, ref. 11 states that reserve quantities must have a 'reasonable timetable for development'). However, in this work, to ensure that the reserve estimates provided in Table 1 are not substantially different from the global totals provided by these industry databases, we follow their convention of classifying these quantities as reserves.

There are fewer independent estimates of reserves for coal and so we simply relied upon the estimates provided by the BGR[21] for the reserve figures in Extended Data Table 1. The RURR of coal are more problematic to characterize, however. The 'resource' estimates provided by the BGR are not estimates of the quantities that can actually be extracted but are the in-place quantities; large portions of these are unlikely ever to be technically recoverable.

We therefore used the proved, probable and possible reserve estimates for hard coal and lignite provided by the World Energy Council[26] for a selection of countries. The sum of these three figures gives an estimate of the 'tonnage within the estimated additional amount in place that geological and engineering information indicates with reasonable certainty might be recovered in the future' (the definition provided by the World Energy Council). Since the sum of these three figures takes account of technical recoverability, we consider that, while imperfect, they provide a better estimate of the ultimately recoverable resources of coal than either the (narrower) proved reserve or the (broader) in-place resource estimates.

There are a number of countries that are estimated by the BGR to hold large quantities of coal in place but for which no probable and possible reserve estimates are provided by the World Energy Council. The ratio of the World Energy Council resource estimate to the BGR in-place estimate in countries that have estimates provided by both sources can vary substantially, but the average ratio is 16% for hard coal and 31% for lignite. We therefore assumed this ratio to generate resource estimates for all countries for which only BGR in-place estimates are provided. The proved reserve estimates of coal are so large themselves that the resource estimates are less important than is the case for oil and gas resource estimates.

There are few other sources providing a comprehensive overview of fossil fuel availability. Further, these often do not provide their sources or the methods used to generate estimates, do not define fully what categories or elements are included or excluded, and do not indicate sufficient conversion factors that would allow a like-with-like comparison. Some exceptions, however, are the IEA[27,28], the IIASA Global Energy Assessment (GEA)[29], and the BGR[21]. Their estimates are shown together with our aggregated reserve and resource estimates in Extended Data Table 5.

A number of factors contribute to the large variation between these estimates. A key reason is that the definitions of 'reserves' and 'resources' differ among sources, and so it is problematic to seek to compare them directly. For example, as noted above, the BGR, whose estimates are followed closely by the other sources, gives the total coal in place rather than an estimate of the resources that can be recovered, as in our study. Other reasons for the differences seen include: (1) the exclusion or inclusion of certain categories of fossil fuels such as light tight oil, aquifer gas, and methane hydrates; (2) whether proved (1P) or proved plus probable (2P) reserves are reported, and the methods used to generate the 1P reserve estimates; (3) the potential inflation of reserve estimates for political reasons, and whether they should consequently be increased or reduced[30]; (4) the inclusion of stranded gas volumes in gas reserve estimates; (5) differences in the functional form used to estimate volumes of reserve growth (if reserve growth is included at all); (6) the difficulty in estimating current recovery factors (the ratio of recoverable resources to total resources in place), and how these may increase in the future; (7) differences between the methods used to estimate undiscovered oil and gas volumes; (8) the scarcity of reports providing reliable estimates of the potential resources of Arctic oil and gas, light tight oil, tight gas and coal bed methane, and the frequent consequent reliance upon expert judgement; (9) variation in what unconventional oil production technologies, which vary considerably in their recovery factors, will be used in the future; and (10) the chosen cut-off 'yield' (the volume of synthetic oil produced from a given weight of shale rock) for kerogen oil.

The estimates considered in our model are the result of careful and explicit consideration of all these issues, with our choices justified in the light of available knowledge. It can be seen in Extended Data Table 5, however, that our median figures are generally lower than the estimates provided by the other sources shown there. Therefore, although we consider our median resource estimates to be more robust than the figures used by these other sources, if in fact these other estimates were found to be closer to being correct, then the unburnable resources given in Extended Data Table 3 would also be larger. For example, if total gas resources are actually at the GEA high estimate, then the percentage that should be classified as unburnable before 2050 under the 2 °C scenario would increase to 99% rather than our estimate of 75%.

The cut-off date after which quantities that have not been produced should be considered 'unburnable' is also an important assumption. While there are no specific timeframes attached to the definition of reserves, quantities are usually required to be developed within, for example, a 'reasonable timeframe'[11]. It is doubtful whether any reserves not produced by 2050 would fulfil this criterion. We therefore take cumulative production of reserves between 2010 and 2050 as the reserve 'utilization', and classify any quantities not used within this time as those that should be 'unburnable' if a certain temperature rise is not to be exceeded. Similarly, if none, or only a minor proportion, of a certain non-reserve resource is produced before 2050, then any current interest in developing it would be questionable. We thus also rely on 2050 as the cut-off date for classifying resources that should be considered as unburnable.

Description and key assumptions in TIAM-UCL. The TIMES Integrated Assessment Model in University College London ('TIAM-UCL') is a technology-rich, bottom-up, whole-system model that maximizes social welfare under a number of imposed constraints. It models all primary energy sources (oil, gas, coal, nuclear, biomass, and renewables) from resource production through to their conversion, infrastructure requirements, and finally to sectoral end-use. An extended explanation of input assumptions, approaches and data sources can be found in ref. 13. The base year of TIAM-UCL is 2005, the model is run in full to 2100, and thereafter the climate module is run to 2200. Results are presented here only between 2010 and 2050 (and are reported in five-year increments). All scenarios in this paper are run with the assumption of perfect foresight.

Resources and costs of all primary energy production are specified separately within 16 regions covering the world, and separately within the regions that contain members of the Organisation of Petroleum Exporting Countries (OPEC); the names of these are presented in Extended Data Table 6. For clarity in the main text, we have aggregated some of these regions into ten more-encompassing groups.

The climate module of TIAM-UCL is calibrated to the MAGICC model[14]. This module can be used to project the effects of greenhouse gas emissions on: atmospheric concentrations of greenhouse gas, radiative forcing, and average global temperature rises. It can also be used to constrain the model to certain bounds on these variables. In this work, the climate module is used to restrict the temperature rise to certain levels (as explained below). For the calibration to MAGICC, values from the probability distributions of climate parameters in MAGICC were selected so that there is a 60% chance that the temperature rise will remain below any level reported. Any constraints imposed using the TIAM-UCL climate module thus also correspond to this probability.

The emissions profiles[5] used in Fig. 2 were converted to temperature rises using MAGICC. To ensure consistency with TIAM-UCL, we use the 60th percentile temperature trajectory from MAGICC and then group by the final temperature rise in 2100; there is therefore also a 60% chance that the temperature rise will be below the level indicated.

For each of the scenarios run in this paper using TIAM-UCL, a 'base case' is first formed that incorporates no greenhouse gas abatement policies. This base case uses the standard version of the model that relies upon minimizing the discounted system cost. This is used to generate base prices for each commodity in the model. TIAM-UCL is then re-run using the elastic-demand version with the greenhouse gas abatement policies introduced. This version of the model maximizes social welfare (the sum of consumer and producer surplus) and allows the energy-service demands to respond to changes in the endogenously determined prices resulting from these new constraints.

Fossil fuel modelling in TIAM-UCL. Oil and gas are both modelled in a similar manner in TIAM-UCL. The nine categories of conventional and unconventional oil and eight categories of conventional and unconventional gas identified above are all modelled separately. Coal production in TIAM-UCL is modelled more collectively, with only two categories, reserves and resources, for hard coal and lignite.

Natural bitumen and kerogen oil resources can be produced using either mining or *in situ* means, the technologies for which have different costs, efficiencies, and energy inputs. Although natural gas is predominantly used at present for the energy inputs to these unconventional resources, the model is free to choose any source of heat, electricity and hydrogen to allow greater flexibility. The costs of the auxiliary energy inputs required to extract and upgrade the native unconventional oils are determined endogenously by the model.

Each of the coal, gas and oil categories are modelled separately within the regions listed in Extended Data Table 6, with each resource category within each region split into three cost steps. As discussed above, the supply cost curves given in Fig. 1 comprise the data input to TIAM-UCL.

After processing, oil is next refined into products (gasoline, diesel, naphtha and so on), whereas processed gas and coal can be used directly. Fuel switching to and from all of the fossil fuels is possible. Trade of hard coal, crude oil, refined products, natural gas, both in pipelines and as liquefied natural gas, is allowed. Lignite cannot be traded between the regions.

Refined oil products can also be produced directly using Fischer–Tropsch processes with possible feedstocks of coal, gas, or biomass; these technologies can also be employed either with or without carbon capture and storage. Regional coal, oil and gas prices are generated endogenously within the model. These incorporate the marginal cost of production, scarcity rents, rents arising from other imposed constraints, and transportation costs.

A new key aspect of TIAM-UCL is the imposition of asymmetric constraints on the rate of production of oil and gas given a certain resource availability; these are intended to represent 'depletion rate constraints'. In TIAM-UCL, these constraints are modelled through introducing maximum annual production growth and maximum 'decline rate' restrictions. These are imposed on each cost step of each category of both oil and gas in each region, and ensure that the production follows a more realistic profile over time.

Data for these constraints are available at the field level from the bottom-up economic and geological oil field production model ('BUEGO')[31]. BUEGO contains a data-rich representation of 7,000 producing 'undiscovered' and discovered but undeveloped oil fields. These data include each field's 2P reserves, potential production capacity increases, water depth, capital and operating costs, and natural decline rate (the rate at which production would decline in the absence of any additional capital investment).

We used production-weighted averages (as of 2010) of the individual fields within each region to give average regional natural decline rates, which were imposed as maximum decline constraints in TIAM-UCL in the form of equal maximum annual percentage reductions. Although data on gas natural decline rates are much more sparse, some are available at a regional level[32], which can be compared with similar results for oil natural decline rates[25]. This comparison suggests that gas natural decline rates are on average 1% per year greater than for oil, with similar distributions for location (onshore/offshore) and size. The constraints placed on the maximum annual reductions in natural gas production were thus assumed to be 1% higher than those derived for oil.

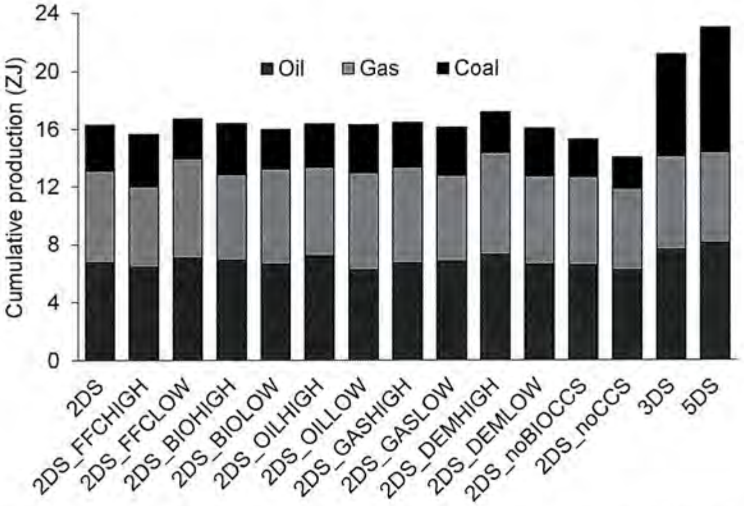
As identified in the main text, to understand the quantities of reserves of oil and gas that are unburnable, production of reserve sources only should be compared with reserve estimates, while cumulative production of all sources should be compared with the resource estimates. For coal, the reserves are so much greater than cumulative production under any scenario that this distinction is not as important.

The base year of TIAM-UCL is 2005, but the base year of this study is 2010. Since reserves have grown, and oil and gas have been discovered in the intervening five years, some quantities that were classified as reserve growth and undiscovered oil and gas in 2005 should be classified as reserves in 2010. Within each region, the cumulative production figures to which the reserve estimates in Extended Data Table 1 are compared therefore contain production from the conventional 2P reserves in the 'fields in production or scheduled to be developed' category, as well as some portions of production from the 'reserve growth' and 'undiscovered' categories. In addition, since, for example, reserves of natural bitumen are included in the reserves figures of Canada and unconventional gas reserves are included in the reserves figures of the United States, production of some of the unconventional categories are also included in these cumulative production figures. To ensure consistency within each region, the maximum production potentials over the modelling period from the categories included in the cumulative production figures are equal to the reserve estimates given in Extended Data Table 1.

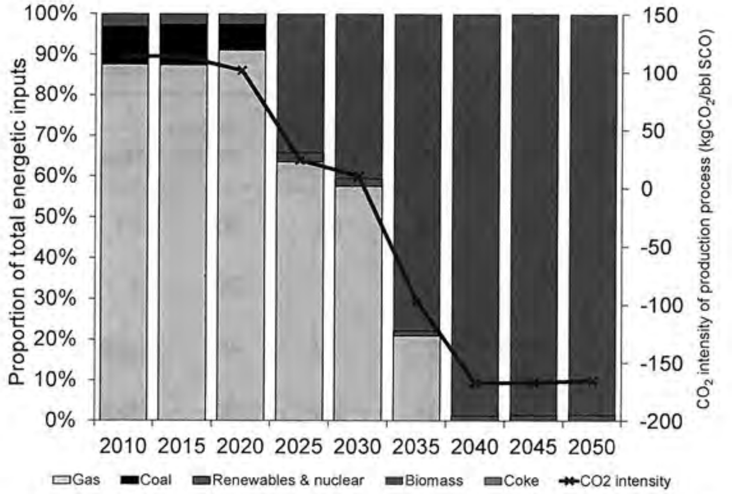
Overview of scenarios implemented. A brief overview of the main assumptions within the four scenarios run as part of this work is provided in Extended Data Table 7. For the emissions mitigation scenarios (those that limit the temperature rise to 3 °C and 2 °C), we assume that there are only relatively modest efforts to limit emissions in early periods as explained. The assumptions within the 2 °C sensitivity scenarios used to construct Extended Data Fig. 1 are provided in Extended Data Table 2.

19. McKelvey, V. E. Mineral resource estimates and public policy. *Am. Sci.* **60,** 32–40 (1972).
20. McGlade, C. E., Speirs, J. & Sorrell, S. Unconventional gas—a review of regional and global resource estimates. *Energy* **55,** 571–584 (2013).
21. Federal Institute for Geosciences and Natural Resources (BGR). *Energy Study 2012. Reserves, Resources and Availability of Energy Resources.* http://www.bgr.bund.de/DE/Gemeinsames/Produkte/Downloads/DERA_Rohstoffinformationen/rohstoffinformationen-15e.pdf?__blob=publicationFile&v=3 (BGR, 2012).
22. McGlade, C. E. *Uncertainties in the outlook for oil and gas.* PhD thesis, UCL, http://discovery.ucl.ac.uk/1418473/2/131106%20Christophe%20McGlade_PhD%20Thesis.pdf (2013).

