The Land Breathes

http://acamedia.info/sciences/sciliterature/globalw/reference/pffnb/aeg_nb-25.6.2019/videos/AEG&25_6_2019_HD.mp4

Short-term Coupled Climate / Carbon-Cycle Model

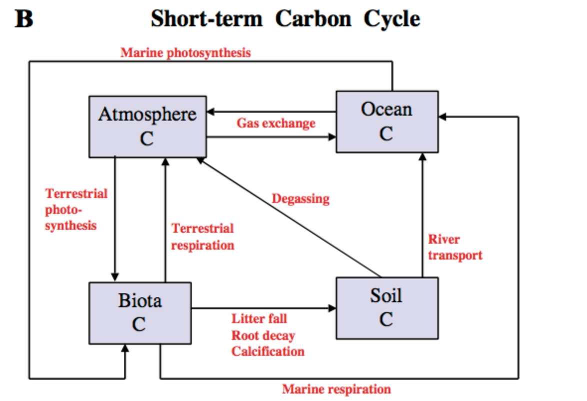


Fig.B. For those concerned with the present growth of CO2 in the atmosphere, due to deforestation and the burning of fossil fuels, the carbon cycle consists of those sources and sinks that exchange carbon with the atmosphere on a human time scale. This includes the biosphere, oceans, and soils, and I refer to it here as the short-term carbon cycle (Atmosphere C, Ocean C, Biota C, Soil C). This cycle is also the dominant control on atmospheric CO2 over longer periods, including the glacial-interglacial stages of the Quaternary.

Source: Robert A. Berner, A New Look at the Long-term Carbon Cycle

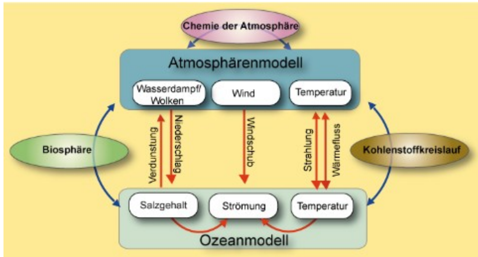
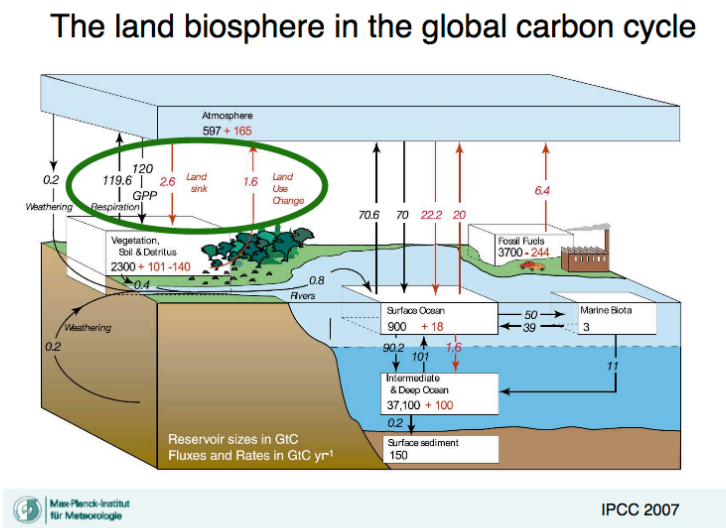


Abb. 1: Schema eines gekoppelten Ozean-Atmosphäremodells (ocean–atmosphere general circulation model, OAGCM) mit Biosphären- und Kohlenstoffkreislauf-Modell

Source: https://wiki.bildungsserver.de/klimawandel/index.php/Klimamodelle



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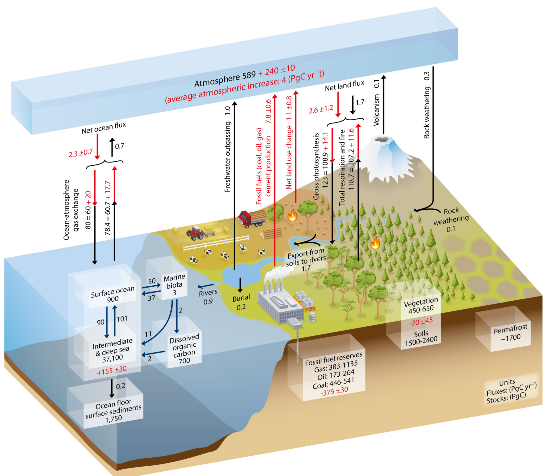
Climate Change 2013 The Physical Science Basis

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

WG1AR5_all_final



Quelle (mit hoher Auflösung): http://www.climatechange2013.org/images/figures/WGI_AR5_Fig6-1_errata.jpg cache

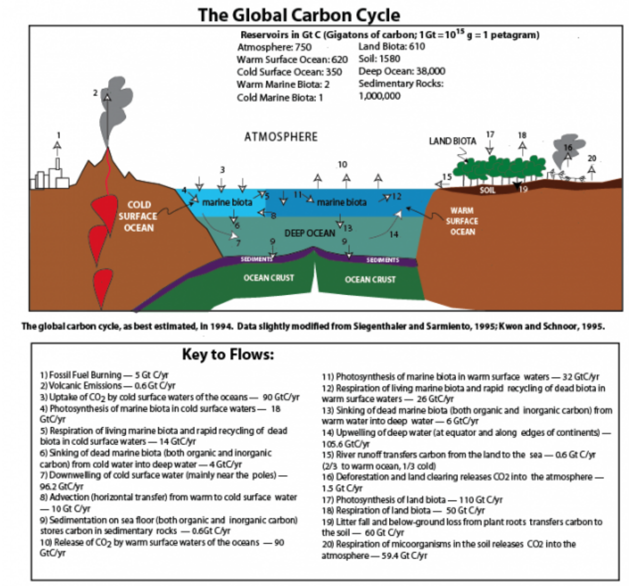
Figure 6.1 I Simplified schematic of the global carbon cycle.

- Numbers represent
  - reservoir mass, also called 'carbon stocks' in PgC (1 PgC = 1 GtC) and
  - annual carbon exchange fluxes (in GtC yr–1).

- Black numbers and arrows indicate reservoir mass and exchange fluxes estimated for the time prior to the Industrial Era, about 1750 (see Section 6.1.1.1 for references).
  - Fossil fuel reserves are from GEA (2006) and are consistent with numbers used by IPCC WGIII for future scenarios.
  - The sediment storage is a sum of
    - 150 GtC of the organic carbon in the mixed layer
    - and 1600 GtC of the deep-sea $CaCO_3$ sediments available to neutralize fossil fuel CO_2 (Archer et al., 1998).
- Red arrows and numbers indicate annual 'anthropogenic' fluxes averaged over the 2000–2009 time period.
  - These fluxes are a perturbation of the carbon cycle during Industrial Era post 1750.
  - These fluxes (red arrows) are:
    - Fossil fuel and cement emissions of CO_2 (Section 6.3.1),
    - Net land use change (Section 6.3.2), and the
    - Average atmospheric increase of CO_2 in the atmosphere, also called 'CO_2 growth rate' (Section 6.3).
- The uptake of anthropogenic CO_2 by the ocean and by terrestrial ecosystems, often called 'carbon sinks' are the red arrows part of Net land flux and Net ocean flux.
- Red numbers in the reservoirs denote cumulative changes of anthropogenic carbon over the Industrial Period 1750–2011 (column 2 in Table 6.1).
  - By convention, a positive cumulative change means that a reservoir has gained carbon since 1750.
  - The cumulative change of anthropogenic carbon in the terrestrial reservoir is the sum of
    - carbon cumulatively lost through land use change
    - and carbon accumulated since 1750 in other ecosystems (Table 6.1).
- Note that the mass balance of the two ocean carbon stocks Surface ocean and Intermediate and deep ocean includes a yearly accumulation of anthropogenic carbon (not shown).
- Uncertainties are reported as 90% confidence intervals.

- Emission estimates and land and ocean sinks (in red) are from Table 6.1 in Section 6.3.
- The change of gross terrestrial fluxes (red arrows of Gross photosynthesis and Total respiration and fires) has been estimated from CMIP5 model results (Section 6.4).
- The change in air–sea exchange fluxes (red arrows of ocean atmosphere gas exchange) have been estimated from the difference in atmospheric partial pressure of CO_2 since 1750 (Sarmiento and Gruber, 2006).
- Individual gross fluxes and their changes since the beginning of the Industrial Era have typical uncertainties of more than 20%, while their differences (Net land flux and Net ocean flux in the figure) are determined from independent measurements with a much higher accuracy (see Section 6.3). Therefore, to achieve an overall balance, the values of the more uncertain gross fluxes have been adjusted so that their difference matches the Net land flux and Net ocean flux estimates.
- Fluxes
  - from volcanic eruptions,
  - rock weathering (silicates and carbonates weathering reactions resulting into a small uptake of atmospheric CO_2),
  - export of carbon from soils to rivers,
  - burial of carbon in freshwater lakes and reservoirs and
  - transport of carbon by rivers to the ocean
- are all assumed to be pre-industrial fluxes, that is, unchanged during 1750–2011. Some recent studies (Section 6.3) indicate that this assumption is likely not verified, but global estimates of the Industrial Era perturbation of all these fluxes was not available from peer-reviewed literature.
- **The atmospheric inventories have been calculated using a conversion factor of 2.12 GtC per ppm (Prather et al., 2012)**.

Penn State University
Earth 103: Earth in the Future
Module 5: Global Carbon Cycle



The global carbon cycle, as best estimated, in 1994. Data slightly modified from Siegenthaler and Sarmiento, 1995; Kwon and Schnoor, 1995.

Quelle:
Earth in the Future, Module 5: The Global Carbon Cycle,
Penn State University - A Public Research University Serving Pennsylvania and the Global Community
https://www.e-education.psu.edu/earth103/node/525

Corinne Le Quéré et al.,
Global Carbon Budget 2018,
Earth Syst. Sci. Data, 10, 2141–2194, 2018
https://doi.org/10.5194/essd-10-2141-2018

page 4
The components of the CO_2 budget that are reported annually in this paper include separate estimates for [the emissions 1 and 2]
1. the CO_2 emissions from fossil fuel combustion and oxidation from all energy and industrial processes and cement production (**EFF**; GtC yr−1);
2. the emissions resulting from deliberate human activities on land, including those leading to land-use change (**ELUC**; GtC yr−1); and
3. the partitioning of 1 and 2 among the growth rate of [i.e. compartments]
   - atmospheric CO_2 concentration (**GATM**; GtC yr−1),
   - the uptake of CO_2 (the "CO_2 sinks") in the ocean (**SOCEAN**; GtC yr−1), and
   - the uptake of CO_2 on land (**SLAND**; GtC yr−1).

The CO_2 sinks as defined here conceptually include the response of the land (including inland waters and estuaries) and ocean (including coasts and territorial sea) to elevated CO_2 and changes in climate, rivers, and other environmental conditions, although in practice not all processes are accounted for (see Sect. 2.8).

The global emissions and their partitioning among the atmosphere, ocean, and land are in reality in balance; however due to imperfect spatial and/or temporal data coverage, errors in each estimate, and smaller terms not included in our budget estimate (discussed in Sect. 2.8), their sum does not necessarily add up to zero. We estimate a budget imbalance (**BIM**), which is a measure of the mismatch between the estimated emissions and the estimated changes in the atmosphere, land, and ocean, with the full global carbon budget as follows:

EFF + ELUC = GATM + SOCEAN + SLAND + BIM. (1)

GATM is usually reported in ppm yr−1, which we convert to units of carbon mass per year, GtC yr−1, using 1 ppm = 2.124 GtC (Table 1). We also include a quantification of EFF by country, computed with both territorial and consumption-based accounting (see Sect. 2), and discuss missing terms from sources other than the combustion of fossil fuels (see Sect. 2.8).