23. Klett, T. & Schmoker, J. in *Giant Oil and Gas fields of the Decade 1990–1999* (ed. Halbouty, M. T.) 107–122 (The American Association of Petroleum Geologists, 2003).
24. Attanasi, E. D. & Freeman, P. A. Survey of Stranded Gas and Delivered Costs to Europe of Selected Gas Resources. *SPE Econ. Manag.* **3,** 149–162 (2011).
25. International Energy Agency (IEA). *World Energy Outlook*. http://www.worldenergyoutlook.org/media/weowebsite/2008-1994/weo2008.pdf (IEA, 2008).
26. Trinnaman, J. & Clarke, A. *Survey of Energy Resources* http://www.worldenergy.org/wp-content/uploads/2012/09/ser_2010_report_1.pdf (World Energy Council, 2010).
27. International Energy Agency (IEA). *World Energy Outlook*. http://www.worldenergyoutlook.org/publications/weo-2013/ (IEA, 2013).
28. International Energy Agency (IEA). *World Energy Outlook*. http://www.iea.org/publications/freepublications/publication/weo2011_web.pdf (IEA, 2011).
29. Rogner, H.-H. *et al.* in *Global Energy Assessment—Towards a Sustainable Future* Ch. 7, 423–512 (Cambridge University Press, 2012).
30. Owen, N. A., Inderwildi, O. R. & King, D. A. The status of conventional world oil reserves—hype or cause for concern? *Energy Policy* **38,** 4743–4749 (2010).
31. McGlade, C. & Ekins, P. Un-burnable oil: an examination of oil resource utilisation in a decarbonised energy system. *Energy Policy* **64,** 102–112 (2014).
32. International Energy Agency (IEA). *World Energy Outlook*. http://www.worldenergyoutlook.org/media/weowebsite/2009/WEO2009.pdf (IEA, 2009).
33. Leatherdale, A. *et al. Bioenergy Review: Technical Paper 2—Global and UK Bioenergy Supply Scenarios.* http://archive.theccc.org.uk/aws2/Bioenergy/1463%20CCC_Bio-TP2_supply-scen_FINALwithBkMks.pdf (Committee on Climate Change, 2011).
34. O'Neill, B. C. *et al.* A new scenario framework for climate change research: the concept of shared socioeconomic pathways. *Clim. Change* **122,** 387–400 (2014).
35. Campbell, C. J. *Atlas of Oil and Gas Depletion* (Springer, 2013).
36. Herrmann, L. *et al. Oil and Gas for Beginners* 270–413 (Deutsche Bank, 2013).
37. Klett, T. R. *et al.* An Assessment of Potential Additions to Conventional Oil and Gas Resources of the World (outside the United States) from Reserve Growth. http://pubs.usgs.gov/fs/2012/3052/fs2012-3052.pdf (USGS, 2012).
38. Klett, T. R. *et al. Potential Additions to Conventional Oil and Gas Resources in Discovered Fields of the United States from Reserve Growth, 2012.* http://pubs.usgs.gov/fs/2012/3108/ (USGS, 2012).
39. Ahlbrandt, T., Charpentier, R., Klett, T., Schmoker, J. & Schenk, C. *USGS World Petroleum Assessment 2000.* http://pubs.usgs.gov/dds/dds-060/ (USGS, 2000).
40. Bentley, R., Miller, R., Wheeler, S. & Boyle, G. *UKERC Review of Evidence on Global Oil Depletion: Annex 1—Models of global oil supply for the period 2008-2030.* http://www.ukerc.ac.uk/support/tiki-download_file.php?fileId=292 (UKERC, 2009).
41. Brownfield, M., Charpentier, R. R., Cook, T., Gautier, D. L. & Higley, D. K. *An Estimate of Undiscovered Conventional Oil and Gas Resources of the World, 2012.* http://pubs.usgs.gov/fs/2012/3042/fs2012-3042.pdf (USGS, 2012).
42. Gautier, D. L. *et al.* Assessment of undiscovered oil and gas in the Arctic. *Science* **324,** 1175–1179 (2009).
43. Smith, T. Arctic dreams—a reality check. Geo ExPro **4,** 16–24 (2007).
44. Shah, A. *et al.* A review of novel techniques for heavy oil and bitumen extraction and upgrading. *Energy Environ. Sci.* **3,** 700–714 (2010).
45. Clarke, B. *NPC Global Oil and Gas Study: Topic Paper 22—Heavy Oil.* www.npc.org/study_topic_papers/22-ttg-heavy-oil.pdf (National Petroleum Council, 2007).
46. Schenk, C. *et al. An Estimate of Recoverable Heavy Oil Resources of the Orinoco Oil Belt, Venezuela.* http://pubs.usgs.gov/fs/2009/3028/pdf/FS09-3028.pdf (USGS, 2009).
47. Attanasi, E. D. & Meyer, R. F. in *2010 Survey of Energy Resources* 123–150 (World Energy Council, 2010).
48. Johnson, R. C., Mercier, T. J. & Brownfield, M. Assessment of in-place oil shale resources of the Green River Formation, Greater Green River Basin in Wyoming, Colorado, and Utah. http://pubs.usgs.gov/fs/2011/3063/pdf/FS11-3063.pdf (USGS, 2011).
49. Dyni, J. *Geology and Resources of Some World Oil-Shale Deposits.* http://pubs.usgs.gov/sir/2005/5294/pdf/sir5294_508.pdf (USGS, 2006).
50. Biglarbigi, K., Mohan, H. & Carolus, M. *Potential for Oil Shale Development in the United States.* http://www.inteki.com/reports.html (INTEK, 2009).
51. CEDIGAZ. *Natural Gas in the World, End of July 2008* (Centre International d'Information sur le Gaz Naturel et tous Hydrocarbures Gazeux (CEDIGAZ), 2009).



Extended Data Figure 1 | Cumulative fossil fuel production under a range of sensitivity scenarios run using TIAM-UCL. Scenario names and characteristics are given in Extended Data Table 2.



Extended Data Figure 2 | The auxiliary energy inputs for natural bitumen production in Canada by *in situ* technologies in the 2 °C scenario and the CO_2 intensity of these. bbl SCO, a barrel of synthetic crude oil, the oil that results after upgrading the natural bitumen.

Extended Data Table 1 | Best estimates of remaining reserves and remaining ultimately recoverable resources from 2010

	Oil (Gb)			Gas (Tcm)			Hard coal (Gt)		Lignite (Gt)	
Country or region	Res	Con RURR	Uncon RURR	Res	Con RURR	Uncon RURR	Res	RURR	Res	RURR
Africa	111	280	70	13	45	35	31	45	2	5
Canada	53	60	640	1	5	25	4	35	2	40
China and India	38	90	110	5	10	40	255	1,080	16	120
FSU	152	370	360	61	95	30	123	580	94	490
CSA	148	360	450	9	30	55	10	25	5	10
Europe	25	110	30	6	25	20	17	70	66	160
Middle East	689	1,050	10	76	105	20	2	10	2	5
OECD Pacific	6	30	130	4	10	20	45	120	44	200
ODA	23	75	5	9	25	15	15	40	14	155
United States	50	190	650	8	25	40	226	560	31	335
Global	1,294	2,615	2,455	192	375	300	728	2,565	276	1,520

'Con' and 'Uncon' stand for conventional and unconventional sources, respectively. Coal is specified in billions of tonnes (Gt), gas in trillions of cubic metres (Tcm) and oil in billions of barrels (Gb). Res, reserves.

Extended Data Table 2 | Labels and description of the sensitivity scenarios modelled in this project

Sensitivity Name	Description
2DS_FFCHIGH	Production costs of all fossil fuel technologies are 50% larger in 2015 and 100% larger in 2020 than in 2DS, with equal annual percentage changes between these dates and remaining at this level for the model horizon
2DS_FFCLOW	Production costs of all fossil fuel technologies are 33% lower in 2015 and 50% lower in 2020 than in 2DS, with equal annual percentage changes between these dates and remaining at this level for the model horizon
2DS_BIOHIGH	The maximum annual production of solid biomass and bio-crops in 2050 is assumed to be 350 EJ. This is close to the highest level of production of bio-energy in any of the scenarios from the AR5 scenario database[5] and is around three times the equivalent figure in 2DS (119 EJ).
2DS_BIOLOW	The maximum annual production of solid biomass and bio-crop in 2050 is assumed to be 38 EJ. This is similar to the figure given in the central scenario from [33] and is around a third of the equivalent figure in 2DS (119 EJ).
2DS_OILHIGH	Uses the high values of each category of oil in each region from the aggregate resource distributions described in the methods section (Extended Data Table 4)
2DS_OILLOW	Uses the low values of each category of oil in each region (Extended Data Table 4)
2DS_GASHIGH	Uses the high values of each category of gas in each region (Extended Data Table 4)
2DS_GASLOW	Uses the low values of each category of gas in each region (Extended Data Table 4)
2DS_DEMHIGH	The major drivers of energy service demands in TIAM-UCL are growth in GDP, population, and GDP/capita. Future regional growth in GDP and population are therefore modified to the values given in Shared Socioeconomic Pathway (SSP) number 5[34] the SSP with the highest GDP and GDP/capita growth by 2050 (a 240% increase in the global average; cf. a 120% increase in 2DS). All other energy service demands (not relying on GDP or population) are also modified commensurately.
2DS_DEMLOW	Future regional growth in GDP and population are modified to the values given in Shared Socioeconomic Pathway (SSP) number 3:[34] the SSP with the lowest GDP and GDP/capita growth by 2050 (a 50% increase in the global average).
2DS_NOBIOCCS	No negative emissions technologies are permitted i.e. carbon capture and storage (CCS) cannot be applied to any electrical or industrial process that uses biomass or bio-energy as feedstock in any period.
2DS_NOCCS	CCS is not permitted to be applied to any electrical or industrial process in any period.

Data for bio-energy sensitivities from refs 5 and 33, and for demand sensitivities from ref. 34.

Extended Data Table 3 | Regional distribution of resources unburnable before 2050 in absolute terms and as a percentage of current resources under the 2 °C scenario that allows CCS

	Conven oil		Unconven oil		Conven Gas		Unconven Gas		Hard Coal		Lignite	
Country or region	Gb	%	Gb	%	Tcm	%	Tcm	%	Gt	%	Gt	%
Africa	141	50%	70	100%	28	61%	35	100%	42	94%	2.8	56%
Canada	43	72%	633	99%	3.6	73%	18	71%	34	98%	39	97%
China and India	54	60%	110	100%	8.0	80%	35	88%	1,003	93%	106	88%
FSU	201	54%	360	100%	63	67%	27	89%	576	99%	480	98%
CSA	198	55%	447	99%	23	76%	51	92%	21	85%	6.3	63%
Europe	64	58%	30	100%	18	72%	16	78%	69	99%	142	89%
Middle East	554	53%	10	100%	72	68%	20	100%	10	100%	5.0	99%
OECD Pacific	23	77%	130	100%	9.0	90%	15	74%	116	97%	198	99%
ODA	38	51%	5.0	100%	14	55%	12	78%	34	84%	142	92%
United States	99	52%	650	100%	19	75%	20	50%	556	99%	317	95%
Global	1,417	54%	2,445	100%	257	69%	247	82%	2,462	96%	1,438	95%

'Conven' and 'Unconven' stand for conventional and unconventional resources, respectively.

Extended Data Table 4 | Principal data sources used to derive reserve and resource estimates and estimates at the global level for each category of production

Category	Data sources used to provide country-level estimates of resources	Aggregated high estimate	Aggregated median estimate	Aggregated low estimate
Oil		(in Gb)	(in Gb)	(in Gb)
Current conventional 2P reserves in fields in production or scheduled to be developed	[21,31,35,36]	950	820	620
Reserve growth	[37,38]	1,200	850	610
Undiscovered oil	Fact sheets since USGS World Petroleum Assessment [39] and [35,40,41]	580	300	180
Arctic oil	[42,43]	80	65	40
Light tight oil	[10]	470	300	150
Natural gas liquids (NGL)	[26] Ancillary data associated with [39]	380	280	170
Natural bitumen	Oil in place estimates [17,26] Extraction technologies [44–46]	Mined RURR 130 *In situ* RURR 1290	Mined RURR 100 *In situ* RURR 840	Mined RURR 70 *In situ* RURR 520
Extra-heavy oil	Oil in place estimates [47,48] Extraction technologies [47] and refs for bitumen	750	440	230
Kerogen oil	Oil in place estimates [49,50] Extraction technologies [51]	Mined RURR 740 *In situ* RURR 1,080	Mined RURR 485 *In situ* RURR 590	Mined RURR 270 *In situ* RURR 190
Total		7,650	5,070	3,050
Gas		(in tcm)	(in tcm)	(in tcm)
Current conventional 2P reserves in fields in production or scheduled to be developed	[35,52]	140	130	110
Reserve growth	[24,37,38]	125	90	60
Undiscovered gas	Fact sheets since USGS World Petroleum Assessment [39] and [35,41]	180	120	80
Arctic gas	[42,43]	40	35	25
Tight gas	[20]	60	60	60
Coal-bed methane	[20]	45	40	20
Shale gas	[20]	310	200	120
Associated gas	[36,37,44]	Included in the above		
Total		900	675	475

High and low values are the aggregated 95th and 5th percentile estimates, respectively. 'tcm', trillions of cubic metres. Data are from references 10, 17, 20, 21, 31, 35, 36, 37, 38, 39, 40, 41, 42, 43, 44, 45, 46, 47, 48, 49, 50 and 51.

Extended Data Table 5 | Global aggregated oil, gas and coal reserve and resource estimates from a selection of data sources

	Oil (Gb)		Gas (Tcm)		Coal (Gt)	
Organisation	Reserves	Resources	Reserves	Resources	Reserves	Resources
BGR	1,600	4,750	195	825	1,000	23,500
IEA	1,700	5,950	190	810	1,000	21,000
GEA	1,500 - 2,300	4,200 - 6,000	670 - 2,000	2,000 - 12,500	850 - 1,000	14,000 - 20,000
This study's median figures	1,300	5,070	190	675	1,000	4,085

BGR, Federal Institute for Geosciences and Natural Resources[21]; IEA, International Energy Agency[27,28]; GEA, Global Energy Assessment[29].

Extended Data Table 6 | Regions included in TIAM-UCL and their aggregation to the regions given in the main text

Region	Aggregated region in main text
Non-OPEC Africa	Africa
OPEC Africa	Africa
Australia	OECD Pacific
Canada	Canada
Non-OPEC Central and South America	Central and South America (CSA)
OPEC Central and South America	Central and South America (CSA)
China	China and India
Eastern Europe	Europe
Former Soviet Union	Former Soviet Union (FSU)
India	China and India
Japan	OECD Pacific
Non-OPEC Middle	Middle East
OPEC Middle East	Middle East
Mexico	Central and South America (CSA)
Other Developing Asia	Other Developing Asia (ODA)
South Korea	OECD Pacific
United Kingdom	Europe
United States	United States
Western Europe	Europe

Extended Data Table 7 | Labels and description of the four core scenarios modelled in this project

Scenario Name	Description
5DS	The model is constrained to keep the average global surface temperature rise to less than 5°C in all years to 2200. No other emissions constraints are imposed, and since allowed emissions under this scenario are so high (i.e. the constraint is very lax), no real emissions mitigation is required. These constraints result in 2050 GHG emissions of 71 Gt CO_2-eq (up from around 48 Gt CO_2-eq in 2010).
3DS	From 2005 to 2010, the model is fixed to the solution given in the 5°C temperature i.e. we assume that no emissions reductions are required. From 2010-2015, it is assumed that the model must be on track to achieve the emissions reduction pledges set out in the Copenhagen Accord[1], but no other emissions reductions are required. From 2015 onwards the model must meet the Copenhagen Accord emissions reductions in 2020, and emissions must be such as to keep the average global surface temperature rise below 3°C in all years to 2200. These constraints result in 2050 GHG emissions of 54 Gt CO_2-eq
2DS	The constraints between 2005 and 2015 in this scenario are identical to the 3DS. From 2015 onwards the model must meet the Copenhagen Accord emissions reductions in 2020, and emissions must be such as to keep the average global surface temperature rise below 2°C in all years to 2200. These constraints result in 2050 GHG emissions of 21 Gt CO_2-eq
2DS-noCCS	Emissions reduction requirements are identical to 2DS. Carbon capture and storage (CCS) is not permitted to be applied to any electricity or industrial process in any period.