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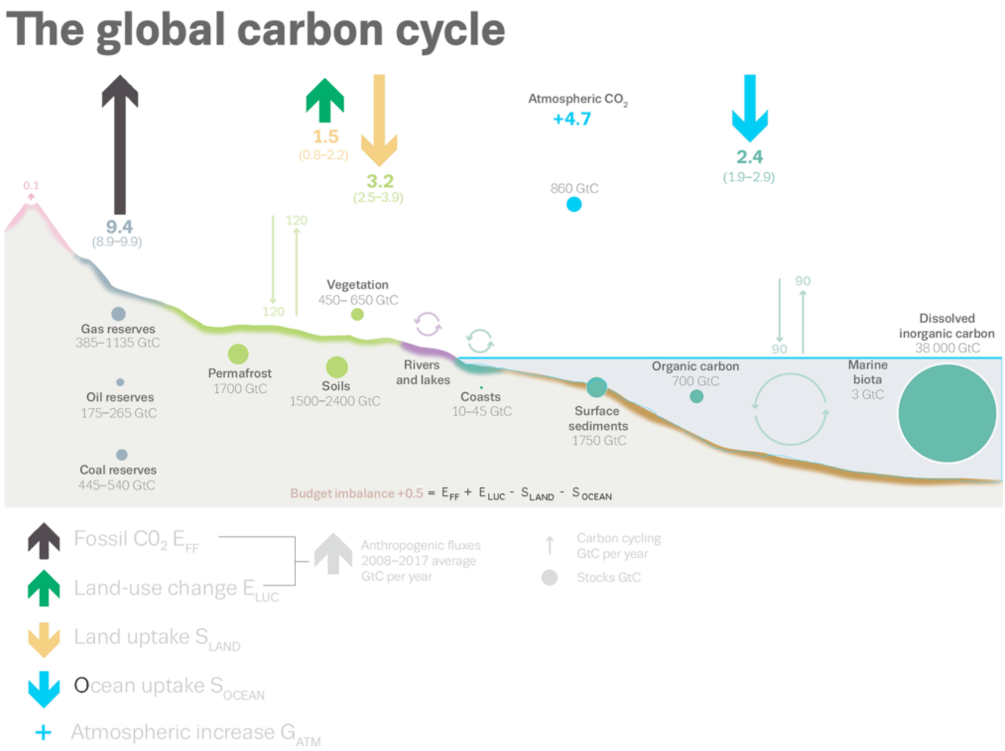

Source: https://www.earth-syst-sci-data.net/10/2141/2018/essd-10-2141-2018-f02.png

Figure 2. Schematic representation of the overall perturbation of the global carbon cycle caused by anthropogenic activities, averaged globally for the decade 2008–2017.

- See legends for the corresponding arrows and units.
- The uncertainty in the atmospheric CO2 growth rate is very small (±0.02 GtC yr−1) and is neglected for the figure.
- The anthropogenic perturbation occurs on top of an active carbon cycle, with fluxes and stocks represented in the background and taken from Ciais et al. (2013) for all numbers, with the ocean fluxes updated to 90 GtC yr−1 to account for the increase in atmospheric CO2 since publication, and except for the carbon stocks at the coasts, which are from a literature review of coastal marine sediments (Price and Warren, 2016).

GATM growth rate of atmospheric C (GtC y-1)

ELUC [emissions due to land use change] is the net sum of emissions and removals due to all anthropogenic activities considered (land use, land-use change, and forestry).ELUC includes CO2 fluxes from

- deforestation, afforestation, logging and forest degradation (including harvest activity),
- shifting cultivation (cycle of cutting forest for agriculture, then abandoning), and regrowth of forests following wood harvest or abandonment of agriculture.
- Only some land management activities are included in our land-use change emission estimates (Table A1 in the Appendix). Some of these activities lead to emissions of CO2 to the atmosphere, while others lead to CO2 sinks.

Table A1Comparison of the processes included (Y) or not (N) in the bookkeeping and dynamic global vegetation models (DVGM) for their estimates of ELUC and SLAND. See Table 4 for model references. All models include deforestation and forest regrowth after abandonment of agriculture (or from afforestation activities on agricultural land). (Source: https://www.earth-syst-sci-data.net/10/2141/2018/essd-10-2141-2018-t10.png)

	Bookkeeping models		DGVMs															
	H&N2017	BLUE	CABLE-POP	CLASS-CTEM	CLM5.0	DLEM	ISAM	JSBACH	JULES	LPJ-GUESS	LPJ	LPX-Bern	OCN	ORCHIDEE-CNP	ORCHIDEE-Trunk	SDGVM	SURFEX	VISIT
Processes relevant for E_{LUC}																		
Wood harvest and forest degradation[a]	Y	Y	Y	N	Y	Y	Y	Y	N	Y	Y	N[d]	Y	N	Y	N	N	Y
Shifting cultivation/sub-grid-scale transitions	N[b]	Y	Y	N	Y	N	N	Y	N	Y	Y	N[d]	N	N	N	N	N	Y
Cropland harvest (removed, r, or added to litter, l)	Y(r)[h]	Y(r)[h]	Y(r)	Y(l)	Y(r)	Y	Y	Y(r,l)	N	Y(r)	Y(l)	Y(r)	Y(r,l)	Y(r)	Y(r)	Y(r)	N	Y(r)
Peat fires	Y	Y	N	N	Y	N	N	N	N	N	N	N	N	N	N	N	N	N
Fire as a management tool	Y[h]	Y[h]	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N
N fertilisation	Y[h]	Y[h]	N	N	Y	Y	Y	N	N	Y	N	Y	Y	Y	N	N	N	N
Tillage	Y[h]	Y[h]	Y	Y[c]	N	N	N	N	N	Y	N	N	N	N	Y[g]	N	N	N
Irrigation	Y[h]	Y[h]	N	N	Y	Y	Y	N	N	Y	N	N	N	N	N	N	Y[g]	N
Wetland drainage	Y[h]	Y[h]	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N
Erosion	Y[h]	Y[h]	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	Y
Southeast Asia peat drainage	Y	Y	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N
Grazing and mowing harvest (removed, r, or added to litter, l)	Y(r)[h]	Y(r)[h]	Y(r)	N	N	N	Y(l)	Y(l)	N	Y(r)	Y(l)	N	Y(r,l)	N	N	N	N	N
Processes relevant also for S_{LAND}																		
Fire simulation	US only	N	N	Y	Y	Y	N	Y	N	Y	Y	Y	N	N	N	Y	Y	Y
Climate and variability	N	N	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y
CO_2 fertilisation	N[f]	N[f]	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y[e]	Y	Y	Y
Carbon–nitrogen interactions, including N deposition	N[h]	N[h]	Y	N[d]	Y	Y	Y	Y	N	Y	N	Y	Y	Y	N	Y[c]	N[i]	N

a Refers to the routine harvest of established managed forests rather than pools of harvested products.
b No back-and-forth transitions between vegetation types at the country level, but if forest loss based on FRA exceeded agricultural expansion based on the FAO, then this amount of area is interpreted as shifting cultivation.
c Limited. Nitrogen uptake is simulated as a function of soil C, and photosynthesis is directly related to canopy N. Does not consider N deposition.
d Although C–N cycle interactions are not represented, the model includes a parameterization of down-regulation of photosynthesis as CO2 increases to emulate nutrient constraints (Arora et al., 2009).
e Tillage is represented over croplands by increased soil carbon decomposition rate and reduced humification of litter to soil carbon.
f Bookkeeping models include the effect of CO2 fertilisation as captured by observed carbon densities, but not as an effect that is transient in time.
g A 20 % reduction of active soil organic carbon (SOC) pool turnover time for C3 crops and 40 % reduction for C4 crops.
h Process captured implicitly by use of observed carbon densities. i Simple parameterization of nitrogen limitation based on Yin (2002; assessed on FACE experiments).

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2.3.1 Bookkeeping Models

The bookkeeping models do not include land ecosystems' transient response to changes in climate, atmospheric CO2, and other environmental factors, and the carbon densities are based on contemporary data reflecting environmental conditions at (and up to) that time. Since carbon densities remain fixed over time in bookkeeping models, the additional sink capacity that ecosystems provide in response to CO2 fertilisation and some other environmental changes is not captured by these models (Pongratz et al., 2014; see Sect. 2.8.4).

2.3.2 Dynamic global vegetation models (DGVMs)

All DGVMs represent processes of vegetation growth and mortality, as well as decomposition of dead organic matter associated with natural cycles, and include the vegetation and soil carbon response to increasing atmospheric CO2 levels and to climate variability and change.

2.3.3 Uncertainty assessment for ELUC

Differences between the bookkeeping models and DGVM models originate from three main sources: the different methodologies, the underlying land use/land cover data set, and the different processes represented (Table A1). We examine the results from the DGVM models and from the bookkeeping method and use the resulting variations as a way to characterise the uncertainty in ELUC.

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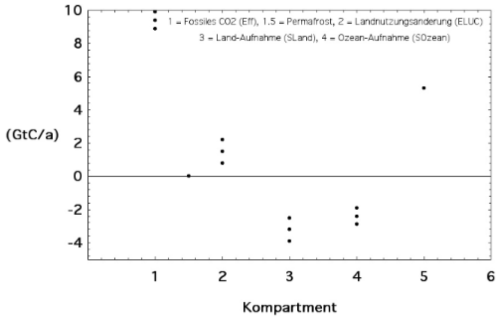
Table 5 Comparison of results from the **bookkeeping** method and budget residuals with results from the **DGVMs** and inverse estimates for different periods, the last decade, and the last year available. All values are in GtC yr−1. The DGVM uncertainties represent ±1σ of the decadal or annual (for 2017 only) estimates from the individual DGVMs: for the inverse models the range of available results is given.

	Mean (GtC yr^{-1}) $\pm 1\sigma$						
	1960–1969	1970–1979	1980–1989	1990–1999	2000–2009	2008–2017	2017
Land-use change emissions (E_{LUC})							
Bookkeeping methods	1.5 ± 0.7	1.2 ± 0.7	1.2 ± 0.7	1.4 ± 0.7	1.3 ± 0.7	1.5 ± 0.7	1.4 ± 0.7
DGVMs	1.5 ± 0.7	1.4 ± 0.7	1.5 ± 0.7	1.3 ± 0.6	1.4 ± 0.6	1.9 ± 0.6	2.0 ± 0.7
Terrestrial sink (S_{LAND})							
Residual sink from global budget ($E_{FF} + E_{LUC} - G_{ATM} - S_{OCEAN}$)	1.8 ± 0.9	1.8 ± 0.9	1.5 ± 0.9	2.6 ± 0.9	2.9 ± 0.9	3.5 ± 1.0	4.1 ± 1.0
DGVMs	1.2 ± 0.5	2.1 ± 0.4	1.8 ± 0.6	2.4 ± 0.5	2.7 ± 0.7	3.2 ± 0.7	3.8 ± 0.8
Total land fluxes ($S_{LAND} - E_{LUC}$)							
Budget constraint ($E_{FF} - G_{ATM} - S_{OCEAN}$)	0.3 ± 0.5	0.6 ± 0.6	0.4 ± 0.6	1.2 ± 0.6	1.6 ± 0.6	2.1 ± 0.7	2.7 ± 0.7
DGVMs	-0.3 ± 0.6	0.7 ± 0.5	0.3 ± 0.6	1.1 ± 0.5	1.3 ± 0.5	1.3 ± 0.5	1.8 ± 0.5
Inversions*	–/–/–	–/–/–	−0.2–0.1	0.5–1.1	0.8–1.5	1.4–2.4	1.2–3.1

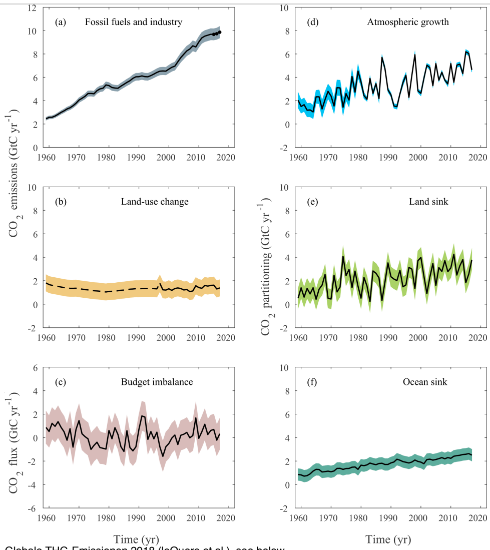
Table 8. Decadal mean in the five components of the anthropogenic CO_2 budget for the periods 1960–1969, 1970–1979, 1980–1989, 1990–1999, and 2000–2009, as well as the last decade and last year available. All values are in GtC yr^{-1}. All uncertainties are reported as $\pm 1\sigma$. A data set containing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

	Mean (GtC yr^{-1})						
	1960–1969	1970–1979	1980–1989	1990–1999	2000–2009	2006–2015	2015
Emissions							
Fossil fuels and industry (E_{FF})	3.1 ± 0.2	4.7 ± 0.2	5.5 ± 0.3	6.3 ± 0.3	8.0 ± 0.4	9.3 ± 0.5	9.9 ± 0.5
Land-use-change emissions (E_{LUC})	1.5 ± 0.5	1.3 ± 0.5	1.4 ± 0.5	1.6 ± 0.5	1.0 ± 0.5	1.0 ± 0.5	1.3 ± 0.5
Partitioning							
Growth rate in atmospheric CO_2 concentration (G_{ATM})	1.7 ± 0.1	2.8 ± 0.1	3.4 ± 0.1	3.1 ± 0.1	4.0 ± 0.1	4.5 ± 0.1	6.3 ± 0.2
Ocean sink (S_{OCEAN})	1.2 ± 0.5	1.5 ± 0.5	1.9 ± 0.5	2.2 ± 0.5	2.3 ± 0.5	2.6 ± 0.5	3.0 ± 0.5
Residual terrestrial sink (S_{LAND})	1.7 ± 0.7	1.7 ± 0.8	1.6 ± 0.8	2.6 ± 0.8	2.6 ± 0.8	3.1 ± 0.9	1.9 ± 0.9

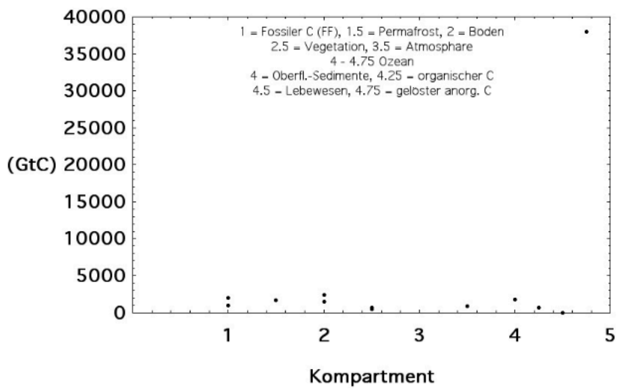
SLAND

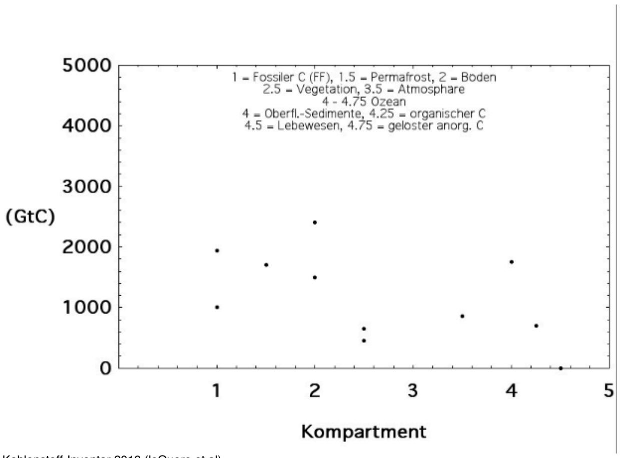


Globale THG-Emissionen 2018 (leQuere et al.)
5 = atmosphärischer Anstieg

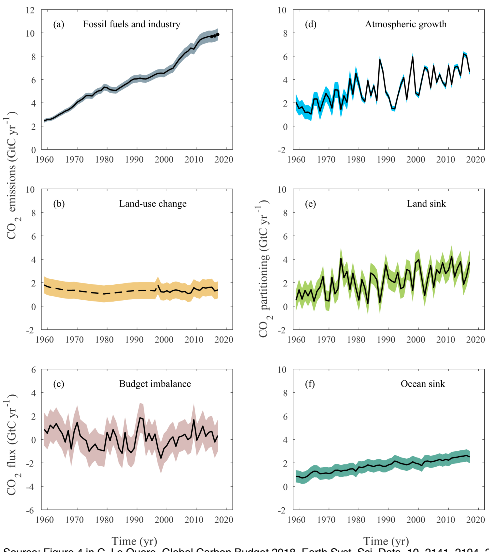


Globale THG-Emissionen 2018 (leQuere et al.), see below





Kohlenstoff-Inventar 2018 (leQuere et al)



Source: Figure 4 in C. Le Quere, Global Carbon Budget 2018, Earth Syst. Sci. Data, 10, 2141–2194, 2018,
https://www.earth-syst-sci-data.net/10/2141/2018/#top
https://doi.org/10.5194/essd-10-2141-2018,

	Mean (GtC yr^{-1})						
	1960–1969	1970–1979	1980–1989	1990–1999	2000–2009	2008–2017	2017
Total emissions ($E_{FF} + E_{LUC}$)							
Fossil CO_2 emissions (E_{FF})	3.1 ± 0.2	4.7 ± 0.2	5.4 ± 0.3	6.3 ± 0.3	7.8 ± 0.4	9.4 ± 0.5	9.9 ± 0.5
Land-use change emissions (E_{LUC})	1.5 ± 0.7	1.2 ± 0.7	1.2 ± 0.7	1.4 ± 0.7	1.3 ± 0.7	1.5 ± 0.7	1.4 ± 0.7
Total emissions	4.7 ± 0.7	5.8 ± 0.7	6.6 ± 0.8	7.6 ± 0.8	9.0 ± 0.8	10.8 ± 0.8	11.3 ± 0.9
Partitioning							
Growth rate in atmospheric CO_2 concentration (G_{ATM})	1.7 ± 0.07	2.8 ± 0.07	3.4 ± 0.02	3.1 ± 0.02	4.0 ± 0.02	4.7 ± 0.02	4.6 ± 0.2
Ocean sink (S_{OCEAN})	1.0 ± 0.5	1.3 ± 0.5	1.7 ± 0.5	2.0 ± 0.5	2.1 ± 0.5	2.4 ± 0.5	2.5 ± 0.5
Terrestrial sink (S_{LAND})	1.2 ± 0.5	2.1 ± 0.4	1.8 ± 0.6	2.4 ± 0.5	2.7 ± 0.7	3.2 ± 0.7	3.8 ± 0.8
Budget imbalance							
$B_{IM} = E_{FF} + E_{LUC} - (G_{ATM} + S_{OCEAN} + S_{LAND})$	(0.6)	(−0.3)	(−0.3)	(0.2)	(0.2)	(0.5)	(0.3)

Source: Table. 6 in C. Le Quere, Global Carbon Budget 2018, Earth Syst. Sci. Data, 10, 2141–2194, 2018,
https://www.earth-syst-sci-data.net/10/2141/2018/#top
https://doi.org/10.5194/essd-10-2141-2018,

------------------------ Climate Change 2013 The Physical Science Basis
Working Group I Contribution to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change
(T.F. Stocker, D. Qin eds.)

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Table 6.1 | Global anthropogenic CO2 budget, accumulated since the Industrial Revolution (onset in 1750) and averaged over the 1980s, 1990s, 2000s, as well as the last 10 years until 2011. By convention, a negative ocean or land to atmosphere CO2 flux is equivalent to a gain of carbon by these reservoirs. The table does not include natural exchanges (e.g., rivers, weathering) between reservoirs. The uncertainty range of 90% confidence interval presented here differs from how uncertainties were reported in AR4 (68%).

	1750–2011 Cumulative PgC	1980–1989 PgC yr^{-1}	1990–1999 PgC yr^{-1}	2000–2009 PgC yr^{-1}	2002–2011 PgC yr^{-1}
Atmospheric increase[a]	240 ± 10[f]	3.4 ± 0.2	3.1 ± 0.2	4.0 ± 0.2	4.3 ± 0.2
Fossil fuel combustion and cement production[b]	375 ± 30[f]	5.5 ± 0.4	6.4 ± 0.5	7.8 ± 0.6	8.3 ± 0.7
Ocean-to-atmosphere flux[c]	−155 ± 30[f]	−2.0 ± 0.7	−2.2 ± 0.7	−2.3 ± 0.7	−2.4 ± 0.7
Land-to-atmosphere flux *Partitioned as follows*	30 ± 45[f]	−0.1 ± 0.8	−1.1 ± 0.9	−1.5 ± 0.9	−1.6 ± 1.0
Net land use change[d]	180 ± 80[f,g]	1.4 ± 0.8	1.5 ± 0.8	1.1 ± 0.8	0.9 ± 0.8
Residual land sink[e]	−160 ± 90[f]	−1.5 ± 1.1	−2.6 ± 1.2	−2.6 ± 1.2	−2.5 ± 1.3

Notes:
a Data from Charles D. Keeling, (http://scrippsco2.ucsd.edu/data/data.html), Thomas Conway and Pieter Tans, National Oceanic and Atmospheric Administration–Earth System Research Laboratory (NOAA–ESRL, www.esrl.noaa.gov/gmd/ccgg/trends/) using a conversion factor of 2.120 PgC per ppm (Prather et al., 2012). Prior to the atmospheric record in 1960, ice core data is used (Neftel et al., 1982; Friedli et al., 1986; Etheridge et al., 1996).
b Estimated by the Carbon Dioxide Information Analysis Center (CDIAC) based on UN energy statistics for fossil fuel combustion (up to 2009) and US Geological Survey for cement production (Boden et al., 2011), and updated to 2011 using BP energy statistics.
c Based on observations for 1990–1999, with the trends based on existing global estimates (see Section 6.3.2.5 and Table 6.4).
d Based on the "bookkeeping" land use change flux accounting model of Houghton et al. (2012) until 2010, and assuming constant LUC emissions for 2011, consistent with satellite-based fire emissions (Le Quéré et al., 2013; see Section 6.3.2.2 and Table 6.2).
e Calculated as the sum of the Land-to-atmosphere flux minus Net land use change flux, assuming the errors on each term are independent and added quadratically.
f The 1750–2011 estimate and its uncertainty is rounded to the nearest 5 PgC.
g Estimated from the cumulative net land use change emissions of Houghton et al. (2012) during 1850–2011 and the average of four publications (Pongratz at al., 2009; van Minnen et al., 2009; Shevliakova et al., 2009; Zaehle et al., 2011) during 1750–1850.

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Table 6.8 I Global CH4 budget for the past three decades (in Tg(CH4) yr–1) and present day (2011)38. The bottom-up estimates for the decade of 2000–2009 are used in the Executive Summary and in Figure 6.2. T-D stands for Top-Down inversions and B-U for Bottom-Up approaches. Only studies covering at least 5 years of each decade have been used. Reported values correspond to the mean of the cited references and therefore not always equal (max-min)/2; likewise, ranges [in brackets] represent minimum and maximum values of the cited references. The sum of sources and sinks from B-U approaches does not automatically balance the atmospheric changes. For B-U studies, individual source types are also presented. For T-D inversions, the 1980s decade starts in 1984. As some atmospheric inversions did not reference their global sink, balance with the atmosphere and the sum of the sources has been assumed. One biomass burning estimate (Schultz et al., 2007) excludes biofuels (a). Stratospheric loss for B-U is the sum of the loss by OH radicals, a 10 Tg yr–1 loss due to O1D radicals (Neef et al., 2010) and a 20 to 35% contribution due to Cl radicals24 (Allan et al., 2007). Present day budgets39 adopt a global mean lifetime of 9.14 yr (±10%).