GHG, greenhouse gas measured in tonnes of CO_2 equivalent (CO_2-eq). Data from ref. 1.

Exhibit 24

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PERSPECTIVE

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Sharing a quota on cumulative carbon emissions

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Any limit on future global warming is associated with a quota on cumulative global CO_2 emissions. We translate this global carbon quota to regional and national scales, on a spectrum of sharing principles that extends from continuation of the present distribution of emissions to an equal per-capita distribution of cumulative emissions. A blend of these endpoints emerges as the most viable option. For a carbon quota consistent with a 2 °C warming limit (relative to pre-industrial levels), the necessary long-term mitigation rates are very challenging (typically over 5% per year), both because of strong limits on future emissions from the global carbon quota and also the likely short-term persistence in emissions growth in many regions.

Climate modelling studies[1–6] have established a robust near-linear relationship between global warming and cumulative CO_2 emissions since industrialization. This implies that a 'carbon quota' or cap on future cumulative CO_2 emissions is required if global warming is to be kept below any nominated limit (such as 2 °C above pre-industrial temperatures[7]) with a nominated chance of success[8–10]. Estimated carbon quotas are significantly smaller than the known global fossil-fuel reserves[2,11,12].

The carbon quota implies that future cumulative CO_2 emissions consistent with a given warming limit are a finite common global resource that must necessarily be shared among countries, whether through prior agreement or as an emergent property of individually determined national efforts. The problem of sharing the global mitigation effort is addressed in an extensive literature, from the perspectives of equity, international policy and institutions, and economics and financing[13–22]. Here, we combine perspectives from two previously distinct strands of analysis — the global carbon quota and effort sharing — to infer the regional and national implications of global carbon quotas under a wide range of possible sharing strategies.

The need for multiple approaches is heightened by the present impasse in the search for long-term climate safety. Two broad approaches have been pursued hitherto in international negotiations: 'top-down' international agreements, such as the 1997 Kyoto Protocol[23], and 'bottom-up' nationally determined contributions to a global outcome. The top-down approach has made little progress over the last two decades[24]. An approach based on nationally determined contributions is now being explored[25], but current commitments in sum are far short of what is needed to meet internationally agreed climate goals[26–29].

The present impasse arises in part because the sharing challenge forms a 'tragedy of the commons'[30] or collective-action dilemma[31]. The challenge of governing common natural resources has developed a rich literature encompassing issues of governance, institutions, communities and ethics[32–34]. In broad terms, this literature suggests that solutions to the underlying problem of collective action can emerge from individual actions by participants (here, countries), given adequate social capital[35] to support a framework for adaptive governance[33]. When the sharing challenge is framed in this way, the emphasis shifts away from questions about global rules ("What shares of the carbon quota should be allocated to every country?") to questions about consistent local behaviours ("If others acted consistently with our proposed share of the carbon quota, would the global outcome be acceptable to us?"). This view further motivates a direct connection between the global carbon quota and effort-sharing analyses, to explore frameworks that can infer the global implications of a proposed share of the carbon quota by any one country, were others to act on similar principles.

To establish principles, we focus on the sharing of fossil-fuel CO_2 emissions, the largest single contributor to radiative forcing and climate change[36]. Emissions of CO_2 from land-use change are now a relatively small fraction of total CO_2 emissions (8 ± 3%)[37], declining with time, and subject to significant uncertainty at the global scale and even more at regional scales[37,38]. Inclusion of CO_2 emissions from land-use change is straightforward in principle, though data uncertainties would require careful assessment. In the absence of historic attribution, the effects would be small for most regions, but large for tropical forest countries where land clearing is still ongoing. More significant at the global scale is the role of non-CO_2 forcing agents, both those accounted (the major non-CO_2 greenhouse gases) and unaccounted (aerosols) in inventories. However, full inclusion of these forcing agents in extensions to carbon quotas at regional and national scales is beyond the present scope, requiring more complex climate modelling to resolve issues such as local impacts of short-lived climate forcers[39,40], nonlinear force–response relationships[41] and cooling by some aerosol species[36].

Ways of sharing a cumulative emissions quota

A common-pool resource can be shared objectively among participants in a social–ecological system by distributing the resource according to a set of observable metrics. In the case of the carbon quota, two generic metrics are measures of 'inertia' (also known as 'grandfathering'[22]) and 'equity', the inertia metric reflecting

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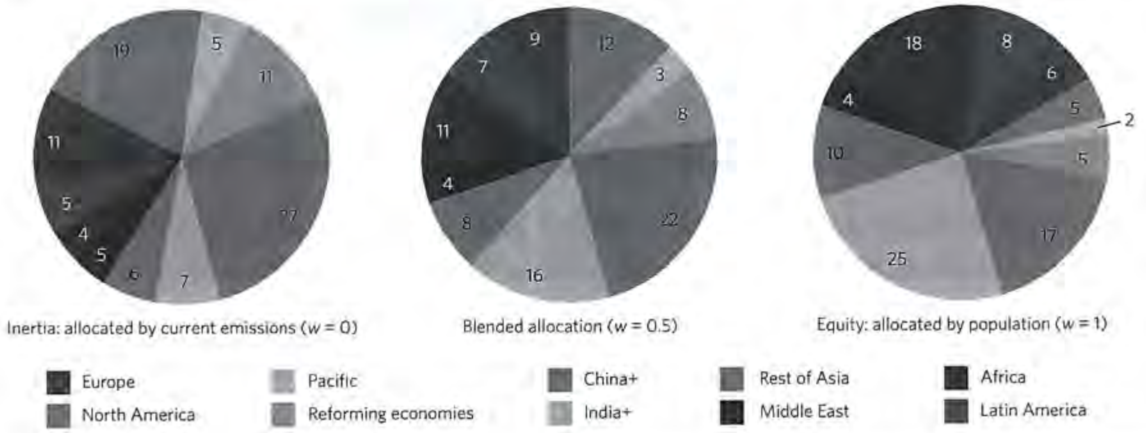

Inertia: allocated by current emissions ($w = 0$)

Blended allocation ($w = 0.5$)

Equity: allocated by population ($w = 1$)

Figure 1 | Sharing the carbon-quota pie. The share of an available carbon quota allocated to 10 regions (Europe, North America, Pacific Organisation for Economic Co-operation and Development countries, reforming economies, China+, India+, Rest of Asia, Middle East, Africa, Latin America) under three sharing principles based on equation (2), with sharing index $w = 0$, 0.5 and 1. Numbers give the percentage share of the global quota allocated to each region, summing to 100 for each chart. Shares are calculated using equation (2) with emissions (f_j) averaged over last five years of data, and population (p_j) averaged over a five-year period centred on the time at which world population reaches nine billion. See Supplementary Text 1 for details.

the distribution of emissions and the equity metric reflecting the population distribution. These metrics would suggest two alternative sharing principles:

$$s_j\,(\text{emissions}) = \frac{f_j}{F};\; s_j\,(\text{population}) = \frac{p_j}{P} \qquad (1)$$

where s_j is the share of the quota to country j; f_j and p_j are the emissions (current or cumulative) and population (present or future), respectively, for country j; and F and P are the corresponding emissions and population for the world. Shares sum to one over all countries ($\Sigma s_j = 1$) because $\Sigma f_j = F$ and $\Sigma p_j = P$. Depending on the choice of reference times for emissions and population, this formulation can accommodate sharing by current or historic emissions, and can account for expected future changes in population.

In their simplest forms, both options in equation (1) face major difficulties. Sharing by present emissions (inertia) would leave developing countries with little access to the energy and development opportunities embodied in remaining future carbon emissions, whereas sharing by population (equity) would impose extremely high mitigation demands on many developed countries. This has motivated the analysis of 'blended' sharing principles[16–18] that can compromise between the endpoint positions. One possibility (among others explored below) is that the share of the quota to country j is:

$$s_j(w) = (1 - w)\frac{f_j}{F} + w\frac{p_j}{P} \qquad (2)$$

where w is a 'sharing index' between 0 and 1, weighting between the endpoints of sharing by inertia ($w = 0$) and by equity ($w = 1$). This principle also satisfies the requirement $\Sigma s_j = 1$. It can be regarded as a simplified form of the contraction-and-convergence algorithm[16–18], applied to a total carbon quota rather than to emissions trajectories specified through time; the key simplification is independence from specific assumptions about emissions pathways through time.

Using equation (2), Fig. 1 shows how w influences the share of a global carbon quota assigned to 10 regions that span the world (Europe, North America, Pacific Organisation for Economic Co-operation and Development countries, reforming economies, Middle East, China+, India+, Rest of Asia, Africa, Latin America; Supplementary Text 1). The last four regions receive a greater share with increasing weighting of equity (increasing w), while the share for the other six regions decreases. This occurs because the response to increasing w of the share s_j for a region j hinges on whether its per-capita emissions (f_j/p_j) are less or greater than the global average per-capita emissions (F/P) (Supplementary Text 2); the last four regions have below-global-average per-capita emissions (Supplementary Fig. 1).

The concept of a blended sharing principle can potentially be generalized to include additional metrics of responsibility and/or capability[19,21] — for example, the distribution of gross domestic product (GDP) as a measure of capability to undertake mitigation efforts (Supplementary Text 2). The influences of emissions and GDP on sharing are broadly similar because both are correlated with development status, and both are very different to the influence of population (Supplementary Fig. 1). Therefore, we focus mainly on emissions and population using equation (2), and briefly explore later the effect of also including GDP in the sharing principle. We also note that allocated shares and quotas are not the same as actual future cumulative emissions if emissions are tradable between countries, as discussed later.

Regional carbon quotas

The global carbon quota from the past to the long-term future (when emissions fall to zero) is:

$$Q_{\text{tot}} = Q_{\text{past}}(\text{FFI}) + Q_{\text{past}}(\text{LUC}) + Q_{\text{future}}(\text{FFI}) + Q_{\text{future}}(\text{LUC}) \quad (3)$$

where Q_{tot} is the quota for anthropogenic CO_2 emissions from a reference time (here 1870) to the far future, including contributions from fossil-fuel combustion and industrial processes (FFI) and net land-use change (LUC); Q_{past} is the past emissions and Q_{future} is the shared available future emissions. Past cumulative CO_2 emissions from 1870 to the end of 2012 were 1,922 Gt CO_2 (1,396 Gt CO_2 from FFI and 526 Gt CO_2 from LUC)[37]. Global LUC emissions have decreased since 2000 to 8 ± 3% of total emissions in 2013[37] and are expected to continue to decrease; a linear decrease to zero in 2100 would imply $Q_{\text{future}}(\text{LUC}) = 137$ Gt CO_2.

Estimation of the global carbon quota Q_{tot} is an ongoing scientific issue. The estimates used here[10] are $Q_{\text{tot}} = 3{,}500$, 4,400 and 5,300 Gt CO_2 for warming limits of 2, 2.5 and 3 °C, respectively, with 50% chance of success and accounting for both CO_2 and non-CO_2 forcings (all quota estimates are rounded to nearest 100 Gt CO_2). These are larger (more conservative) quotas than estimated elsewhere[8].

We consider sharing of the available quota of future fossil-fuel emissions $Q_{\text{future}}(\text{FFI})$ from equation (3), henceforth Q_{avail}. The above estimates for Q_{tot} imply that $Q_{\text{avail}} = 1{,}400$, 2,300 and 3,200 Gt CO_2, for warming limits of 2, 2.5 and 3 °C at 50% chance of success.

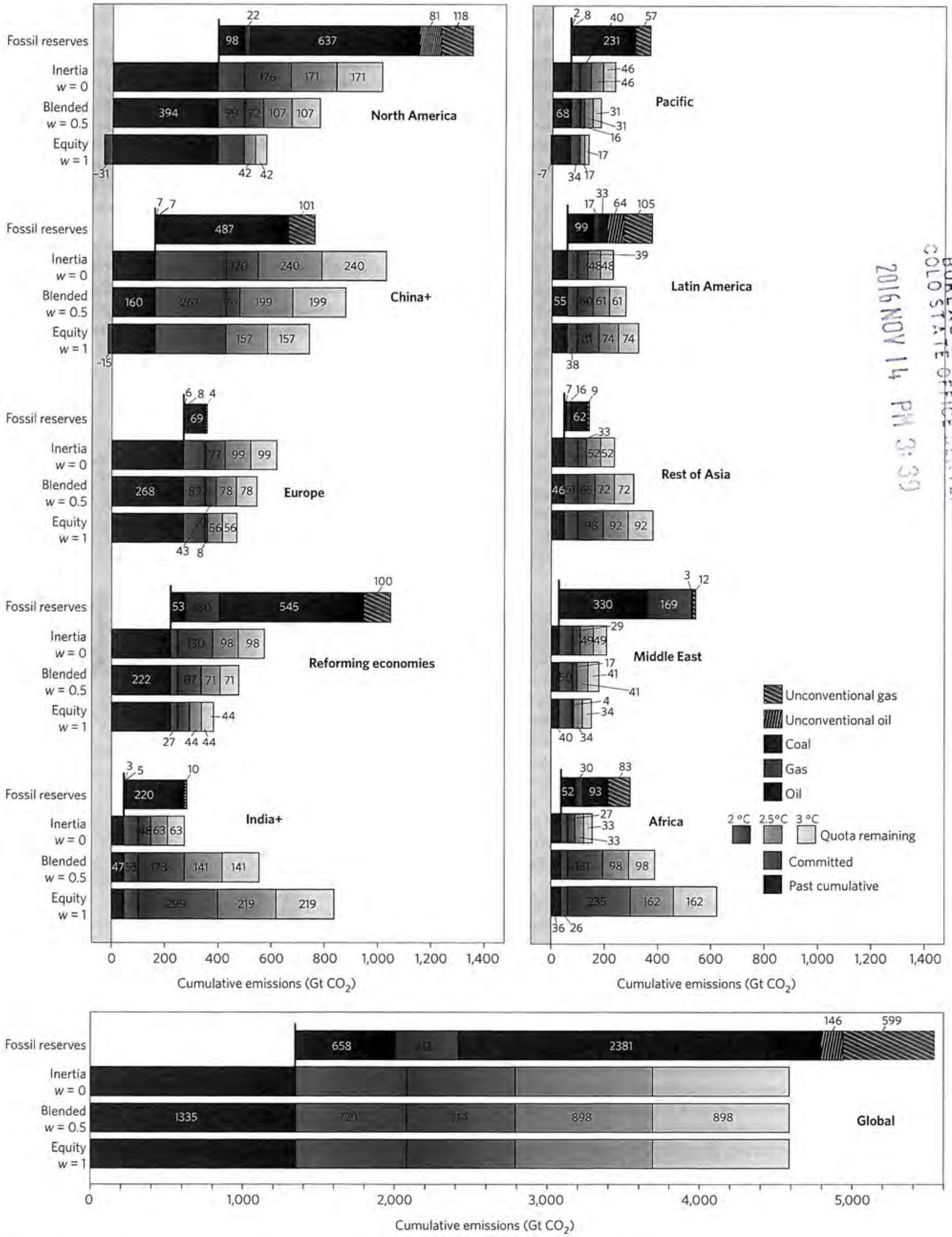

Figure 2 | Quotas, cumulative committed emissions and fossil-fuel reserves. Past cumulative fossil-fuel CO_2 emissions (purple), future committed emissions[42,43] (orange) and available fossil-fuel carbon quotas to meet warming limits of 2, 2.5 and 3 °C with 50% probability (green), for 10 regions and the world, under inertia, blended and equity sharing principles. Stacked bars are cumulative; numbers give the contribution of each increment in Gt CO_2. Negative increments are shown below the zero axis. Also shown are fossil-fuel reserves (coal, oil, gas, unconventional oil, unconventional gas)[12].

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The available carbon quota for country j is a share $s_j Q_{\text{avail}}$ of the global quota. Figure 2 shows the resulting quotas for 10 regions (Fig. 1) and for the world, with shares s_j from equation (2) for three values of w (0, 0.5 and 1, corresponding to inertia-based, blended and equity-based sharing, respectively), and with available quotas Q_{avail} corresponding to warming limits of 2, 2.5 and 3 °C at 50% chance of success. Global quotas are independent of w, but the regional quotas depend strongly on w, with increasing w causing the quotas to increase for regions with low per-capita emissions, and vice versa (Supplementary Text 2).

The regional quotas can be assessed against two independently determined quantities. First, committed emissions (orange bars in Fig. 2) are estimates of future emissions from existing CO_2-emitting infrastructure that will continue for infrastructure lifetimes without early retirement[42–44] (Supplementary Text 1). Committed emissions in North America, Europe and China exceed quotas for a 2 °C warming limit under equity sharing ($w = 1$), implying a requirement to either retire or improve such infrastructure before its design lifetime, or to compensate these emissions by negative emissions later in the century or by some form of offset such as emissions trading (see below). For the world, committed emissions are about half of the available quota Q_{avail} for a 2 °C warming limit.

Second, quotas can be compared with fossil-fuel reserves of coal, oil, gas, unconventional oil and unconventional gas (Fig. 2). Reserves are the part of total resources currently identified as economically viable for extraction. Globally and in most regions, estimated reserves[12] substantially exceed the global quota Q_{avail} for warming limits up to and beyond 3 °C, in agreement with other assessments[2,11]. Estimates of total fossil-fuel resources are even larger.

The distribution of the mitigation challenge

A simple measure of the challenge implied by the available quota for any region or country (before any possible redistribution by emissions trading) is the time for which the quota would last if emissions were held steady at current levels until the quota is exhausted, $T_j = s_j Q_{\text{avail}}/f_j$. This 'emission time'[10] depends strongly on the sharing index w (Supplementary Fig. 2). With pure emission-based sharing ($w = 0$), the emission time for all countries is the same and equals the global emission time Q_{avail}/F. As w increases to yield pure population-based sharing at $w = 1$, the emission time increases (decreases) for regions with per-capita emissions less (greater) than the global average. The response of emission times to w is the same as, and is determined by, the response of shares (s_j) to w (Supplementary Text 2).

If emissions were to decrease at a steady exponential rate starting immediately, an emission time T would correspond to a decrease in emissions at a fractional rate $1/T$ (or $100/T$ per cent per year). However, this estimate of a required reduction rate to meet a given quota is too low if the mitigation effort must first overcome existing emissions growth, because of persistence effects. Persistence in emissions growth arises from the time needed to implement new low-emission energy technologies on the energy supply side, and to adopt energy-efficiency measures and make behavioural changes in energy consumption on the demand side. Persistence is evident in emissions data (Supplementary Fig. 3). The supply-side aspects of this persistence arise mainly from the committed emissions in existing, long-lived energy infrastructure[42,43] (Fig. 2).

We account for persistence in emissions growth by representing the future emissions of a country, region or the world with an analytic capped-emissions trajectory that blends an initially linear growth at rate r with eventual exponential decline at a mitigation rate m. Continuity requirements determine this trajectory uniquely (Supplementary Text 3):

$$f(t) = f_0\left(1 + \left(r + m\right)t\right)\exp\left(-mt\right) \qquad (4)$$

where $f(t)$ is the emissions at time t, f_0 is the emissions at the start of mitigation ($t = 0$), and r and m both have units of per year. When mitigation is started at $t = 0$ (with a positive initial growth rate r), the resulting emissions trajectory increases, peaks and eventually declines exponentially at the rate m (Supplementary Fig. 4). A possible delay in starting mitigation can also be included (Supplementary Text 3). By incorporating such a delay, equation (4) can provide a good representation of the trajectories of CO_2 emissions from fossil fuels in the four representative concentration pathway scenarios[45] before any introduction of negative emissions (Supplementary Fig. 5). This indicates that equation (4) is suitable for empirically describing persistence effects in emissions trajectories.

To meet a specified available cumulative emission quota, persistence in emissions growth causes the necessary eventual characteristic rate of decline in emissions (m) to be typically more than twice the rate $1/T$ that would be required if exponential decline could commence immediately (Supplementary Text 3, Supplementary equation (8)).

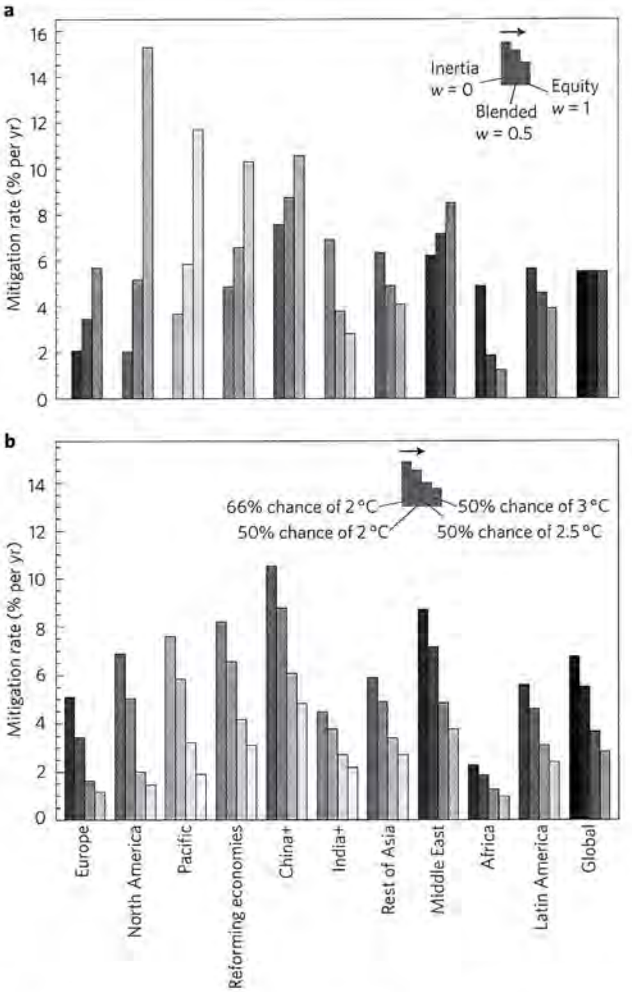

Figure 3 | Dependence of the regional mitigation challenge on the sharing index (*w*) and the warming limit. a, Mitigation rates for 10 regions and the world at $w = 0$, 0.5 and 1. Available global fossil-fuel combustion and industrial processes (FFI) carbon quota from 2013 is $Q_{\text{avail}} = 1{,}400$ Gt CO_2, corresponding to a 2 °C warming limit with 50% success probability. **b**, Mitigation rates under a blended sharing principle ($w = 0.5$) in four cases with warming limit and success probability, respectively, equal to 2 °C and 50%; 2.5 °C and 50%; 3 °C and 50%; and 2 °C and 66%. The available global FFI carbon quotas for these four cases are $Q_{\text{avail}} = 1{,}400$, 2,300, 3,200 and 1,100 Gt CO_2, respectively[10].

This occurs because the persistence in emissions growth in the early phase of the mitigation effort has to be compensated by more rapid later decline (larger m).

Figure 3a shows the mitigation rates m needed to meet an available carbon quota $Q_{avail} = 1{,}400$ Gt CO_2 (a 2 °C warming limit at 50% success probability), for the world and in 10 regions, with sharing index $w = 0$, 0.5 and 1. The required global mitigation rate to meet the quota is 5.5% per year (independent of sharing index) — more than twice the reduction rate $1/T$ if exponential decline could start immediately, because of persistence in emissions growth. This result is consistent with scenario-based analyses that account for policy delay[46,47].

With pure emissions-based sharing ($w = 0$), m varies little among regions (Fig. 3a); it is not identical across regions (in contrast with the emission time T; Supplementary Fig. 2) because of regional variations in the initial growth rate r. With pure population-based sharing ($w = 1$), m varies greatly among regions, from 1.4% per year (Africa) to over 15% per year (North America). With a blended sharing principle ($w = 0.5$), required mitigation rates are intermediate between the endpoint options $w = 0$ and $w = 1$, but very different in most cases from a simple average of the endpoints. For North America, the required mitigation rate at $w = 0.5$ is about 30% more than with emissions-based sharing ($w = 0$); for Africa, it is about 70% less. Therefore, a shift from an emissions-based to blended sharing principle leads to large benefits for developing regions at the cost of a much smaller increase in the demands on developed regions, as quantified by fractional changes in the required mitigation rates m.

Regional mitigation rates are also strongly sensitive to the global carbon quota, determined by the warming limit and probability of success. If the required probability of success for a 2 °C limit is increased from 50% (as in Fig. 3a) to 66%, then the required global mitigation rate m increases from 5.5 to 7% per year, with commensurate increases for regions and countries (Fig. 3b). For warming limits of 2.5 and 3 °C at 50% success probability, the required global mitigation rates fall to 3.7 and 2.9% per year, respectively, with commensurate decreases at regional and national levels. Even a 3 °C limit (with a much higher risk of dangerous climate change[48]) requires significant global and national mitigation.

To explore further the distribution of the mitigation challenge at national level, we focus on a set of 14 representative countries (Supplementary Text 1) that span the development spectrum in terms of both per-capita emissions and rates of development (Supplementary Fig. 6; a national-level counterpart of Fig. 2 is given in Supplementary Fig. 7). The required mitigation rates m for these countries, before any possible emissions trading, are plotted against present per-capita emissions in Fig. 4. Increasing equity (larger w) causes the mitigation challenge to respectively increase and decrease for countries with per-capita emissions above and below the world average, pivoting about that point. For least-developed countries with very low per-capita emissions, a shift from $w = 0$ (inertia) to 0.5 (blended) reduces the mitigation challenge from near the world average to near zero, because these countries collectively account only for a small share of global emissions.

The implication is that a blended sharing principle can ameliorate the opposite difficulties associated with the endpoint sharing principles at $w = 0$ (which would be prohibitive for least-developed countries) or $w = 1$ (which would be prohibitive for developed countries because of required mitigation rates exceeding 15% per year). Such compromises will be necessary in applying "equity principles of responsibility and capability to apportion the burden of emissions reductions [and] address concerns of both the global North and South"[24].

Together, Figs 3 and 4 demonstrate the interplay between the three major factors determining required regional and national mitigation rates: the warming limit, the nominated chance of success and the sharing principle (here w). The first two are comparably important everywhere. The sharing principle (w) has dominant but opposite effects for countries at opposite ends of the development spectrum, but small effects for countries close to the pivot point defined by global-average per-capita emissions (Fig. 4). In particular, China has a high required mitigation rate (because of currently high emissions growth) that is not strongly sensitive to the choice of w.

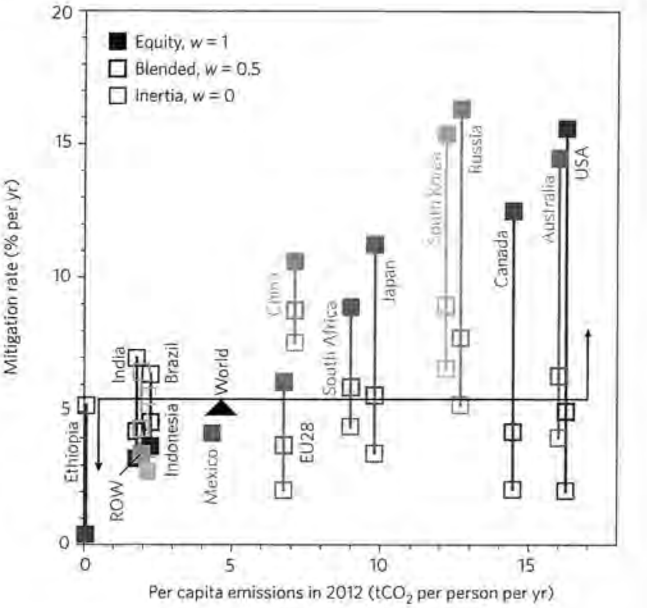

Figure 4 | Distribution of the mitigation challenge among countries. Mitigation rates (m) for 14 countries and regions spanning the development spectrum and for the whole world, with sharing index $w = 0$ (open squares), 1 (filled squares) and 0.5 (half-open squares). Horizontal axis is 2012 per-capita fossil-fuel CO_2 emissions. Available global fossil-fuel carbon quota from 2013 is $Q_{avail} = 1{,}400$ Gt CO_2, corresponding to a 2 °C warming limit with 50% success probability. With increasing equity in the sharing principle, the mitigation challenge increases for countries to the right of the point for the world (the pivot for the see-saw) and decreases for countries to the left. Mexico is so close to the pivot that symbols are indistinguishable. ROW, rest of world; EU28, the 28 member states of the European Union.

The regional mitigation rates in Figs 3a and 4 pivot around a very challenging global mitigation rate of 5.5% per year, for a warming limit of 2 °C with 50% chance of success. If the associated global carbon quota from ref. 10 ($Q_{tot} = 3{,}500$ Gt CO_2) is reduced to a more stringent 3,000 Gt CO_2 (ref. 8), then the required global mitigation rate increases further to 7.9% per year, and regional rates increase correspondingly.

Additional factors

To this point, we have not yet considered several additional factors that can be assessed within the framework of equation (2) or its generalizations (Supplementary Text 3) as part of future climate policy regimes.

Extent of inclusion of historic emissions. It has been suggested[41,49,50] that historic responsibility for climate change be included in principles for sharing the mitigation challenge. In a carbon-quota approach, this involves defining an attribution start date in the past and then sharing cumulative global emissions from that time onwards rather than from the present (Supplementary Text 4). A shift to this sharing principle has no effect on the required global mitigation rates, but has large implications for regions and countries. With historic attribution, required mitigation rates for developed regions become very large because attributed historic emissions approach (or even exceed) allocated shares for future emissions (Supplementary Fig. 8). The corresponding benefits for developing regions are not as large as might be expected because historic emissions for these regions are low.

Effect of delaying mitigation. It is well known that a delay in starting mitigation has a profound effect on the steepness of the mitigation challenge[51,52]. Noting that our analysis already includes persistence before a peak in emissions is reached, an additional 10-year delay would increase the required global mitigation rate m from 5.5 to over 9% per year (with global quota Q_{avail} = 1,400 Gt CO_2), with commensurate increases in regions (Supplementary Fig. 9).