$Tg(CH_4)\ yr^{-1}$	1980–1989		1990–1999		2000–2009	
	Top-Down	Bottom-Up	Top-Down	Bottom-Up	Top-Down	Bottom-Up
Natural Sources	193 [150–267]	355 [244–466]	182 [167–197]	336 [230–465]	218 [179–273]	347 [238–484]
Natural wetlands	157 [115–231][1,2,3]	225 [183–266][4,5]	150 [144–160][1,28,29]	206 [169–265][4,5,27]	175 [142–208][1,29,33,34,35,36]	217 [177–284][4,5,27]
Other sources	36 [35–36][1,2]	130 [61–200]	32 [23–37][1,28,29]	130 [61–200]	43 [37–65][1,29,33,34,35,36]	130 [61–200]
Freshwater (lakes and rivers)		40 [8–73][6,7,8]		40 [8–73][6,7,8]		40 [8–73][6,7,8]
Wild animals		15 [15–15][9]		15 [15–15][9]		15 [15–15][9]
Wildfires		3 [1–5][9,10,11,12,13]		3 [1–5][9,10,11,12,13]		3 [1–5][9,10,11,12,13]
Termites		11 [2–22][9,10,14,15,x]		11 [2–22][9,10,14,15,x]		11 [2–22][9,10,14,15,x]
Geological (incl. oceans)		54 [33–75][10,16,17]		54 [33–75][10,16,17]		54 [33–75][10,16,17]
Hydrates		6 [2–9][9,18,19]		6 [2–9][9,18,19]		6 [2–9][9,18,19]
Permafrost (excl. lakes and wetlands)		1 [0–1][10]		1 [0–1][10]		1 [0–1][10]
Anthropogenic Sources	348 [305–383]	308 [292–323]	372 [290–453]	313 [281–347]	335 [273–409]	331 [304–368]
Agriculture and waste	208 [187–220][1,2,3]	185 [172–197][20]	239 [180–301][1,28,29]	187 [177–196][20,30,31]	209 [180–241][1,29,33,34,35,36]	200 [187–224][20,30,31]
Rice		45 [41–47][20]		35 [32–37][20,27,30,31]		36 [33–40][20,27,30,31]
Ruminants		85 [81–90][20]		87 [82–91][20,30,31]		89 [87–94][20,30,31]
Landfills and waste		55 [50–60][20]		65 [63–68][20,30,31]		75 [67–90][20,30,31]
Biomass burning (incl. biofuels)	46 [43–55][1,2,3]	34 [31–37][20,21,22a,38]	38 [26–45][1,28,29]	42 [38–45][13,20,21,22a,32,38]	30 [24–45][1,29,33,34,35,36]	35 [32–39][13,20,21,32,37,38]
Fossil fuels	94 [75–108][1,2,3]	89 [89–89][20]	95 [84–107][1,28,29]	84 [66–96][20,30,31]	96 [77–123][1,29,33,34,35,36]	96 [85–105][20,30,31]
Sinks						
Total chemical loss	490 [450–533][1,2,3]	539 [411–671][23,24,25,26]	515 [491–554][1,28,29]	571 [521–621][23,24,25,26]	518 [510–538][1,29,33,34,36]	604 [483–738][23,24,25,26]
Tropospheric OH		468 [382–567][26]		479 [457–501][26]		528 [454–617][25,26]
Stratospheric OH		46 [16–67][23,25,26]		67 [51–83][23,25,26]		51 [16–84][23,25,26]
Tropospheric Cl		25 [13–37][24]		25 [13–37][24]		25 [13–37][24]
Soils	21 [10–27][1,2,3]	28 [9–47][27,34,36]	27 [27–27][1]	28 [9–47][27,34,36]	32 [26–42][1,33,34,35,36]	28 [9–47][27,34,36]
Global						
Sum of sources	541 [500–592]	663 [536–789]	554 [529–596]	649 [511–812]	553 [526–569]	678 [542–852]
Sum of sinks	511 [460–559]	567 [420–718]	542 [518–579]	599 [530–668]	550 [514–560]	632 [592–785]
Imbalance (sources minus sinks)	30 [16–40]		12 [7–17]		3 [–4–19]	
Atmospheric growth rate	34		17		6	
Global top-down (year 2011)	2011 (AR5)[38]					
Burden ($Tg\ CH_4$)	4954±10					
Atmospheric loss ($Tg\ CH_4\ yr^{-1}$)	542±56					
Atmos. increase ($Tg\ CH_4\ yr^{-1}$)	14±3					
Total source ($Tg\ CH_4\ yr^{-1}$)	556±56					
Anthropogenic source ($Tg\ CH_4\ yr^{-1}$)	354±45					
Natural source ($Tg\ CH_4\ yr^{-1}$)	202±35					

References:

1 Bousquet et al. (2011)
2 Fung et al. (1991)
3 Hein et al. (1997)
4 Hodson et al. (2011)
5 Ringeval et al. (2011)
6 Bastviken et al. (2004)
7 Bastviken et al. (2011)
8 Walter et al. (2007)
9 Denman et al. (2007)
10 EPA (2010)

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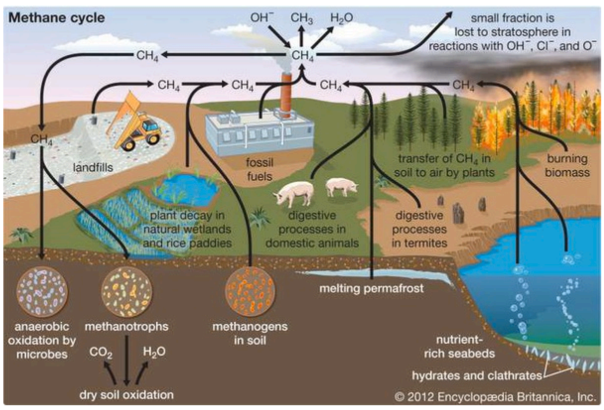
Table 6.8 References (continued)

11 Hoelzemann et al. (2004)
12 Ito and Penner (2004)
13 van der Werf et al. (2010)
14 Sanderson (1996)
15 Sugimoto et al. (1998)
16 Etiope et al. (2008)
17 Rhee et al. (2009)
18 Dickens (2003)
19 Shakhova et al. (2010)
20 EDGAR4-database (2009)
21 Mieville et al. (2010)
22 Schultz et al. (2007) (excluding biofuels)
23 Neef et al. (2010)
24 Allan et al. (2007)
25 Williams et al. (2012b)
26 Voulgarakis et al. (2013)
27 Spahni et al. (2011)
28 Chen and Prinn (2006)
29 Pison et al. (2009)
30 Dentener et al. (2005)
31 EPA (2011a)
32 van der Werf (2004)
33 Bergamaschi et al. (2009)
34 Curry (2007)
35 Spahni et al. (2011)
36 Ito and Inatomi (2012)
37 Wiedinmyer et al. (2011)
38 Andreae and Merlet (2001)
39 Prather et al. (2012), updated to 2011 (Table 2.1) and used in Chapter 11 projections; uncertainties evaluated as 68% confidence intervals, see also Annex II.2.2 and II.4.2.

Scott Strough, Researcher in carbon farming as a climate change mitigation strategy

Updated Nov 26, 2019 · Author has **2.3k** answers and **2.3m** answer views



Source: https://www.quora.com/What-happens-to-methane-once-it-is-released-into-the-atmosphere

Atmospheric methane has 1 of 3 fates.

1. Rapid oxidation. Burning methane is basically the same as burning Natural gas. Usually you see this at land fills where they purposely catch and burn the methane as it is released into the atmosphere from the rotting garbage. For this reason sometimes methane can be collected and used as a biofuel.

2. Slow oxidation. Methane that comes into contact with highly reactive atmospheric gasses like ozone will oxidize on contact usually producing CO2 + H2O. This slow oxidation removes that methane in about 9.6 years.

3. Biotic oxidation. Methanotrophs in aerobic upland soils are prokaryotes that metabolize methane as their only source of carbon and energy. Even though rotting vegetation in well drained aerobic (oxic) soils does produce methane, those soils are a net sink for atmospheric methane. The subsurface location of methanotrophs means that energy requirements for maintenance and growth are obtained from methane concentrations that are lower than atmospheric.[2] As methane diffuses from the atmosphere into these soils, methane consuming bacteria oxidize it.[3] Of all the methane sinks, the biotic sink strength is the most responsive to variation in human activities. Currently that sink strength is highly degraded due to the widespread use of haber process nitrogen in agriculture and generally unhealthy agricultural soils worldwide.[4]

Assessment of methane emissions from the U.S. oil and gas supply chain
Ramón A Alvarez, Daniel Zavala-Araiza, David R. Lyon, Steven P. Hamburg
June 2018, Science 361(6398):eaar7204
DOI: 10.1126/science.aar7204
Project: Methane emissions
@ResearcgGate:
[Assessment of methane emissionsfrom the U.S. oil and gas supply chain]
Ramón A. Alvarez, Daniel Zavala-Araiza, David R. Lyon et al.

Methane emissions from the U.S. oil and natural gas supply chain were estimated using ground-based, facility-scale measurements and validated with aircraft observations in areas accounting for ~30% of U.S. gas production. When scaled up nationally, our facility-based estimate of 2015 supply chain emissions is 13 ± 2 Tg/y, equivalent to 2.3% of gross U.S. gas production. This value is ~60% higher than the U.S. EPA inventory estimate, likely because existing inventory methods miss emissions released during abnormal operating conditions. Methane emissions of this magnitude, per unit of natural gas consumed, produce radiative forcing over a 20-year time horizon comparable to the CO2 from natural gas combustion. Significant emission reductions are feasible through rapid detection of the root causes of high emissions and deployment of less failure-prone systems.

more

The carbon cycle and changing atmospheric CO2
https://www.youtube.com/watch?v=y45Eu-DaBeQ&list=PL8it3FfYrgvMi0vf_j_O0B0YaWBPrIqSB&index=23

Integrated (Climate) Science Assessment Model (ISAM)
a fully coupled ocean-atmosphere-terrestrial biogeochemistry model
Atul Jain, U Illinois
http://climate.atmos.uiuc.edu/isam2/index.html
David Archer, U Chicago: http://climatemodels.uchicago.edu/isam/

more models
David Archer, U Chicago: http://climatemodels.uchicago.edu/models.html

Mit dem **Kohlenstoffkreislaufmodell ISAM** kann man berechnen, wie stark die globale mittlere Temperatur steigt, wenn Treibhausgasemissionen einen beliebig vorgegebenen Verlauf nehmen. Die Methode, mit der dieses Modell erstellt wird, habe ich häufig in den wissenschaftlichen Gebieten angetroffen, in denen ich gearbeitet habe.

1. Man stellt sich vor, der Kohlenstoff bewege sich auf Grund von natürlichen und von Menschen gemachten Prozessen in einem Netzwerk von Töpfen im Kreis (Kohlenstoffkreislauf).
2. Der Kohlenstoff kann eine Vielzahl von chemischen Verbindungen eingehen, gasförmige (wie CO2, CH4), wässrige und feste Karbonate (wie H2CO3, HCO3, CO3, CaCO3).
3. Diese Verbindungen können an verschiedenen Orten sein.
4. Jeder Ort und jede chemisch Verbindung stellt einen Topf dar.
5. Physikalische Verlagerungen und chemische Reaktionen bewegen den Kohlenstoff durch das Netzwerk von Töpfen, d.h. jeder Topf hat 2 Eigenschaften: einen Zufluss und einen Abfluss.
6. Man bildet das Netzwerk mathematisch nach und macht Annahmen über die Größe der Zu- und Abflüsse, die "Parameter", wiederum gestützt auf Vorstellungen über die physikalischen und chemischen Prozesse, welche man hinter den Zu- und Abflüssen vermutet.
7. Man beginnt mit einer möglichst kleinen Anzahl von Töpfen und Austauschprozessen zwischen den Töpfen und erweitert das System, bis man den Eindruck hat, alle wesentlichen Beobachtungen in der Natur im Modell nachgebildet zu haben. Man nennt dieses Verfahren "Anpassen" und das Ergebnis englisch "best fit", weil man solange Topfanzahl und Austauschparameter ändert, bis das Modell ausreichend "passt", d.h. bis die Abweichungen zwischen Beobachtungen und Modellergebnissen akzeptabel erscheinen.