Consumption-based and territorial emissions accounting. Consumption-based inventories for national CO_2 emissions[53] augment established territorial inventories[54] by attributing emissions to countries where products are consumed rather than where emissions of manufacture occur[55–57]. Under consumption-based accounting, the emissions of manufacturing-export countries, such as China, are reduced by up to 20% in recent years (relative to territorial accounting) and emissions of importing countries are correspondingly increased[37,58]. Use of consumption-based rather than territorial emissions leads to only a small change in shares and mitigation rates for regions and countries (Supplementary Fig. 10), because the favourable effects of consumption-based accounting for manufacturing-export countries are offset by the effects of their typically high persistence in emissions growth. Still, consumption-based emissions accounting may contribute to negotiation of agreements[24].

Effect of timing of population distribution. Sharing by population can be based on a future population forecast (the default for this Perspective; Supplementary Text 1), or on the present population distribution. There is only a small sensitivity of required mitigation rates to whether sharing occurs on the population distribution at a future time when the global population is nine billion, or on the distribution in 2013 with a global population of seven billion (Supplementary Fig. 11).

Effect of including GDP in the sharing principle. Equation (2) can be generalized to include additional metrics such as GDP (Supplementary Text 2). If the emissions distribution in equation (2) is replaced completely with the GDP distribution, the resulting effect on shares and mitigation rates is moderate, but not large (Supplementary Fig. 12), because both emissions and GDP are correlated with development status. Sharing principles combining three or more metrics (emissions, GDP, population, and so on) can be constructed (Supplementary Text 2). The most important clusters of metrics are those that represent development status (such as emissions and GDP) and those representing population.

Negative emissions. Model-based scenario studies indicate pathways to a range of warming limits, through transformations in energy systems and other mitigation measures[13]. For limits around 2 °C or less, such scenarios often depend on the use of negative emissions[13,59–61] through strategies such as land-based biosequestration or bioenergy with carbon capture and storage. Most 2 °C scenarios propose significant gross negative emissions to offset gross positive emissions that may be difficult or impossible to avoid, and many propose net negative emissions from the late twenty-first century. To the extent that gross negative emissions offset gross positive emissions, they are handled naturally by the cumulative carbon quota approach because the carbon quota applies to net (gross positive less gross negative) emissions. This applies at regional and national scales just as at the global scale.

Shared responsibility and collective achievability

A longstanding idea in analyses of burden sharing has been that countries need to test and explain how their own nominated climate goals fit with a global outcome[16,20,22,62,63]. Engagement in such testing is a key requirement for a robust solution to the climate change challenge through adaptive governance. As a methodological contribution to assist in this kind of testing, the present work combines existing analyses of the global carbon quota and effort sharing. The carbon-quota approach offers the important simplification of independence from assumptions about emissions pathways in time, yielding a transparent methodology for translating global to national carbon quotas under a wide range of possible sharing principles.

The question of achievability is clearly central[13]. The required global mitigation rates emerging from our analysis are high, typically over 5% per year for a 2 °C limit at 50% success probability (and 8% per year for China, a rate that remains very high under any sharing principle; Fig. 4). These rates can be compared with the distribution of maximum mitigation rates in the ensemble of scenarios in the Intergovernmental Panel on Climate Change Fifth Assessment Report (Supplementary Fig. 13). For scenarios with CO_2 peaking below 530 ppm, the median of the distribution of maximum rate of emissions decline is approximately consistent with the required rates from our analysis if there is no delay in starting mitigation, but even a five-year delay causes the required rate to approach the upper edge of the distribution.

Although the global quota is determined biophysically, the resulting distribution of effort among countries can be made more achievable by emissions or quota trading and related instruments. These can help to make very high national mitigation targets achievable, given sufficient globally connected trading systems and an effective price on emissions. Quota trading means that an initial quota does not determine the actual future cumulative emissions for a country; it also can improve the overall cost-effectiveness of the global mitigation effort, and facilitate transfer payments between countries to help achieve desired distributional outcomes. It is an open question whether such payments can be actually implemented on a large scale.

For the emergence of long-term, cooperative solutions to anthropogenic climate change[33,35], one essential element is an ability to perceive the consistent global consequences of local actions, given great differences in national economies and histories. The social capital that underpins cooperative governance of the commons takes time to evolve, but the biophysical realities of climate change demand solutions within decades. This is why the development of new perspectives on the sharing challenge is vital.

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References

1. Allen, M. R. *et al.* Warming caused by cumulative carbon emissions: towards the trillionth tonne. *Nature* **458,** 1163–1166 (2009).
2. Meinshausen, M. *et al.* Greenhouse gas emission targets for limiting global warming to 2 °C. *Nature* **458,** 1158–1162 (2009).
3. Zickfeld, K., Eby, M., Matthews, H. D. & Weaver, A. J. Setting cumulative emissions targets to reduce the risk of dangerous climate change. *Proc. Natl Acad. Sci. USA* **106,** 16129–16134 (2009).
4. Matthews, H. D., Gillett, N. P., Stott, P. A. & Zickfeld, K. The proportionality of global warming to cumulative carbon emissions. *Nature* **459,** 829–833 (2009).
5. Raupach, M. R. *et al.* The relationship between peak warming and cumulative CO_2 emissions, and its use to quantify vulnerabilities in the carbon–climate–human system. *Tellus B* **63,** 145–164 (2011).
6. Raupach, M. R. The exponential eigenmodes of the carbon–climate system, and their implications for ratios of responses to forcings. *Earth Syst. Dynam.* **4,** 31–49 (2013).
7. European Commission *The 2 °C Target: Background on Impacts, Emission Pathways, Mitigation Options and Costs* (European Commission, 2008).
8. Collins, M. *et al.* in *IPCC Climate Change 2013: The Physical Science Basis* (eds Stocker, T. F. *et al.*) Ch. 12, 1029–1136 (Cambridge Univ. Press, 2013).
9. Matthews, H. D., Solomon, S. & Pierrehumbert, R. Cumulative carbon as a policy framework for achieving climate stabilization. *Phil. Trans. R. Soc. A* **370,** 4365–4379 (2012).
10. Friedlingstein, P. *et al.* Persistent growth of CO_2 emissions and implications for reaching climate targets. *Nature Geosci.* (in the press).
11. GEA *Global Energy Assessment — Toward a Sustainable Future* (Cambridge Univ. Press and International Institute for Applied Systems Analysis, 2012).

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12. BGR *Energy Study 2013: Reserves, Resources and Availability of Energy Resources* (Federal Institute for Geosciences and Natural Resources, 2013).
13. Clarke, L. *et al.* in *IPCC Climate Change 2014: Mitigation of Climate Change* (eds Edenhofer, O. *et al.*) Ch. 6 (Cambridge Univ. Press, 2014).
14. Stavins, R. *et al.* in *IPCC Climate Change 2014: Mitigation of Climate Change* (eds Edenhofer, O. *et al.*) Ch. 13 (Cambridge Univ. Press, 2014).
15. Höhne, N., den Elzen, M. G. J. & Escalante, D. Regional GHG reduction targets based on effort sharing: a comparison of studies. *Clim. Policy* **14,** 122–147 (2014).
16. Meyer, A. *Contraction and Convergence. The Global Solution to Climate Change* Schumacher Briefings 5 (Green Books, 2000).
17. Hohmeyer, O. & Rennings, K. *Man-made Climate Change: Economic Aspects and Policy Considerations* (ZEW Economic Studies, Centre for European Economic Research, 1999).
18. Bows, A. & Anderson, K. Contraction and convergence: an assessment of the CCOptions model. *Climatic Change* **91,** 275–290 (2008).
19. Dellink, R. *et al.* Sharing the burden of financing adaptation to climate change. *Glob. Environ. Change* **19,** 411–421 (2009).
20. Bartsch, U. & Müller, B. *Fossil Fuels in a Changing Climate — Impacts of the Kyoto Protocol and Developing Country Participation* (Oxford Univ. Press, 2000).
21. Füssel, H-M. How inequitable is the global distribution of responsibility, capability, and vulnerability to climate change: a comprehensive indicator-based assessment. *Glob. Environ. Change* **20,** 597–611 (2010).
22. Ringius, L., Torvanger, A. & Underdal, A. Burden sharing and fairness principles in international climate policy. *Int. Environ. Agreem. P.* **2,** 1–22 (2002).
23. UNFCCC *Kyoto Protocol to the United Nations Framework Convention on Climate Change* (United Nations Framework Convention on Climate Change, 1997).
24. Grasso, M. & Roberts, T. A compromise to break the climate impasse. *Nature Clim. Change* **4,** 543–549 (2014).
25. European Climate Foundation *Taking Stock — The Emission Levels Implied by the Pledges to the Copenhagen Accord* (European Climate Foundation, 2010).
26. Den Elzen, M. G. J. *et al.* The Copenhagen Accord: abatement costs and carbon prices resulting from the submissions. *Environ. Sci. Policy* **14,** 28–39 (2011).
27. Rogelj, J. *et al.* Analysis of the Copenhagen Accord pledges and its global climatic impacts — a snapshot of dissonant ambitions. *Environ. Res. Lett.* **5,** 034013 (2010).
28. Rogelj, J. *et al.* Copenhagen Accord pledges are paltry. *Nature* **464,** 1126–1128 (2010).
29. UNEP *The Emissions Gap Report 2013* (United Nations Environment Program, 2013).
30. Hardin, G. The tragedy of the commons. *Science* **162,** 1243–1248 (1968).
31. Kolstad, C. *et al.* in *IPCC Climate Change 2014: Mitigation of Climate Change* (eds Edenhofer, O. *et al.*) Ch. 3 (Cambridge Univ. Press, 2014).
32. Ostrom, E. *Governing the Commons: The Evolution of Institutions for Collective Action* (Cambridge Univ. Press, 1990).
33. Dietz, T., Ostrom, E. & Stern, P. C. The struggle to govern the commons. *Science* **302,** 1907–1912 (2003).
34. Lejano, R. P., Araral, E. & Araral, D. Interrogating the commons: introduction to the Special Issue. *Environ. Sci. Policy* **36,** 1–7 (2014).
35. Pretty, J. Social capital and the collective management of resources. *Science* **302,** 1912–1914 (2003).
36. Myhre, G. *et al.* in *IPCC Climate Change 2013: The Physical Science Basis* (eds Stocker, T. F. *et al.*) Ch. 8, 659–740 (Cambridge Univ. Press, 2013).
37. Le Quéré, C. *et al.* Global carbon budget 2013. *Earth Syst. Sci. Data* **6,** 235–263 (2014).
38. Gasser, T. & Ciais, P. A theoretical framework for the net land-to-atmosphere CO_2 flux and its implications in the definition of "emissions from land-use change". *Earth Syst. Dynam.* **4,** 171–186 (2013).
39. Shindell, D. & Faluvegi, G. Climate response to regional radiative forcing during the twentieth century. *Nature Geosci.* **2,** 294–300 (2009).
40. Berntsen, T. K. *et al.* Response of climate to regional emissions of ozone precursors: sensitivities and warming potentials. *Tellus B* **57,** 283–304 (2005).
41. Trudinger, C. M. & Enting, I. G. Comparison of formalisms for attributing responsibility for climate change: non-linearities in the Brazilian proposal approach. *Climatic Change* **68,** 67–99 (2005).
42. Davis, S. J., Caldeira, K. & Matthews, H. D. Future CO_2 emissions and climate change from existing energy infrastructure. *Science* **329,** 1330–1333 (2010).
43. Davis, S. J. & Socolow, R. H. Commitment accounting of CO_2 emissions. *Environ. Res. Lett.* **9,** 084018 (2014).
44. Davis, S. J., Peters, G. P. & Caldeira, K. The supply chain of CO_2 emissions. *Proc. Natl Acad. Sci. USA* **108,** 18554–18559 (2011).
45. van Vuuren, D. P. *et al.* The representative concentration pathways: an overview. *Climatic Change* **109,** 5–31 (2011).
46. Kriegler, E. *et al.* The role of technology for achieving climate policy objectives: overview of the EMF 27 study on global technology and climate policy strategies. *Climatic Change* **123,** 353–367 (2014).
47. Riahi, K. *et al.* Locked into Copenhagen pledges — implications of short-term emission targets for the cost and feasibility of long-term climate goals. *Technol. Forecast. Soc.* http://dx.doi.org/10.1016/j.techfore.2013.09.016 (in the press).
48. Schellnhuber, H. J., Cramer, W., Nakicenovic, N., Wigley, T. M. L. & Yohe, G. *Avoiding Dangerous Climate Change* (Cambridge Univ. Press, 2006).
49. Den Elzen, M. G. J. *et al. The Brazilian Proposal and Other Options for International Burden Sharing: An Evaluation of Methodological and Policy Aspects using the FAIR Model* (National Institute of Public Health and the Environment, 1999).
50. Den Elzen, M. G. J., Schaeffer, M. & Lucas, P. L. Differentiating future commitments on the basis of countries' relative historical responsibility for climate change: uncertainties in the 'Brazilian proposal' in the context of a policy implementation. *Climatic Change* **71,** 277–301 (2005).
51. Den Elzen, M. G. J., van Vuuren, D. P. & van Vliet, J. Postponing emission reductions from 2020 to 2030 increases climate risks and long-term costs. *Climatic Change* **99,** 313–320 (2010).
52. Stocker, T. F. The closing door of climate targets. *Science* **339,** 280–282 (2013).
53. Peters, G. P., Minx, J. C., Weber, C. L. & Edenhofer, O. Growth in emission transfers via international trade from 1990 to 2008. *Proc. Natl Acad. Sci. USA* **108,** 8903–8908 (2011).
54. Andres, R. J. *et al.* A synthesis of carbon dioxide emissions from fossil-fuel combustion. *Biogeosciences* **9,** 1845–1871 (2012).
55. Peters, G. P. & Hertwich, E. G. CO_2 embodied in international trade with implications for global climate policy. *Environ. Sci. Technol.* **42,** 1401–1407 (2008).
56. Hertwich, E. G. & Peters, G. P. Carbon footprint of nations: a global, trade-linked analysis. *Environ. Sci. Technol.* **43,** 6414–6420 (2009).
57. Davis, S. J. & Caldeira, K. Consumption-based accounting of CO_2 emissions. *Proc. Natl Acad. Sci. USA* **107,** 5687–5692 (2010).
58. Peters, G. P. *et al.* Rapid growth in CO_2 emissions after the 2008–2009 global financial crisis. *Nature Clim. Change* **2,** 2–4 (2011).
59. Azar, C., Lindgren, K., Larson, E. & Mollersten, K. Carbon capture and storage from fossil fuels and biomass — costs and potential role in stabilizing the atmosphere. *Climatic Change* **74,** 47–79 (2006).
60. Van Vuuren, D. P. & Riahi, K. The relationship between short-term emissions and long-term concentration targets. *Climatic Change* **104,** 793–801 (2011).
61. Fuss, S. *et al.* Betting on negative emissions. *Nature Clim. Change* **4,** 850–853 (2014).
62. Garnaut, R. *Garnaut Climate Change Review: Final Report* (Cambridge Univ. Press, 2008).
63. Garnaut, R. *The Garnaut Review 2011: Australia in the Global Response to Climate Change* (Cambridge Univ. Press, 2011).

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Author contributions

M.R.R. designed the study, carried out calculations and coordinated the conception and writing of the paper. S.J.D. contributed data on committed emissions and drew figures. G.P.P. and R.M.A. contributed data on committed emissions and resources. All authors contributed to the writing of the paper.

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 M.R.R.

Competing financial interests

The authors declare no competing financial interests.