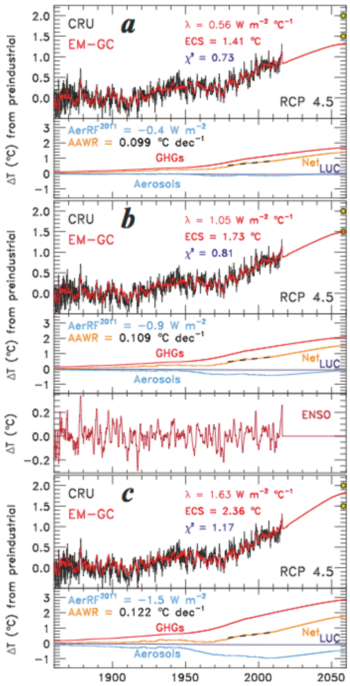


Fig. 2.9 Observed and EM-GC simulated global warming, 1860–2015 as well as global warming
Quelle: R.J. Salawitch et al., Paris Climate Agreement: Beacon of Hope, DOI 10.1007/978-3-319-46939-3_1

Einen perfekten "Sitz" des Modells, d.h. eine exakte Übereinstimmung zwischen den in der Natur gemessenen Daten und den Modellergebnissen wird man mit dem Verfahren 1 - 7 nicht erreichen, insbesondere wenn man viele beobachtete Daten mit dem Modell darstellen will. Ein grundsätzlicher Grund ist: Das Modell bildet
a) im besten Fall nur die wesentlichen natürlichen Vorgänge ab, nicht die tatsächlich gemessenen Verläufe (s. Salawitch et al, 2017, Fig. 2.9)
b) im schlechtesten Fall nicht einmal einen einzigen.

Im Fall b ist das Modell wegen seiner vielen Parameter (Anzahl der Töpfe und deren Austauschprozesse) täuschend anpassungsfähig ("model degeneracy", Salawitch et al., 2017).

Man kann prinzipiell nicht wissen, ob im betrachteten Fall die Extrema (a) oder (b) oder ein Fall dazwischen vorliegt.

(Beispielsweise bei der Modellierung der Wanderung von hochradioaktiven Schadstoffen aus einem nuklearen Endlager kann man seit Jahrzehnten nur unzureichend beschreiben, wie die Schadstoffe chemisch mit ihrer Umgebung reagieren und dadurch in ihrer Wanderung behindert werden.Man findet sich also zunächst damit ab, dass solche Modelle vielleicht die physikalischen und chemischen Vorgänge nicht abbilden, aber Bekanntes gut wiedergeben und nützliche Vorhersagen machen.)

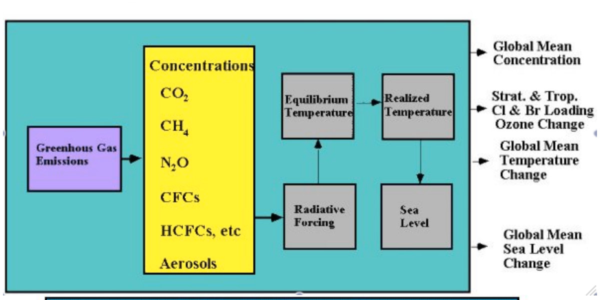
8. Um dieser Unsicherheit Rechnung zu tragen, haben sich die im IPCC zusammengekommenen Wissenschaftler auf eine Vielzahl von Modellen und dazugehörende Parameter geeinigt, die
   - alle die Beobachtungen ausreichend nachbilden,
   - aber zu voneinander abweichenden Vorhersagen kommen, je weiter sie in die Zukunft schauen.

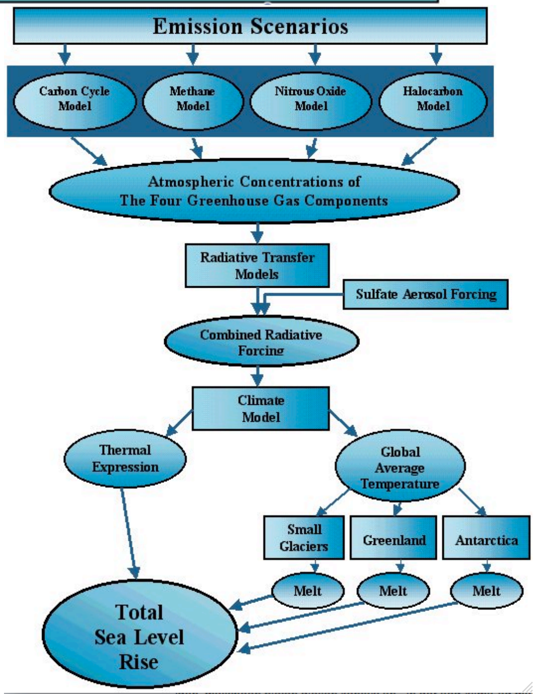
   Man vermutet die Realität in dem Band, das durch z.B. 90% der Modellergebnisse aufgespannt wird.

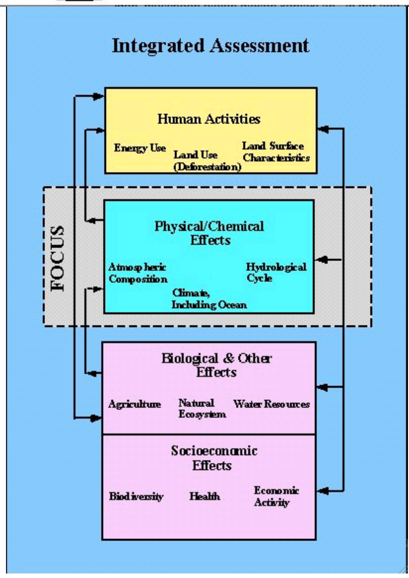
9.. Beim Durchlaufen der Schritte 1 - 8 beeinflussen sich die Wissenschaftler gegenseitig und kommen im IPCC zu einem Konsens bzgl. dessen, welche Topfnetzwerke und Parameter als sinnvoll angesehen werden.

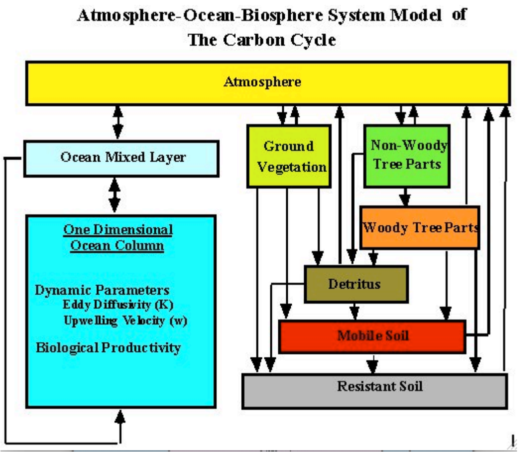
10. Diese Beliebigkeit unterscheidet die Klimawissenschaft (und einen sehr großen Teil der heutigen Wissenschaft) von der Physik und Chemie des 19. und beginnenden 20. Jhds., vertreten durch z.B. Ludwig Boltzmann, Max Planck, Albert Einstein und Linus Pauling. (Im Unterschied zur nuklearen Endlagerforschung hat sich das IPCC jedoch -nach meiner Erfahrung- durch seine Vorgehensweise der politischen Einflussnahme weitgehend entzogen.)

Integrated Science Assessment Model









The concentration of CO2 is calculated by a globally averaged carbon cycle model (Quelle: ISAM, Atul Jain)

Carbon Cycle Module

Ocean Component

Upwelling Velocity	3.5	yr.
Vertical Diffusion	4700	yr.
Ocean Net Primary Productivity	8.5	yr.
Mixed Layer Depth	75	m.
Ocean Parameter	.475	p_c.
Pre industrial CO_2 concentrations (1765)	278	ppm.

Terrestrial Component

Fertilization Factor, b	.52	.
Translocation Q_{10}	1.2	°C
Respiration Q_{10}	2.0	°C
Net Primary Productivity Q_{10}	1.4	°C
Net Photosynthesis Q_{10}	1.0	°C

Set Carbon Cycle Parameters

Climate/Ocean Module

Climate/Ocean Module Parameters

Temperature sensitivity of the climate system, DT_{2X}	2.5	°C.
Vertical uniform thermal diffusivity, k	2000	m^2/yr.
Vertical uniform upwelling velocity for the global ocean, w	4	m/yr.
Change in the warming of the polar ocean relative to the warming of the non-polar ocean, p	.5	.

Set Climate/Ocean Parameters

Lifetimes		
N_2O	120	yrs.
CF_4	50000	yrs.
C_2F_6	10000	yrs.
C_4F_{10}	2600	yrs.
SF_6	3200	yrs.
CFC-11	45	yrs.
CFC-12	100	yrs.
CFC-113	85	yrs.
CFC-114	300	yrs.
CFC-115	1700	yrs.
H-1211	11	yrs.
H-1301	65	yrs.
H-2408	77	yrs.
CCl_4	35	yrs.
CH_3CCl_3	4.8	yrs.
F-22	11.9	yrs.
HFC-123	1.4	yrs.
HFC-141b	9.3	yrs.
HFC-142b	19.0	yrs.
MB	0.85	yrs.
HFC-23	260	yrs.
HFC-32	5.0	yrs.
HFC-125	29	yrs.
HFC-134a	13.8	yrs.
HFC-143a	52.0	yrs.
HFC-152a	1.4	yrs.
HFC-227ea	33	yrs.
HFC-245ca	5.9	yrs.
HFC-43mee	15.0	yrs.

Atul Jain-brd #18630

Specify Greenhouse Gas Emissions

Use these input boxes to view current values for emissions and to set emissions for specific years.

Year	CO_2 Fossil Fuel (GtC)	CO_2 Land Use (GtC)	CH_4 (MT N)	CO Direct (MT N)	NOX (Mt N)	VOC (Mt)	N_2O (Mt)	SO_2 (Mt S)
2000	30.0	1.6	347	1036	32.5	151	6.9	69.0
2010	27.0	1.8	389	1138	37.6	172	7.1	68.2
2020	21.09	1.6	448	1211	43.4	192	7.1	65.0
2030	15.6	0.3	501	1175	48.4	202	6.7	59.9
2040	10.4	0.0	528	1268	52.8	215	6.4	58.8
2050	7.0	-0.3	538	1351	53.7	217	6.0	57.2
2060	1.7	-0.2	544	1466	55.4	214	5.8	53.7
2070	0	-0.2	542	1625	55.6	202	5.5	51.9
2080	0	-0.2	529	1803	58.5	192	5.4	49.1
2090	0	-0.2	508	1948	60.1	178	5.2	48.0
2100	0	-0.2	508	2067	60.4	170	5.1	47.3

Set Greenhouse Gas Emissions

Climate/Ocean Module

Climate/Ocean Module Parameters

Temperature sensitivity of the climate system, DT_{2X}	2.5	°C.
Vertical uniform thermal diffusitivity, k	2000	m^2/yr.
Vertical uniform upwelling velocity for the global ocean, w	4	m/yr.
Change in the warming of the polar ocean relative to the warming of the non-polar ocean, p	.5	.

Set Climate/Ocean Parameters

Vertical uniform upwelling velocity, w = 40 m/yr

The concentration of CO2 is calculated by a globally averaged carbon cycle model (Figure 3), which consists of 4 reservoirs, namely

- the atmosphere,
- the terrestrial biosphere,
- the mixed ocean layer, and
- the deep ocean (Jain et al., 1995, 1996).

The atmosphere and the mixed layers are modeled as well mixed reservoirs.

Transport of total inorganic carbon in the deep ocean is modeled by a partial differential equation, spanning time and ocean depth, which accounts for vertical diffusion and upwelling. The rate of transport in the deep ocean is dependent on two parameters: eddy diffusivity (k) and upwelling velocity (w). (Jain et al. 1995) determined parameter values k = 4700 m2/yr and w = 3.5 m/yr by calibration of model results to the estimated global-mean pre-anthropogenic depth-profile of ocean 14C concentration). Water upwells through the deep ocean column to the surface ocean layer from where it is returned, through a polar sea, to the bottom of the ocean column thereby completing the thermohaline circulation.