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Exhibit 25

Climate Change 2014
Mitigation of Climate Change

Working Group III Contribution to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change

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Foreword, Preface, Dedication and In Memoriam

Foreword

Climate Change 2014: Mitigation of Climate Change is the third part of the Fifth Assessment Report (AR5) of the Intergovernmental Panel on Climate Change (IPCC)—Climate Change 2013/2014—and was prepared by its Working Group III. The volume provides a comprehensive and transparent assessment of relevant options for mitigating climate change through limiting or preventing greenhouse gas (GHG) emissions, as well as activities that reduce their concentrations in the atmosphere.

This report highlights that despite a growing number of mitigation policies, GHG emission growth has accelerated over the last decade. The evidence from hundreds of new mitigation scenarios suggests that stabilizing temperature increase within the 21st century requires a fundamental departure from business-as-usual. At the same time, it shows that a variety of emission pathways exists where the temperature increase can be limited to below 2 °C relative to pre-industrial level. But this goal is associated with considerable technological, economic and institutional challenges. A delay in mitigation efforts or the limited availability of low carbon technologies further increases these challenges. Less ambitious mitigation goals such as 2.5 °C or 3 °C involve similar challenges, but on a slower timescale. Complementing these insights, the report provides a comprehensive assessment of the technical and behavioural mitigation options available in the energy, transport, buildings, industry and land-use sectors and evaluates policy options across governance levels from the local to the international scale.

The findings in this report have considerably enhanced our understanding of the range of mitigation pathways available and their underlying technological, economic and institutional requirements. The timing of this report is thus critical, as it can provide crucial information for the negotiators responsible for concluding a new agreement under the United Nations Framework Convention on Climate Change in 2015. The report therefore demands the urgent attention of both policymakers and the general public.

As an intergovernmental body jointly established in 1988 by the World Meteorological Organization (WMO) and the United Nations Environment Programme (UNEP), the IPCC has successfully provided policymakers with the most authoritative and objective scientific and technical assessments, which are clearly policy relevant without being policy prescriptive. Beginning in 1990, this series of IPCC Assessment Reports, Special Reports, Technical Papers, Methodology Reports and other products have become standard works of reference.

This Working Group III assessment was made possible thanks to the commitment and dedication of many hundreds of experts, representing a wide range of regions and scientific disciplines. WMO and UNEP are proud that so many of the experts belong to their communities and networks.

We express our deep gratitude to all authors, review editors and expert reviewers for devoting their knowledge, expertise and time. We would like to thank the staff of the Working Group III Technical Support Unit and the IPCC Secretariat for their dedication.

We are also thankful to the governments that supported their scientists' participation in developing this report and that contributed to the IPCC Trust Fund to provide for the essential participation of experts from developing countries and countries with economies in transition.

We would like to express our appreciation to the government of Italy for hosting the scoping meeting for the IPCC's Fifth Assessment Report, to the governments of Republic of Korea, New Zealand and Ethiopia as well as the University of Vigo and the Economics for Energy Research Centre in Spain for hosting drafting sessions of the Working Group III contribution and to the government of Germany for hosting the Twelfth Session of Working Group III in Berlin for approval of the Working Group III Report. In addition, we would like to thank the governments of India, Peru, Ghana, the United States and Germany for hosting the AR5 Expert meetings in Calcutta, Lima, Accra, Washington D. C., and Potsdam, respectively. The generous financial support by the government of Germany, and the logistical support by the Potsdam Institute for Climate Impact Research (Germany), enabled the effective operation of the Working Group III Technical Support Unit. This is gratefully acknowledged.

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M. Jarraud
Secretary-General
World Meteorological Organization

Achim Steiner

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United Nations Environment Programme

Preface

The Working Group III contribution to the Fifth Assessment Report (AR5) of the Intergovernmental Panel on Climate Change (IPCC) provides a comprehensive and transparent assessment of the scientific literature on climate change mitigation. It builds upon the Working Group III contribution to the IPCC's Fourth Assessment Report (AR4) in 2007, the Special Report on Renewable Energy Sources and Climate Change Mitigation (SRREN) in 2011 and previous reports and incorporates subsequent new findings and research. The report assesses mitigation options at different levels of governance and in different economic sectors. It evaluates the societal implications of different mitigation policies, but does not recommend any particular option for mitigation.

Approach to the assessment

The Working Group III contribution to the AR5 explores the solution space of climate change mitigation drawing on experience and expectations for the future. This exploration is based on a comprehensive and transparent assessment of the scientific, technical, and socio-economic literature on the mitigation of climate change.

The intent of the report is to facilitate an integrated and inclusive deliberation of alternative climate policy goals and the different possible means to achieve them (e.g., technologies, policies, institutional settings). It does so through informing the policymakers and general public about the practical implications of alternative policy options, i.e., their associated costs and benefits, risks and trade-offs.

During the AR5 cycle, the role of the Working Group III scientists was akin to that of a cartographer: they mapped out different pathways within the solution space and assessed potential practical consequences and trade-offs; at the same time, they clearly marked implicit value assumptions and uncertainties. Consequently, this report may now be used by policymakers like a map for navigating the widely unknown territory of climate policy. Instead of providing recommendations for how to solve the complex policy problems, the report offers relevant information that enables policymakers to assess alternative mitigation options.

There are four major pillars to this cartography exercise:

Exploration of alternative climate policy goals: The report lays out the technological, economic and institutional requirements for stabilizing global mean temperature increases at different levels. It informs decision makers about the costs and benefits, risks and opportunities of these, acknowledging the fact that often more than one path can lead to a given policy goal.

Transparency over value judgments: The decision which mitigation path to take is influenced by a series of sometimes disputed normative choices which relate to the long-term stabilization goal itself, the weighing of other social priorities and the policies for achieving the goal. Facts are often inextricably interlinked with values and there is no purely scientific resolution of value dissent. What an assessment can do to support a rational public debate about value conflicts is to make implicit value judgments and ethical viewpoints as transparent as possible. Moreover, controversial policy goals and related ethical standpoints should be discussed in the context of the required means to reach these goals, in particular their possible consequences and side-effects. The potential for adverse side-effects of mitigation actions therefore requires an iterative assessment approach.

Multiple objectives in the context of sustainable development and equity: A comprehensive exploration of the solution space in the field of climate change mitigation recognizes that mitigation itself will only be one objective among others for decision makers. Decision makers may be interested in pursuing a broader concept of well-being. This broader concept also involves the sharing of limited resources within and across countries as well as across generations. Climate change mitigation is discussed here as a multi-objective problem embedded in a broader sustainable development and equity context.

Risk management: Climate change mitigation can be framed as a risk management exercise. It may provide large opportunities to humankind, but will also be associated with risks and uncertainties. Some of those may be of a fundamental nature and cannot be easily reduced or managed. It is therefore a basic requirement for a scientific assessment to communicate these uncertainties, wherever possible, both in their quantitative and qualitative dimension.

Scope of the report

During the process of scoping and approving the outline of the Working Group III contribution to the AR5, the IPCC focused on those aspects of the current understanding of the science of climate change mitigation that were judged to be most relevant to policymakers.

Working Group III included an extended framing section to provide full transparency over the concepts and methods used throughout the report, highlighting their underlying value judgments. This includes an improved treatment of risks and risk perception, uncertainties, ethical questions as well as sustainable development.

The exploration of the solution space for climate change mitigation starts from a new set of baseline and mitigation scenarios. The entire scenario set for the first time provides fully consistent information on radiative forcing and temperature in broad agreement with the information provided in the Working Group I contribution to the AR5. The United Nations Framework Convention on Climate Change requested the IPCC to provide relevant scientific evidence for reviewing the 2 °C goal as well as a potential 1.5 °C goal. Compared to the AR4 the report therefore assesses a large number of low stabilization scenarios broadly consistent with the 2 °C goal. It includes policy scenarios that investigate the impacts of delayed and fragmented international mitigation efforts and of restricted mitigation technologies portfolios on achieving specific mitigation goals and associated costs.

The WGIII contribution to the AR5 features several new elements. A full chapter is devoted to human settlements and infrastructures. Governance structures for the design of mitigation policies are discussed on the global, regional, national and sub-national level. The report closes with a novel chapter about investment needs and finance.

Structure of the report

The Working Group III contribution to the Fifth Assessment report is comprised of four parts:

Part I: Introduction (Chapter 1)
Part II: Framing Issues (Chapters 2–4)
Part III: Pathways for Mitigating Climate Change (Chapters 5–12)
Part IV: Assessment of Policies, Institutions and Finance (Chapters 13–16)

Part I provides an introduction to the Working Group III contribution and sets the stage for the subsequent chapters. It describes the 'Lessons learned since AR4' and the 'New challenges for AR5'. It gives a brief overview of 'Historical, current and future trends' regarding GHG emissions and discusses the issues involved in climate change response policies including the ultimate objective of the UNFCCC (Article 2) and the human dimensions of climate change (including sustainable development).

Part II deals with framing issues that provide transparency over methodological foundations and underlying concepts including the relevant value judgments for the detailed assessment of climate change mitigation policies and measures in the subsequent parts. Each chapter addresses key overarching issues (Chapter 2: Integrated Risk and Uncertainty Assessment of Climate Change Response Policies; Chapter 3: Social, Economic and Ethical Concepts and Methods; Chapter 4: Sustainable Development and Equity) and acts as a reference point for subsequent chapters.

Part III provides an integrated assessment of possible mitigation pathways and the respective sectoral contributions and implications. It combines cross-sectoral and sectoral information on long-term mitigation pathways and short- to mid-term mitigation options in major economic sectors. Chapter 5 (Drivers, Trends and Mitigation) provides the context for the subsequent chapters by outlining global trends in stocks and flows of greenhouse gases (GHGs) and short-lived climate pollutants by means of different accounting methods that provide complementary perspectives on the past. It also discusses emissions drivers, which informs the assessment of how GHG emissions have historically developed. Chapter 6 (Assessing Transformation Pathways) analyses 1200 new scenarios generated by 31 modelling teams around the world to explore the economic, technological and institutional prerequisites and implications of mitigation pathways with different levels of ambition. The sectoral chapters (Chapter 7–11) and Chapter 12 (Human Settlements, Infrastructure and Spatial Planning) provide information on the different mitigation options across energy systems, transport, buildings, industry, agriculture, forestry and other land use as well as options specific to human settlements and infrastructure, including the possible co-benefits, adverse side-effects and costs that may be associated with each of these options. Pathways described in Chapter 6 are discussed in a sector-specific context.

Part IV assesses policies across governance scales. Beginning with international cooperation (Chapter 13), it proceeds to the regional (Chapter 14), national and sub-national levels Chapter 15) before concluding with a chapter that assesses cross-cutting investment and financing issues (Chapter 16). It reviews experience with climate change mitigation policies — both the policies themselves and the interactions among policies across sectors and scales — to provide insights to policymakers on the structure of policies which best fulfill evaluation criteria such as environmental and economic effectiveness, and others.

The assessment process

This Working Group III contribution to the AR5 represents the combined efforts of hundreds of leading experts in the field of climate change mitigation and has been prepared in accordance with the rules and procedures established by the IPCC. A scoping meeting for the AR5 was held in July 2009 and the outlines for the contributions of the three Working Groups were approved at the 31st Session of the Panel in November 2009. Governments and IPCC observer organizations nominated experts for the author teams. The team of 235 Coordinating Lead Authors and Lead Authors plus 38 Review Editors selected by the Working Group III Bureau, was accepted at the 41st Session of the IPCC Bureau in May 2010. More than 170 Contributing Authors provided draft text and information to the author teams at their request. Drafts prepared by the authors were subject to two rounds of formal review and revision followed by a final round of government comments on the Summary for Policymakers. More than 38,000 written comments were submitted by more than 800 expert reviewers and 37 governments. The Review Editors for each chapter monitored the review process to ensure that all substantive review comments received appropriate consideration. The Summary for Policymakers was approved line-by-line and the underlying chapters were then accepted at the 12th Session of IPCC Working Group III from 7–11 April 2014 in Berlin.

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Writing this report was only possible thanks to the expertise, hard work and commitment to excellence shown throughout by our Coordinating Lead Authors and Lead Authors, with important assistance by many Contributing Authors and Chapter Science Assistants. We would also like to express our appreciation to the Government and Expert Reviewers, acknowledging their time and energy invested to provide constructive and useful comments to the various drafts. Our Review Editors were also critical in the AR5 process, supporting the author teams with processing the comments and assuring an objective discussion of relevant issues.

We would very much like to thank the governments of the Republic of Korea, New Zealand and Ethiopia as well as the University of Vigo and the Economics for Energy Research Centre in Spain, that, in collaboration with local institutions, hosted the crucial IPCC Lead Author Meetings in Changwon (July 2011), Wellington (March 2012), Vigo (November 2012) and Addis Ababa (July 2013). In addition, we would like to thank the governments of India, Peru, Ghana, the United States and Germany for hosting the Expert Meetings in Calcutta (March 2011), Lima (June 2011), Accra (August 2011), Washington D.C. (August 2012), and Potsdam (October 2013), respectively. Finally, we express our appreciation to the Potsdam Institute for Climate Impact Research (PIK) for welcoming our Coordinating Lead Authors on their campus for a concluding meeting (October 2013).

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Sincerely,

Ottmar Edenhofer

Ottmar Edenhofer
IPCC WG III CO-Chair

Ramon Pichs-Madruga
IPCC WG III CO-Chair

Youba Sokona
IPCC WG III CO-Chair

Dedication

Elinor Ostrom
(7 August 1933 – 12 June 2012)

We dedicate this report to the memory of Elinor Ostrom, Professor of Political Science at Indiana University and Nobel Laureate in Economics. Her work provided a fundamental contribution to the understanding of collective action, trust, and cooperation in the management of common pool resources, including the atmosphere. She launched a research agenda that has encouraged scientists to explore how a variety of overlapping policies at city, national, regional, and international levels can enable humankind to manage the climate problem. The assessment of climate change mitigation across different levels of governance, sectors and regions has been a new focus of the Working Group III contribution to AR5. We have benefited greatly from the vision and intellectual leadership of Elinor Ostrom.

In Memoriam

Luxin Huang (1965–2013)
Lead Author in Chapter 12 on Human Settlements, Infrastructure and Spatial Planning

Leon Jay (Lee) Schipper (1947–2011)
Review Editor in Chapter 8 on Transport

Luxin Huang contributed to Chapter 12 on Human Settlements, Infrastructure and Spatial Planning. During this time, he was the director of the Department of International Cooperation and Development at the China Academy of Urban Planning and Design (CAUPD) in Beijing, China, where he worked for 27 years. The untimely death of Luxin Huang at the young age of 48 has left the Intergovernmental Panel on Climate Change (IPCC) with great sorrow.

Lee Schipper was a leading scientist in the field of transport, energy and the environment. He was looking forward to his role as review editor for the Transport chapter when he passed away at the age of 64. Schipper had been intimately involved with the IPCC for many years, having contributed as a Lead Author to the IPCC's Second Assessment Report's chapter on Mitigation Options in the Transportation Sector. The IPCC misses his great expertise and guidance, as well as his humorous and musical contributions.

Both researchers were dedicated contributors to the IPCC assessment process. Their passing represents a deep loss for the international scientific community. Luxin Huang and Lee Schipper are dearly remembered by the authors and members of the IPCC Working Group III.