Air-sea exchange is modeled by an air sea exchange coefficient in combination with the buffer factor that summarizes the chemical re-equilibration of sea water with respect to CO2 variations.
The buffer factor is calculated from

- the set of equations for borate, silicate, phosphate, and carbonate equilibrium chemistry and
- the temperature-dependent equilibrium constants.

An additional source term is added to the model deep ocean to account for the oxidation of organic debris containing carbon removed in the surface ocean layer by photosynthesis and brought to the deep ocean by particulate settling.

To estimate the flux of CO2 between the terrestrial biosphere and the atmosphere, a 6 box, globally-aggregated, terrestrial-biosphere sub-model is coupled to the atmosphere box.
The six boxes represent

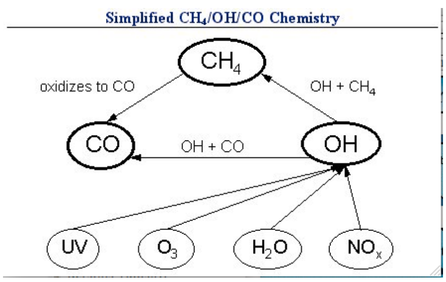
- ground vegetation,
- non-woody tree parts,
- woody tree parts,
- detritus,
- mobile soil (turn-over time 75 years),
- resistant soil (turnover time 500 years).

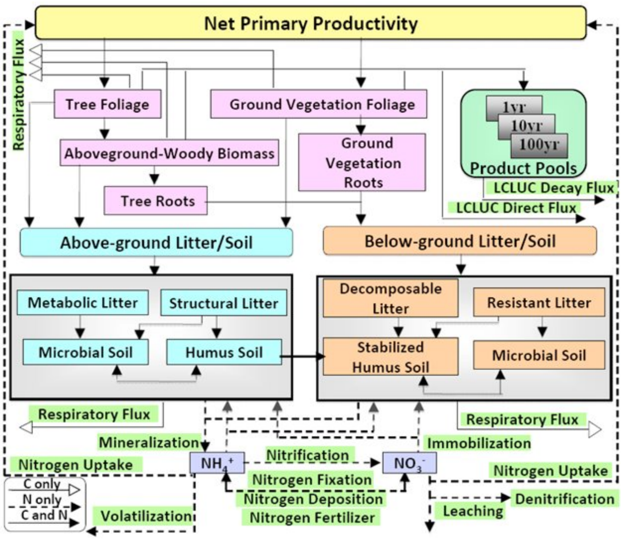
The mass of the carbon contained in the different terrestrial reservoirs and the rate of exchange between them have been based on the analysis by Kheshgi et al. (1996).

The photosynthetic rate of carbon fixation is modeled to increase logarithmically with atmospheric CO2 concentration and is proportional to a CO2 fertilization factor.
The rate of photosynthesis by terrestrial biota is thought to be stimulated by increasing atmospheric carbon dioxide concentration. The increase in the rate of photosynthesis, relative to preindustrial times, is modeled to be proportional to the logarithm of the relative increase in atmospheric CO2 concentration from its pre-industrial value of 278 ppm. The proportionality constant b, known as the CO2 fertilization factor, is chosen to be 0.42.

The rate coefficients for exchange to and from terrestrial biosphere boxes are temperature dependent according to an Arrhenius law.

This model does contain temperature feedbacks on carbon cycle through the
prescription of the temperature-dependent buffer factor, and
exchange (respiration and photosynthesis) raes to and from the biosphere boxes which follow the "Q10 formulation" described in Kheshgi et al. (1996).





Nitrogen attenuation of terrestrial carbon cycle response to global environmental factors

Atul Jain,1 Xiaojuan Yang,1 Haroon Kheshgi,2 A. David McGuire,3 Wilfred Post,4 and David Kicklighter5

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https://www.researchgate.net/publication/44792452_Nitrogen_attenuation_of_terrestrial_carbon_cycle_response_to_global_environmental_factors

Nitrogen cycle dynamics have the capacity to attenuate the magnitude of global terrestrial carbon sinks and sources driven by CO2 fertilization and changes in climate.

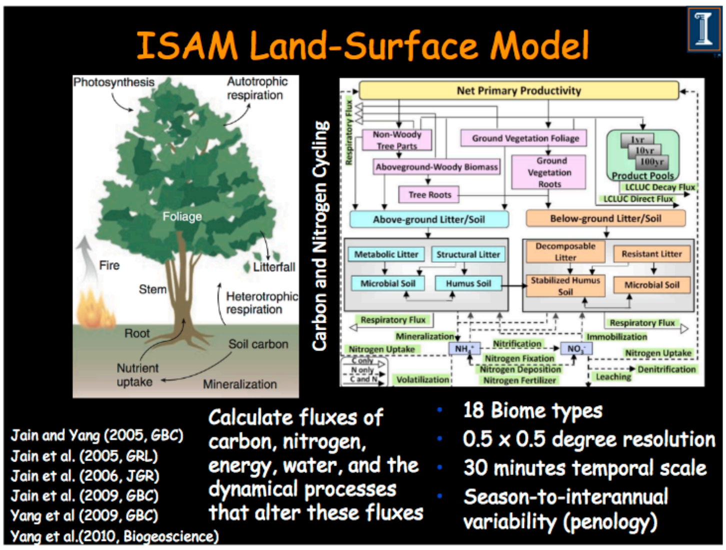
In this study, two versions of the terrestrial carbon and nitrogen cycle components of the Integrated Science Assessment Model (ISAM) are used to evaluate how variation in nitrogen availability influences terrestrial carbon sinks and sources in response to changes over the 20th century in global environmental factors including atmospheric CO2 concentration, nitrogen inputs, temperature, precipitation and land use. The two versions of ISAM vary in their treatment of nitrogen availability:

- ISAM-NC has a terrestrial carbon cycle model coupled to a fully dynamic nitrogen cycle while
- ISAM-C has an identical carbon cycle model but nitrogen availability is always in sufficient supply.

Overall, the two versions of the model estimate approximately the same amount of global mean carbon uptake over the 20th century. However, comparisons of results of ISAM-NC relative to ISAM-C reveal that nitrogen dynamics:

1. reduced the 1990s carbon sink associated with increasing atmospheric CO2 by 0.53 GtC/yr,
2. reduced the 1990s carbon source associated with changes in temperature and precipitation of 0.34 GtC/yr in the 1990s,
3. an enhanced sink associated with nitrogen inputs by 0.26 GtC/yr, and
4. enhanced the 1990s carbon source associated with changes in land use by 0.08 GtC/yr in the 1990s.

These effects of nitrogen limitation influenced the spatial distribution of the estimated exchange of CO2 with greater sink activity inhigh latitudes associated with climate effects and a smaller sink of CO2 in the southeastern United States caused by N limitation associated with both CO2 fertilization and forest regrowth. These results indicate that the dynamics of nitrogen availability are important to consider in assessing the spatial distribution and temporal dynamics of terrestrial carbon sources and sinks.



Quelle: Investigating the Role of Biogeochemical and Biophysical Processes in the Northern High Latitude (NHL) Using an Efficient Scalable Earth System
DOE's Climate and Earth System Modeling PI meeting, Washington, DC, 19-22 September 2011
Atul K Jain
Laxmikant Kalé, Rahul Barman, Celso Mendes,
Gengbin Zheng, Radha Nandkumar
University of Illinois, Urbana,
http://climate.atmos.uiuc.edu/atuljain/presentations/AtulJain_DOE_PI_Meeting_WahingtonDC.pdf

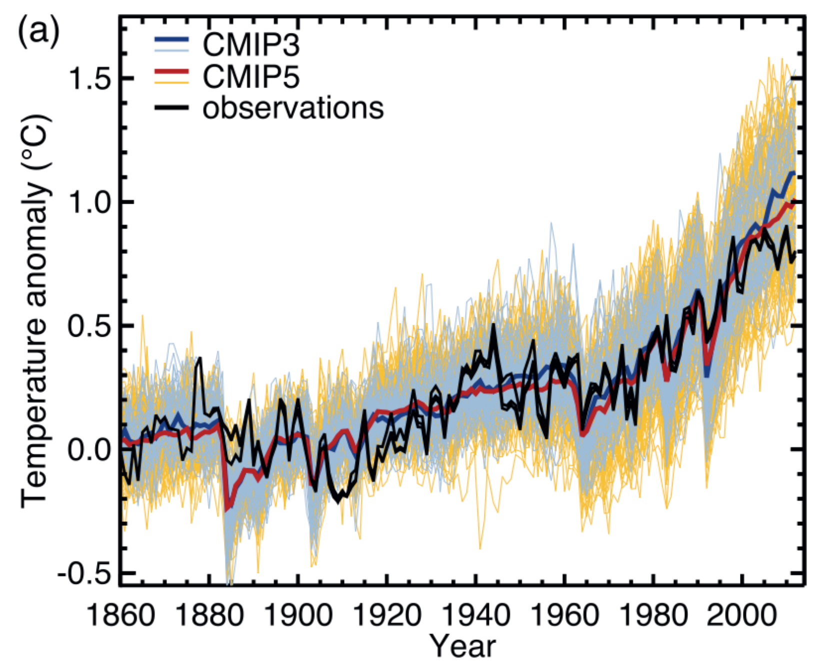


Figure TS.9 | Three observational estimates of global mean surface temperature (black lines) from

- the Hadley Centre/Climatic Research Unit gridded surface temperature data set 4 (HadCRUT4),
- Goddard Institute for Space Studies Surface Temperature Analysis (GISTEMP), and
- Merged Land–Ocean Surface Temperature Analysis (MLOST),

compared to model simulations

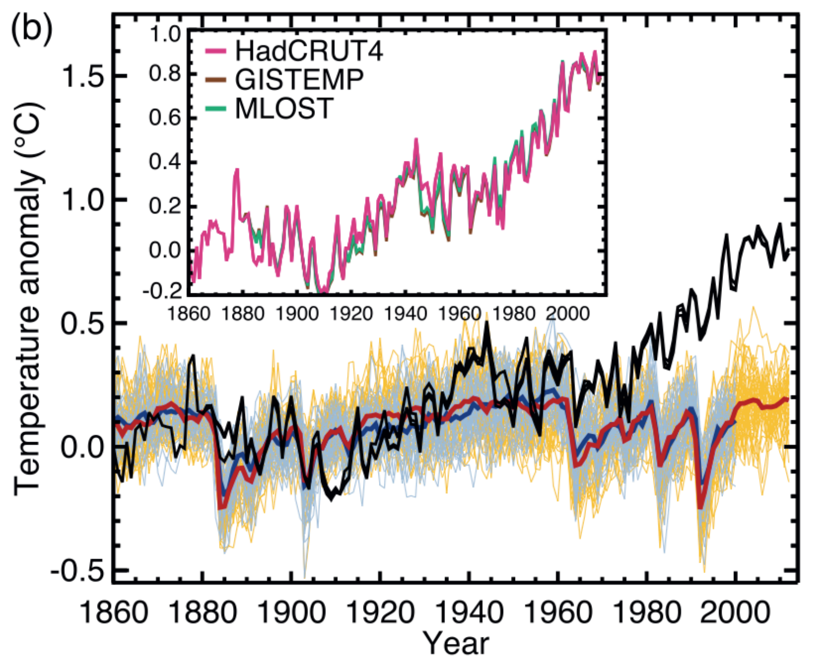
- (CMIP3 models — thin blue lines and
- CMIP5 models — thin yellow lines)

with

a. anthropogenic and natural forcings (a),
b. natural forcings only (b) and
c. greenhouse gas forcing only (c).

Thick red and blue lines are averages across all available CMIP5 and CMIP3 simulations respectively.

All simulated and observed data were masked using the HadCRUT4 coverage (as this data set has the most restricted spatial coverage), and global average anomalies are shown with respect to 1880–1919, where all data are first calculated as anomalies relative to 1961–1990 in each grid box.



Inset to (b) shows the three observational data sets distinguished by different colours. {Figure 10.1}

Figure TS.9 | Three observational estimates of global mean surface temperature (black lines) from

- the Hadley Centre/Climatic Research Unit gridded surface temperature data set 4 (HadCRUT4),
- Goddard Institute for Space Studies Surface Temperature Analysis (GISTEMP), and
- Merged Land–Ocean Surface Temperature Analysis (MLOST),

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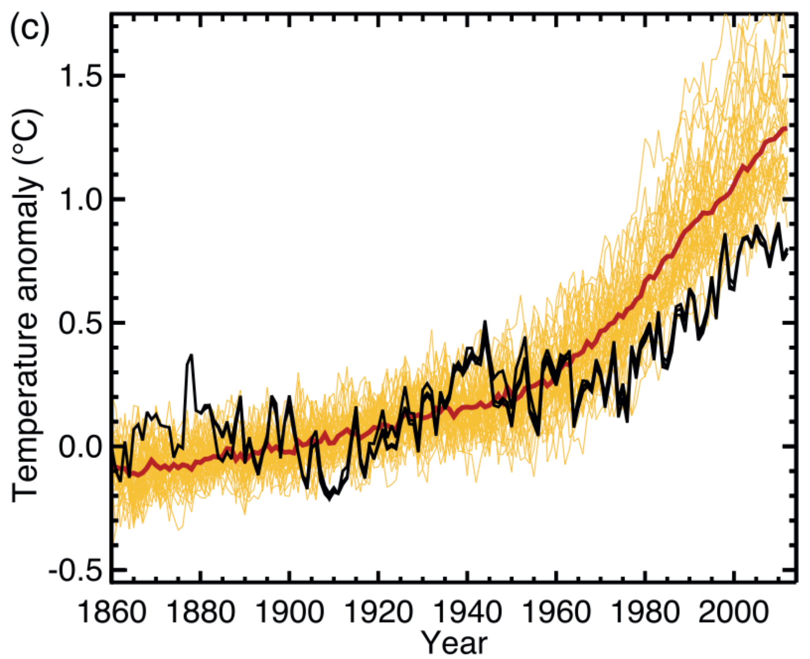

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compared to model simulations
- (CMIP3 models — thin blue lines and
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with
a. anthropogenic and natural forcings (a),
b. natural forcings only (b) and
c. greenhouse gas forcing only (c).

Thick red and blue lines are averages across all available CMIP5 and CMIP3 simulations respectively.

All simulated and observed data were masked using the HadCRUT4 coverage (as this data set has the most restricted spatial coverage), and global average anomalies are shown with respect to 1880–1919, where all data are first calculated as anomalies relative to 1961–1990 in each grid box.

MAGICC

M. Meinshausen1, S. C. B. Raper2, and T. M. L. Wigley3,
Emulating coupled atmosphere-ocean and carbon cycle models with a simpler model, MAGICC6 – Part 1: Model description and calibration,
Atmos. Chem. Phys., 11, 1417–1456, 2011
www.atmos-chem-phys.net/11/1417/2011/
doi:10.5194/acp-11-1417-2011
(im Cache)

MAGICC has a
- hemispherically averaged upwelling- diffusion ocean
- coupled to
  - an atmosphere layer and
  - a globally averaged carbon cycle model

As with most other simple models, MAGICC evolved from a simple global average energy-balance equation.

While MAGICC is designed to provide maximum flexibility in order to match different types of responses seen in more sophisticated models, the approach in MAGICC's model development has always been to derive the simple equations as much as possible from key physical and biological processes. In other words, MAGICC is as simple as possible, but as mechanistic as necessary.

3.1 Introduction of variable climate sensitivities
Climate sensitivity (DT2×) is a useful metric to compare models and is usually defined as the equilibrium global-mean warming after a doubling of CO2 concentrations. In the case of MAGICC, the equilibrium climate sensitivity is a primary model parameter that may be identified with the eventual global-mean warming that would occur if the CO2 concentra- tions were doubled from pre-industrial levels. Climate sensitivity is inversely related to the feedback factor λ:

DT2× = DQ2×/ λ

where DT2× is the climate sensitivity, and DQ2× the radiative forcing after a doubling of CO2 concentrations.

Note that time-varying effective sensitivities are not only empirically observed in AOGCMs, but they are necessary here in order for MAGICC to accurately emulate AOGCM results. Alternative parameterizations to emulate time- variable climate sensitivities are possible, e.g. assuming a dependence on temperatures instead of forcing, or by imple- menting indirect radiative forcing effects that are most often regarded as feedbacks (see Sect. 6.2). However, this study chose to limit the degrees of freedom with respect to time- variable climate sensitivities given that a clear separation into three (or more) different parameterizations seemed unjustified based on the AOGCM data analyzed here.

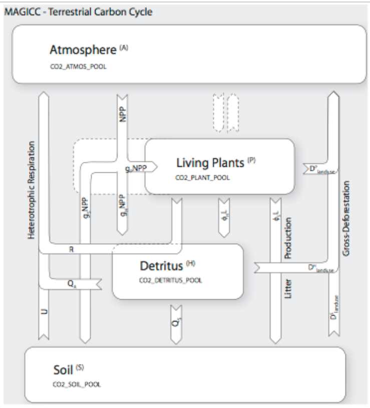


Fig. A2. The terrestrial carbon cycle component in MAGICC with its carbon pools (atmosphere, living plants, detritus, soil) and carbon fluxes. For description of the pools and fluxes, including the treatment of temperature feedbacks and CO2 fertilization, see table below
Quelle: M. Meinshausen, S. C. B. Raper, and T. M. L. Wigley, Emulating coupled atmosphere-ocean and carbon cycle models with a simpler model, MAGICC6 – Part 1: Model description and calibration
Atmos. Chem. Phys., 11, 1417–1456, 2011
www.atmos-chem-phys.net/11/1417/2011/
Cache: http://acamedia.info/sciences/sciliterature/globalw/reference/aeg-ag/literatur/archer(s_recommendatons)/MAGICC/meinshausen_MAGICC_acp-11-1417-2011.pdf

MAGICC Terrestrial Carbon Cycle
http://acamedia.info/sciences/sciliterature/globalw/reference/aeg-ag/literatur/archer(s_recommendatons)/MAGICC/meinshausen_MAGICC_acp-11-1417-2011_figA2.png

MAGICC's terrestrial carbon cycle model is a globally integrated box model. ... The MAGICC6 carbon cycle can emulate temperature-feedback effects on the heterotrophic respiration carbon fluxes. One improvement in MAGICC6 allows increased flexibility when accounting for CO2 fertilization. This increase in flexibility allows a **better fit** to some of the more complex carbon cycle models reviewed in C4MIP.

It is alinear pool system with constant coefficients with variables
NPP being Net Plant Production - for simplification NPP = P (see row 1 column 1 of table below)
C being the amount of carbon in the atmosphere compartment

and with fluxes

R, Q, U external parameters taken from e.g. IPCC WGI AR5, Figure 6.1 | Simplified schematic of the global carbon cycle http://www.climatechange2013.org/images/figures/WGI_AR5_Fig6-1_errata.jpg

carbon in atmosphere $DC/Dt = E_{foss} + E_{landuse} + E_{fCH4} - F_{ocn} - F_{terr}$	E_{foss} CO2 emissions from fossil and industrial sources $E_{landuse}$ directly human induced CO2 emissions/removals from/to terrestrial biosphere E_{fCH4} emissions due to oxidized methane of fossil fuel origin F_{ocn} flux due to ocean carbon uptake F_{terr} net carbon uptake or release by terrestrial biosphere due to CO2 fertilization and climate feedback
carbon in living plant (P), P = NPP (see right column) $DP/Dt = g_p P - R - o_H L - D^P_{landuse}$	- woody material, leaves/needles, grass, and roots, but does not include the rapid turnover part of living biomass, which can be assumed to have a zero lifetime on the timescales of interest here (dashed extension of plant box P in Fig. A2). - Thus, a fraction of gross primary product (GPP) cycles through the plant box directly back to the atmosphere due to autotrophic respiration and can be ignored (dashed arrows). Only the remaining part of GPP, namely the net primary production NPP is simulated. - $g_p = 0.35$ - R = heterotrophic respiration (life that feeds on plants) - L = litter production - D = gross deforestation -

carbon in detritus ("humus" H), P = NPP
$DH/Dt = g_H P + o_H L - Q_A - Q_S - D^H_{landuse}$
	- $g_H = 0.60$
	- $o_H = 0.98$
	- source: litter production (o_H L), sink to atmosphere
	  - due to land use ($D^H_{landuse}$)
	  - to atmosphere:
	    - non-land use related oxidation (Q_A)
	    - to soil: (Q_S)

carbon in soil organic matter (S), P = NPP $DS/Dt = g_S P + o_S L + Q_S - U - D^S_{landuse}$	- $g_S = 0.05$ - $o_S = 0.02$ - source: litter production (o_S L), detritus (Q_S), - sink: flux to atmosphere due to land use ($D^S_{landuse}$), non-land use related oxidation (U)
flux $L_o = P_o / t_o^P$ flux $Q_o = H_o / t_o^H$ flux $U_o = S_o / t_o^S$	- decay rates (fluxes L, Q, U) are assumed to be proportional to the pool's masses P, H, S (linear system) - turnover times t^P, t^H, t^S determined by steady state conditions ($_o$)

David Archers carbon cycle

- *land surface* = biosphere and surface soil. carbon in this compartment is on the surface and in good contact with atmosphere - contrary to the fossil carbon that's buried deep inside the earth (in the solid earth). this compartment is governed by the plants. plants give off carbon at a rate of 100 Gt/year
- *atmosphere* to ocean carbon transfer rate = 100 Gt/year - seems to be wrong. see down below 2.5 Gt C/year
- solid earth = alles unterhalb von land surface, zB die fossil fuels
- *Climate sensitivity*
  - climate sensitivity DT2x = temperature increase when doubling CO2 concentration in atmosphere (climate sensitivty to doubling CO2 concentration)
  - DT2x. A middle-of-the-road estimate for DT2x is 3^o C.
  - If we wish to think about other forcings than CO2, we can express the climate sensitivity as temperature change per W/m2 of heat forcing. A typical estimate DT/(W/m2) would be 0.75^O C / (W/m2).

temperature output data from the Hadley Centre coupled climate model.
http://geosci.uchicago.edu/~archer/PS134/lab.hadley.htm

The Hadley Center is the climate-modeling arm of the UKMO (United Kingdom Met. Office), located in Reading, England. It is one of the world's major general-circulation modeling groups, and has played a particularly important role in the conclusions of the current IPCC report. This model is widely regarded as having perhaps the most sophisticated and accurate physical parameterizations.

2.SM Mitigation Pathways Compatible with 1.5°C in the Context of Sustainable Development – Supplementary Material

page 2SM-2
2.SM.1 Part 1
2.SM.1.1 Geophysical Relationships and Constraints
2.SM.1.1.1 Reduced-complexity climate models
(im Cache)

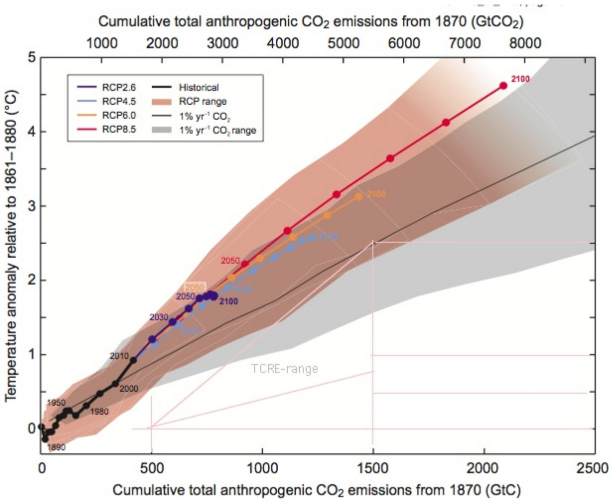
The '**Model for the Assessment of Greenhouse Gas Induced Climate Change' (MAGICC6**, Meinshausen et al., 2011a), is a reduced-complexity carbon cycle, atmospheric composition and climate model that has been widely used in prior IPCC Assessments and policy literature. This model is used with its parameter set as identical to that employed in AR5 for backwards compatibility. This model has been shown to match temperature trends very well compared to **CMIP5** models (Collins et al., 2013; Clarke et al., 2014).