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Table of Contents

SPM.1 Introduction

The Working Group III contribution to the IPCC's Fifth Assessment Report (AR5) assesses literature on the scientific, technological, environmental, economic and social aspects of mitigation of climate change. It builds upon the Working Group III contribution to the IPCC's Fourth Assessment Report (AR4), the Special Report on Renewable Energy Sources and Climate Change Mitigation (SRREN) and previous reports and incorporates subsequent new findings and research. The report also assesses mitigation options at different levels of governance and in different economic sectors, and the societal implications of different mitigation policies, but does not recommend any particular option for mitigation.

This Summary for Policymakers (SPM) follows the structure of the Working Group III report. The narrative is supported by a series of highlighted conclusions which, taken together, provide a concise summary. The basis for the SPM can be found in the chapter sections of the underlying report and in the Technical Summary (TS). References to these are given in square brackets.

The degree of certainty in findings in this assessment, as in the reports of all three Working Groups, is based on the author teams' evaluations of underlying scientific understanding and is expressed as a qualitative level of confidence (from very low to very high) and, when possible, probabilistically with a quantified likelihood (from exceptionally unlikely to virtually certain). Confidence in the validity of a finding is based on the type, amount, quality, and consistency of evidence (e.g., data, mechanistic understanding, theory, models, expert judgment) and the degree of agreement.[1] Probabilistic estimates of quantified measures of uncertainty in a finding are based on statistical analysis of observations or model results, or both, and expert judgment.[2] Where appropriate, findings are also formulated as statements of fact without using uncertainty qualifiers. Within paragraphs of this summary, the confidence, evidence, and agreement terms given for a bolded finding apply to subsequent statements in the paragraph, unless additional terms are provided.

SPM.2 Approaches to climate change mitigation

Mitigation is a human intervention to reduce the sources or enhance the sinks of greenhouse gases. Mitigation, together with adaptation to climate change, contributes to the objective expressed in Article 2 of the United Nations Framework Convention on Climate Change (UNFCCC):

> *The ultimate objective of this Convention and any related legal instruments that the Conference of the Parties may adopt is to achieve, in accordance with the relevant provisions of the Convention, stabilization of greenhouse gas concentrations in the atmosphere at a level that would prevent dangerous anthropogenic interference with the climate system. Such a level should be achieved within a time frame sufficient to allow ecosystems to adapt naturally to climate change, to ensure that food production is not threatened and to enable economic development to proceed in a sustainable manner.*

Climate policies can be informed by the findings of science, and systematic methods from other disciplines. [1.2, 2.4, 2.5, Box 3.1]

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[1] The following summary terms are used to describe the available evidence: limited, medium, or robust; and for the degree of agreement: low, medium, or high. A level of confidence is expressed using five qualifiers: very low, low, medium, high, and very high, and typeset in italics, e.g., *medium confidence*. For a given evidence and agreement statement, different confidence levels can be assigned, but increasing levels of evidence and degrees of agreement are correlated with increasing confidence. For more details, please refer to the guidance note for Lead Authors of the IPCC Fifth Assessment Report on consistent treatment of uncertainties.

[2] The following terms have been used to indicate the assessed likelihood of an outcome or a result: virtually certain 99–100 % probability, very likely 90–100 %, likely 66–100 %, about as likely as not 33–66 %, unlikely 0–33 %, very unlikely 0–10 %, exceptionally unlikely 0–1 %. Additional terms (more likely than not >50–100 %, and more unlikely than likely 0–<50 %) may also be used when appropriate. Assessed likelihood is typeset in italics, e.g., *very likely*.

Sustainable development and equity provide a basis for assessing climate policies and highlight the need for addressing the risks of climate change.[3] Limiting the effects of climate change is necessary to achieve sustainable development and equity, including poverty eradication. At the same time, some mitigation efforts could undermine action on the right to promote sustainable development, and on the achievement of poverty eradication and equity. Consequently, a comprehensive assessment of climate policies involves going beyond a focus on mitigation and adaptation policies alone to examine development pathways more broadly, along with their determinants. [4.2, 4.3, 4.4, 4.5, 4.6, 4.8]

Effective mitigation will not be achieved if individual agents advance their own interests independently. Climate change has the characteristics of a collective action problem at the global scale, because most greenhouse gases (GHGs) accumulate over time and mix globally, and emissions by any agent (e.g., individual, community, company, country) affect other agents.[4] International cooperation is therefore required to effectively mitigate GHG emissions and address other climate change issues [1.2.4, 2.6.4, 3.2, 4.2, 13.2, 13.3]. Furthermore, research and development in support of mitigation creates knowledge spillovers. International cooperation can play a constructive role in the development, diffusion and transfer of knowledge and environmentally sound technologies [1.4.4, 3.11.6, 11.8, 13.9, 14.4.3].

Issues of equity, justice, and fairness arise with respect to mitigation and adaptation.[5] Countries' past and future contributions to the accumulation of GHGs in the atmosphere are different, and countries also face varying challenges and circumstances, and have different capacities to address mitigation and adaptation. The evidence suggests that outcomes seen as equitable can lead to more effective cooperation. [3.10, 4.2.2, 4.6.2]

Many areas of climate policy-making involve value judgements and ethical considerations. These areas range from the question of how much mitigation is needed to prevent dangerous interference with the climate system to choices among specific policies for mitigation or adaptation [3.1, 3.2]. Social, economic and ethical analyses may be used to inform value judgements and may take into account values of various sorts, including human wellbeing, cultural values and non-human values [3.4, 3.10].

Among other methods, economic evaluation is commonly used to inform climate policy design. Practical tools for economic assessment include cost-benefit analysis, cost-effectiveness analysis, multi-criteria analysis and expected utility theory [2.5]. The limitations of these tools are well-documented [3.5]. Ethical theories based on social welfare functions imply that distributional weights, which take account of the different value of money to different people, should be applied to monetary measures of benefits and harms [3.6.1, Box TS.2]. Whereas distributional weighting has not frequently been applied for comparing the effects of climate policies on different people at a single time, it is standard practice, in the form of discounting, for comparing the effects at different times [3.6.2].

Climate policy intersects with other societal goals creating the possibility of co-benefits or adverse side-effects. These intersections, if well-managed, can strengthen the basis for undertaking climate action. Mitigation and adaptation can positively or negatively influence the achievement of other societal goals, such as those related to human health, food security, biodiversity, local environmental quality, energy access, livelihoods, and equitable sustainable development; and vice versa, policies toward other societal goals can influence the achievement of mitigation and adaptation objectives [4.2, 4.3, 4.4, 4.5, 4.6, 4.8]. These influences can be substantial, although sometimes difficult to quantify, especially in welfare terms [3.6.3]. This multi-objective perspective is important in part because it helps to identify areas where support for policies that advance multiple goals will be robust [1.2.1, 4.2, 4.8, 6.6.1].

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[3] See WGII AR5 SPM.

[4] In the social sciences this is referred to as a 'global commons problem'. As this expression is used in the social sciences, it has no specific implications for legal arrangements or for particular criteria regarding effort-sharing.

[5] See FAQ 3.2 for clarification of these concepts. The philosophical literature on justice and other literature can illuminate these issues [3.2, 3.3, 4.6.2].

Climate policy may be informed by a consideration of a diverse array of risks and uncertainties, some of which are difficult to measure, notably events that are of low probability but which would have a significant impact if they occur. Since AR4, the scientific literature has examined risks related to climate change, adaptation, and mitigation strategies. Accurately estimating the benefits of mitigation takes into account the full range of possible impacts of climate change, including those with high consequences but a low probability of occurrence. The benefits of mitigation may otherwise be underestimated (*high confidence*) [2.5, 2.6, Box 3.9]. The choice of mitigation actions is also influenced by uncertainties in many socio-economic variables, including the rate of economic growth and the evolution of technology (*high confidence*) [2.6, 6.3].

The design of climate policy is influenced by how individuals and organizations perceive risks and uncertainties and take them into account. People often utilize simplified decision rules such as a preference for the status quo. Individuals and organizations differ in their degree of risk aversion and the relative importance placed on near-term versus long-term ramifications of specific actions [2.4]. With the help of formal methods, policy design can be improved by taking into account risks and uncertainties in natural, socio-economic, and technological systems as well as decision processes, perceptions, values and wealth [2.5].

SPM.3 Trends in stocks and flows of greenhouse gases and their drivers

Total anthropogenic GHG emissions have continued to increase over 1970 to 2010 with larger absolute decadal increases toward the end of this period (*high confidence*). Despite a growing number of climate change mitigation policies, annual GHG emissions grew on average by 1.0 gigatonne carbon dioxide equivalent ($GtCO_2eq$) (2.2 %) per year from 2000 to 2010 compared to 0.4 $GtCO_2eq$ (1.3 %) per year from 1970 to 2000 (Figure SPM.1).[6,7] Total anthropogenic GHG emissions were the highest in human history from 2000 to 2010 and reached 49 (±4.5) $GtCO_2eq$/yr in 2010. The global economic crisis 2007/2008 only temporarily reduced emissions. [1.3, 5.2, 13.3, 15.2.2, Box TS.5, Figure 15.1]

CO_2 emissions from fossil fuel combustion and industrial processes contributed about 78 % of the total GHG emission increase from 1970 to 2010, with a similar percentage contribution for the period 2000–2010 (*high confidence*). Fossil fuel-related CO_2 emissions reached 32 (±2.7) $GtCO_2$/yr, in 2010, and grew further by about 3 % between 2010 and 2011 and by about 1–2 % between 2011 and 2012. Of the 49 (±4.5) $GtCO_2eq$/yr in total anthropogenic GHG emissions in 2010, CO_2 remains the major anthropogenic GHG accounting for 76 % (38±3.8 $GtCO_2eq$/yr) of total anthropogenic GHG emissions in 2010. 16 % (7.8±1.6 $GtCO_2eq$/yr) come from methane (CH_4), 6.2 % (3.1±1.9 $GtCO_2eq$/yr) from nitrous oxide (N_2O), and 2.0 % (1.0±0.2 $GtCO_2eq$/yr) from fluorinated gases (Figure SPM.1). Annually, since 1970, about 25 % of anthropogenic GHG emissions have been in the form of non-CO_2 gases.[8] [1.2, 5.2]

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[6] Throughout the SPM, emissions of GHGs are weighed by Global Warming Potentials with a 100-year time horizon (GWP_{100}) from the IPCC Second Assessment Report. All metrics have limitations and uncertainties in assessing consequences of different emissions. [3.9.6, Box TS.5, Annex II.9, WGI SPM]

[7] In this SPM, uncertainty in historic GHG emission data is reported using 90 % uncertainty intervals unless otherwise stated. GHG emission levels are rounded to two significant digits throughout this document; as a consequence, small differences in sums due to rounding may occur.

[8] In this report, data on non-CO_2 GHGs, including fluorinated gases, are taken from the EDGAR database (Annex II.9), which covers substances included in the Kyoto Protocol in its first commitment period.

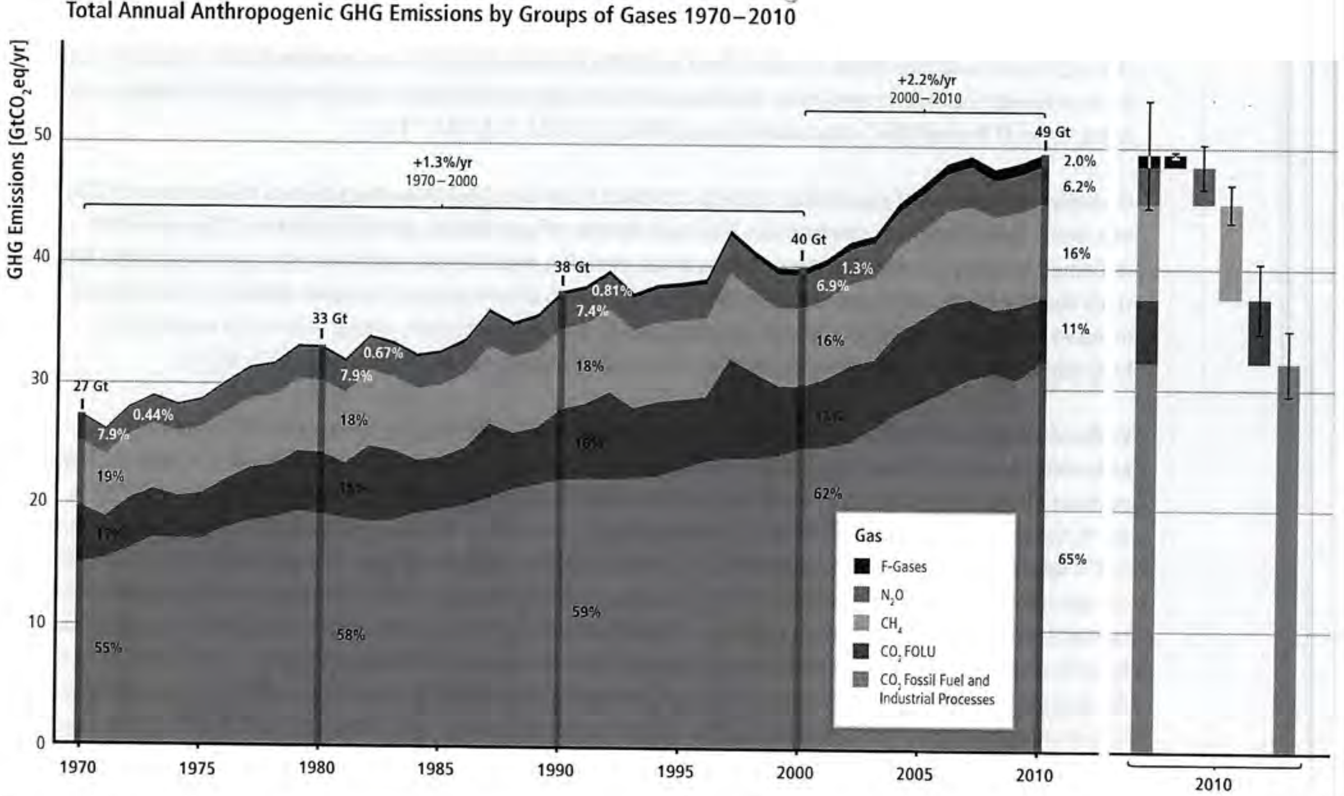

Figure SPM.1 | Total annual anthropogenic GHG emissions ($GtCO_2eq/yr$) by groups of gases 1970–2010: CO_2 from fossil fuel combustion and industrial processes; CO_2 from Forestry and Other Land Use (FOLU); methane (CH_4); nitrous oxide (N_2O); fluorinated gases[8] covered under the Kyoto Protocol (F-gases). At the right side of the figure GHG emissions in 2010 are shown again broken down into these components with the associated uncertainties (90 % confidence interval) indicated by the error bars. Total anthropogenic GHG emissions uncertainties are derived from the individual gas estimates as described in Chapter 5 [5.2.3.6]. Global CO_2 emissions from fossil fuel combustion are known within 8 % uncertainty (90 % confidence interval). CO_2 emissions from FOLU have very large uncertainties attached in the order of ±50 %. Uncertainty for global emissions of CH_4, N_2O and the F-gases has been estimated as 20 %, 60 % and 20 %, respectively. 2010 was the most recent year for which emission statistics on all gases as well as assessment of uncertainties were essentially complete at the time of data cut-off for this report. Emissions are converted into CO_2-equivalents based on GWP_{100}[6] from the IPCC Second Assessment Report. The emission data from FOLU represents land-based CO_2 emissions from forest fires, peat fires and peat decay that approximate to net CO_2 flux from FOLU as described in Chapter 11 of this report. Average annual growth rate over different periods is highlighted with the brackets. [Figure 1.3, Figure TS.1]

About half of cumulative anthropogenic CO_2 emissions between 1750 and 2010 have occurred in the last 40 years (*high confidence*). In 1970, cumulative CO_2 emissions from fossil fuel combustion, cement production and flaring since 1750 were 420±35 $GtCO_2$; in 2010, that cumulative total had tripled to 1300±110 $GtCO_2$. Cumulative CO_2 emissions from Forestry and Other Land Use (FOLU)[9] since 1750 increased from 490±180 $GtCO_2$ in 1970 to 680±300 $GtCO_2$ in 2010. [5.2]

Annual anthropogenic GHG emissions have increased by 10 $GtCO_2eq$ between 2000 and 2010, with this increase directly coming from energy supply (47 %), industry (30 %), transport (11 %) and buildings (3 %) sectors (*medium confidence*). **Accounting for indirect emissions raises the contributions of the buildings and industry sectors** (*high confidence*). Since 2000, GHG emissions have been growing in all sectors, except AFOLU. Of the 49 (±4.5) $GtCO_2eq$ emissions in 2010, 35 % (17 $GtCO_2eq$) of GHG emissions were released in the energy supply sector,

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[9] Forestry and Other Land Use (FOLU)—also referred to as LULUCF (Land Use, Land-Use Change, and Forestry)—is the subset of Agriculture, Forestry and Other Land Use (AFOLU) emissions and removals of GHGs related to direct human-induced land use, land-use change and forestry activities excluding agricultural emissions and removals (see WGIII AR5 Glossary).

24 % (12 $GtCO_2eq$, net emissions) in AFOLU, 21 % (10 $GtCO_2eq$) in industry, 14 % (7.0 $GtCO_2eq$) in transport and 6.4 % (3.2 $GtCO_2eq$) in buildings. When emissions from electricity and heat production are attributed to the sectors that use the final energy (i.e. indirect emissions), the shares of the industry and buildings sectors in global GHG emissions are increased to 31 % and 19 %[7], respectively (Figure SPM.2). [7.3, 8.2, 9.2, 10.3, 11.2]

Globally, economic and population growth continue to be the most important drivers of increases in CO_2 emissions from fossil fuel combustion. The contribution of population growth between 2000 and 2010 remained roughly identical to the previous three decades, while the contribution of economic growth has risen sharply (*high confidence*). Between 2000 and 2010, both drivers outpaced emission reductions from improvements in energy intensity (Figure SPM.3). Increased use of coal relative to other energy sources has reversed the long-standing trend of gradual decarbonization of the world's energy supply. [1.3, 5.3, 7.2, 14.3, TS.2.2]

Without additional efforts to reduce GHG emissions beyond those in place today, emissions growth is expected to persist driven by growth in global population and economic activities. Baseline scenarios, those without additional mitigation, result in global mean surface temperature increases in 2100 from 3.7 °C to 4.8 °C compared to pre-industrial levels[10] (range based on median climate response; the range is 2.5 °C to 7.8 °C when including climate uncertainty, see Table SPM.1)[11] (*high confidence*). The emission scenarios collected for this assessment represent full radiative forcing including GHGs, tropospheric ozone, aerosols and albedo change. Baseline scenarios (scenarios without explicit additional efforts to constrain emissions) exceed 450 parts per million (ppm) CO_2eq by 2030 and reach CO_2eq concentration levels between 750 and more than 1300 ppm CO_2eq by 2100. This is similar to the range in atmospheric concentration levels between the RCP 6.0 and RCP 8.5 pathways in 2100.[12] For comparison, the CO_2eq concentration in 2011 is estimated to be 430 ppm (uncertainty range 340–520 ppm).[13] [6.3, Box TS.6; WGI Figure SPM.5, WGI 8.5, WGI 12.3]

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[10] Based on the longest global surface temperature dataset available, the observed change between the average of the period 1850–1900 and of the AR5 reference period (1986–2005) is 0.61 °C (5–95 % confidence interval: 0.55–0.67 °C) [WGI SPM.E], which is used here as an approximation of the change in global mean surface temperature since pre-industrial times, referred to as the period before 1750.

[11] The climate uncertainty reflects the 5th to 95th percentile of climate model calculations described in Table SPM.1.

[12] For the purpose of this assessment, roughly 300 baseline scenarios and 900 mitigation scenarios were collected through an open call from integrated modelling teams around the world. These scenarios are complementary to the Representative Concentration Pathways (RCPs, see WGIII AR5 Glossary). The RCPs are identified by their approximate total radiative forcing in year 2100 relative to 1750: 2.6 Watts per square meter (W/m^2) for RCP2.6, 4.5 W/m^2 for RCP4.5, 6.0 W/m^2 for RCP6.0, and 8.5 W/m^2 for RCP8.5. The scenarios collected for this assessment span a slightly broader range of concentrations in the year 2100 than the four RCPs.

[13] This is based on the assessment of total anthropogenic radiative forcing for 2011 relative to 1750 in WGI, i.e. 2.3 W/m^2, uncertainty range 1.1 to 3.3 W/m^2. [WGI Figure SPM.5, WGI 8.5, WGI 12.3]

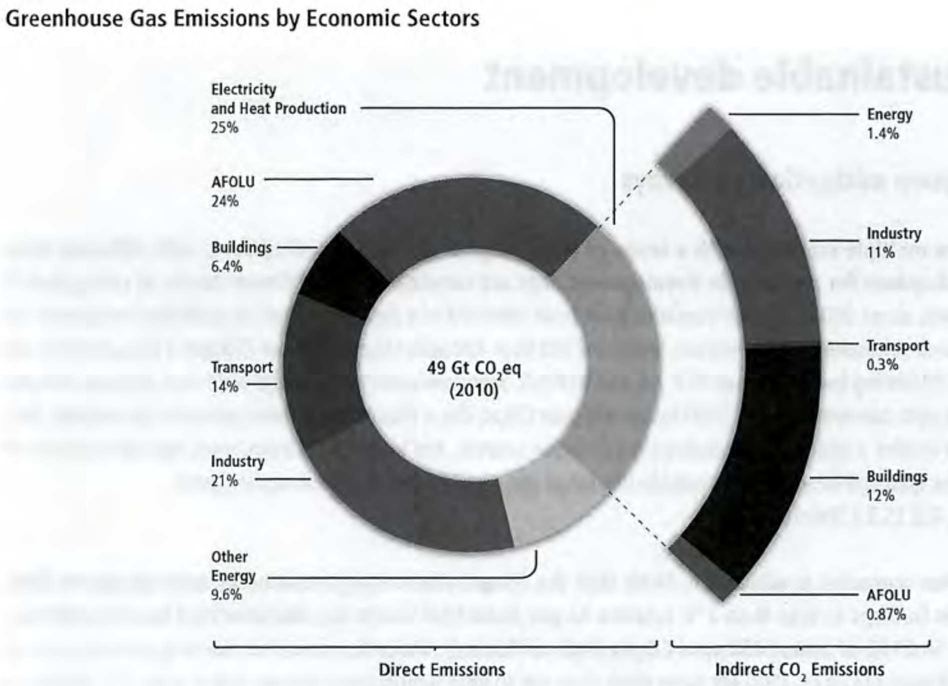

Figure SPM.2 | Total anthropogenic GHG emissions ($GtCO_2eq/yr$) by economic sectors. Inner circle shows direct GHG emission shares (in % of total anthropogenic GHG emissions) of five economic sectors in 2010. Pull-out shows how indirect CO_2 emission shares (in % of total anthropogenic GHG emissions) from electricity and heat production are attributed to sectors of final energy use. 'Other Energy' refers to all GHG emission sources in the energy sector as defined in Annex II other than electricity and heat production [A.II.9.1]. The emissions data from Agriculture, Forestry and Other Land Use (AFOLU) includes land-based CO_2 emissions from forest fires, peat fires and peat decay that approximate to net CO_2 flux from the Forestry and Other Land Use (FOLU) sub-sector as described in Chapter 11 of this report. Emissions are converted into CO_2-equivalents based on GWP_{100}[6] from the IPCC Second Assessment Report. Sector definitions are provided in Annex II.9. [Figure 1.3a, Figure TS.3 upper panel]

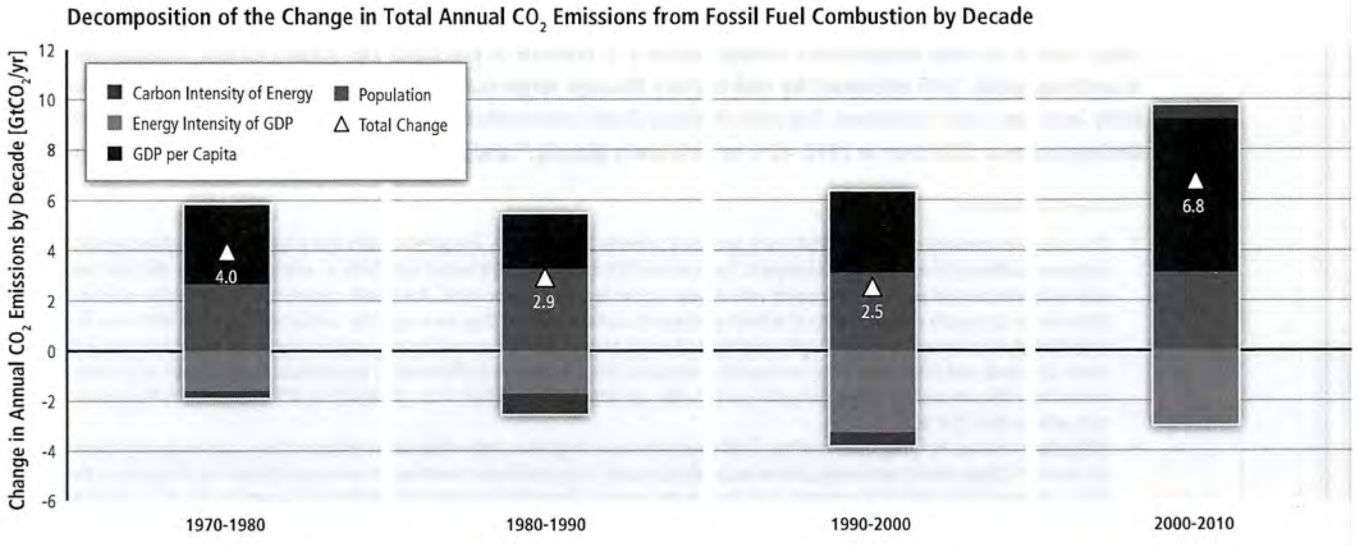

Figure SPM.3 | Decomposition of the change in total annual CO_2 emissions from fossil fuel combustion by decade and four driving factors: population, income (GDP) per capita, energy intensity of GDP and carbon intensity of energy. The bar segments show the changes associated with each factor alone, holding the respective other factors constant. Total emissions changes are indicated by a triangle. The change in emissions over each decade is measured in gigatonnes of CO_2 per year [$GtCO_2/yr$]; income is converted into common units using purchasing power parities. [Figure 1.7]

SPM.4 Mitigation pathways and measures in the context of sustainable development

SPM.4.1 Long-term mitigation pathways

There are multiple scenarios with a range of technological and behavioral options, with different characteristics and implications for sustainable development, that are consistent with different levels of mitigation. For this assessment, about 900 mitigation scenarios have been collected in a database based on published integrated models.[14] This range spans atmospheric concentration levels in 2100 from 430 ppm CO_2eq to above 720 ppm CO_2eq, which is comparable to the 2100 forcing levels between RCP 2.6 and RCP 6.0. Scenarios outside this range were also assessed including some scenarios with concentrations in 2100 below 430 ppm CO_2eq (for a discussion of these scenarios see below). The mitigation scenarios involve a wide range of technological, socioeconomic, and institutional trajectories, but uncertainties and model limitations exist and developments outside this range are possible (Figure SPM.4, upper panel). [6.1, 6.2, 6.3, TS.3.1, Box TS.6]

Mitigation scenarios in which it is *likely* that the temperature change caused by anthropogenic GHG emissions can be kept to less than 2 °C relative to pre-industrial levels are characterized by atmospheric concentrations in 2100 of about 450 ppm CO_2eq (*high confidence*). Mitigation scenarios reaching concentration levels of about 500 ppm CO_2eq by 2100 are *more likely than not* to limit temperature change to less than 2 °C relative to pre-industrial levels, unless they temporarily 'overshoot' concentration levels of roughly 530 ppm CO_2eq before 2100, in which case they are *about as likely as not* to achieve that goal.[15] Scenarios that reach 530 to 650 ppm CO_2eq concentrations by 2100 are *more unlikely than likely* to keep temperature change below 2 °C relative to pre-industrial levels. Scenarios that exceed about 650 ppm CO_2eq by 2100 are *unlikely* to limit temperature change to below 2 °C relative to pre-industrial levels. Mitigation scenarios in which temperature increase is *more likely than not* to be less than 1.5 °C relative to pre-industrial levels by 2100 are characterized by concentrations in 2100 of below 430 ppm CO_2eq. Temperature peaks during the century and then declines in these scenarios. Probability statements regarding other levels of temperature change can be made with reference to Table SPM.1. [6.3, Box TS.6]

Scenarios reaching atmospheric concentration levels of about 450 ppm CO_2eq by 2100 (consistent with a *likely* chance to keep temperature change below 2 °C relative to pre-industrial levels) include substantial cuts in anthropogenic GHG emissions by mid-century through large-scale changes in energy systems and potentially land use (*high confidence*). Scenarios reaching these concentrations by 2100 are characterized by lower global GHG emissions in 2050 than in 2010, 40 % to 70 % lower globally,[16] and emissions levels near zero $GtCO_2$eq or below in

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[14] The long-term scenarios assessed in WGIII were generated primarily by large-scale, integrated models that project many key characteristics of mitigation pathways to mid-century and beyond. These models link many important human systems (e. g., energy, agriculture and land use, economy) with physical processes associated with climate change (e. g., the carbon cycle). The models approximate cost-effective solutions that minimize the aggregate economic costs of achieving mitigation outcomes, unless they are specifically constrained to behave otherwise. They are simplified, stylized representations of highly-complex, real-world processes, and the scenarios they produce are based on uncertain projections about key events and drivers over often century-long timescales. Simplifications and differences in assumptions are the reason why output generated from different models, or versions of the same model, can differ, and projections from all models can differ considerably from the reality that unfolds. [Box TS.7, 6.2]

[15] Mitigation scenarios, including those reaching 2100 concentrations as high as or higher than about 550 ppm CO_2eq, can temporarily 'overshoot' atmospheric CO_2eq concentration levels before descending to lower levels later. Such concentration overshoot involves less mitigation in the near term with more rapid and deeper emissions reductions in the long run. Overshoot increases the probability of exceeding any given temperature goal. [6.3, Table SPM.1]

[16] This range differs from the range provided for a similar concentration category in AR4 (50 %–85 % lower than 2000 for CO_2 only). Reasons for this difference include that this report has assessed a substantially larger number of scenarios than in AR4 and looks at all GHGs. In addition, a large proportion of the new scenarios include Carbon Dioxide Removal (CDR) technologies (see below). Other factors include the use of 2100 concentration levels instead of stabilization levels and the shift in reference year from 2000 to 2010. Scenarios with higher emissions in 2050 are characterized by a greater reliance on CDR technologies beyond mid-century.