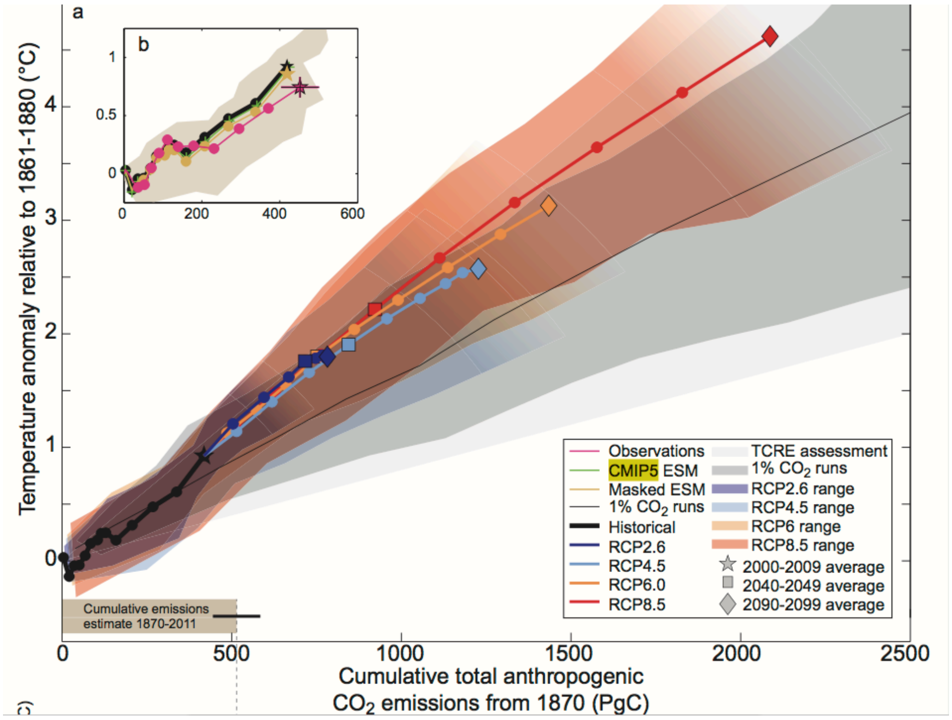
The '**Finite Amplitude Impulse Response' (FAIRv1.3**, Smith et al., 2018) model is similar to MAGICC but has even simpler representations of the carbon cycle and some atmospheric chemistry. Its parameter sets are based on AR5 physics with updated methane radiative forcing (Etminan et al., 2016). The FAIR model is a reasonable fit to CMIP5 models for lower emissions pathways but underestimates the temperature response compared to CMIP5 models for RCP8.5 (Smith et al., 2018). It has been argued that its near-term temperature trends are more realistic than MAGICC (Leach et al., 2018).

... There are ... differences in
- their ranges of climate sensitivity,
- their choice of carbon cycle parameters, and
- how they are constrained, even though both models are consistent with AR5 ranges.

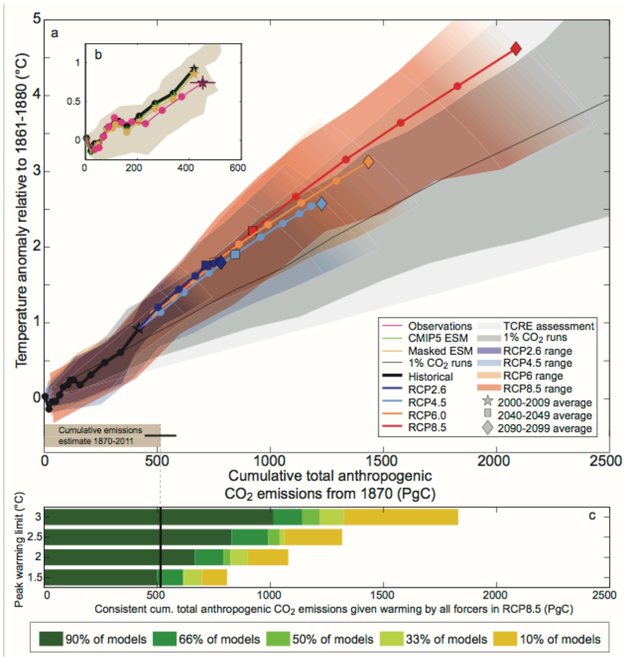
Overall, their temperature trends are similar for the range of emission trajectories (Figure 2.1 of the main report). ... Leach et al. (2018) also note that that MAGICC warms more strongly than current warming rates.
- By adjusting FAIR parameters to match those in MAGICC, more than half the difference in mean near-term warming trends can be traced to parameter choices.
- The remaining differences are due to choices regarding model structure (Figure 2.SM.1).

... The veracity of these reduced-complexity climate models is a substantial knowledge gap in the overall assessment of pathways and their temperature thresholds.





Source of the above Figure: WG1AR5_all_final_TFE.8_fig1, page 104 (large version)



TFE.8, Figure 1 I Global mean temperature increase since 1861–1880 as a function of *cumulative total global CO2 emissions* from various lines of evidence.

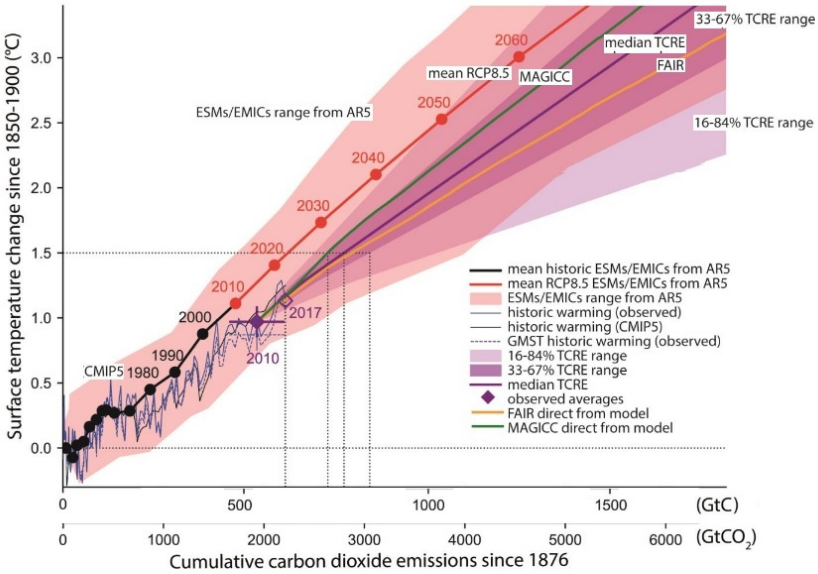
a) Decadal average results are shown over all CMIP5 Earth System Model of Intermediate Complexity (EMICs) and Earth System Models (ESMs) for each RCP respectively, with coloured lines (multi-model average), decadal markers (dots) and with three decades (2000–2009, 2040–2049 and 2090–2099) highlighted with a star, square and diamond, respectively.
   - The historical time period up to decade 2000–2009 is taken from the CMIP5 historical runs prolonged by RCP8.5 for 2006–2010 and is indicated with a black thick line and black symbols.
   - Coloured ranges illustrate the model spread (90% range) over all CMIP5 ESMs and EMICs and do not represent a formal uncertainty assessment.
   - Ranges are filled as long as data of all models is available and until peak temperature. They are faded out for illustrative purposes afterward.
   - CMIP5 simulations with 1% yr–1 CO2 increase only are illustrated by the dark grey area (range definition similar to RCPs above) and the black thin line (multi- model average).
   - The light grey cone represents this Report's assessment of the transient climate response to emissions (TCRE) from CO2 only.
   - Estimated cumulative historical CO2 emissions from 1870 to 2011 with associated uncertainties are illustrated by the grey bar at the bottom of (a).

b) Comparison of historical model results with observations.
   - The magenta line and uncertainty ranges are based on observed emissions from Carbon Dioxide Information Analysis Center (CDIAC) extended by values of the Global Carbon project until 2010 and observed temperature estimates of the Hadley Centre/Climatic Research Unit gridded surface temperature data set 4 (HadCRUT4).
   - The uncertainties in the last decade of observations are based on the assessment in this report.
   - The black thick line is identical to the one in (a).
   - The thin green line with crosses is as the black line but for ESMs only.
   - The yellow-brown line and range show these ESM results until 2010, when corrected for HadCRUT4's incomplete geographical coverage over time.
   - All values are given relative to the 1861–1880 base period.
   - All time-series are derived from decadal averages to illustrate the long-term trends.
   - Note that observations are in addition subject to internal climate variability, adding an uncertainty of about 0.1°C.

c) Cumulative CO2 emissions over the entire industrial era, consistent with four illustrative peak global temperature limits (1.5°C, 2°C, 2.5°C and 3°C, respectively) when taking into account warming by all forcers.
   - Horizontal bars indicate consistent cumulative emission budgets as a function of the fraction of models (CMIP5 ESMs and EMICs) that at least hold warming below a given temperature limit.
   - Note that the fraction of models cannot be interpreted as a probability.
   - The budgets are derived from the RCP8.5 runs, with relative high non-CO2 forcing over the 21st century.
   - If non-CO2 are significantly reduced, the CO2 emissions compatible with a specific temperature limit might be slightly higher, but only to a very limited degree, as illustrated by the other coloured lines in (a), which assume significantly lower non-CO2 forcing.
   - Further detail regarding the related Figure SPM.10 is given in the TS Supplementary Material. {Figure 12.45}

Source of the above Figure: http://acamedia.info/sciences/sciliterature/globalw/reference/ipcc/ar5/WG1AR5_all_final_TFE.8_fig1c.png, page 104

Quelle: IPCC SR15, Chapter 2



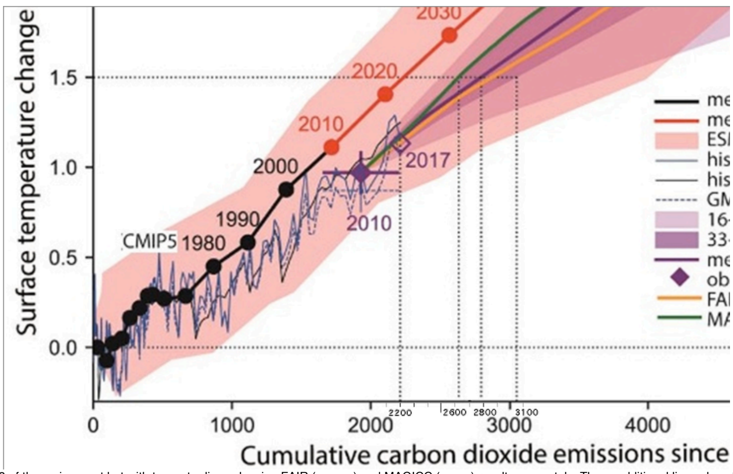


Figure 2.SM.3: This figure follows Figure 2.3 of the main report but with two extra lines showing FAIR (orange) and MAGICC (green) results separately. These additional lines show the full model response averaged across all scenarios and geophysical parameters.

TCRE = Transient climate response to cumulative CO2 emissions (transient global average surface temperature change per unit cumulative CO2 emissions, usually 1000 GtC) combines both information
- on the airborne fraction of cumulative CO2 emissions (the fraction of the total CO2 emitted that remains in the atmosphere, which is determined by carbon cycle processes) and
- on the transient climate response (TCR).

See also Transient climate response (under Climate sensitivity).

Climate Change 2013 The Physical Science Basis
Working Group I Contribution to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change
WGIAR5_all_final,
Chapter 12
page 1033

Climate Stabilization

The principal driver of long-term warming is total emissions of CO2 and the two quantities are approximately linearly related.
- The global mean warming per 1000 GtC ("transient climate response to cumulative carbon emissions", *TCRE*)) is likely between 0.8°C and 2.5°C per 1000 GtC, for cumulative emissions less than about 2000 GtC until the time at which temperatures peak (see the two figures above with full TCRE-range, 16-84% TCRE range and 33-67% TCRE range indicated).
- To limit the warming caused by anthropogenic CO2 emissions alone to be likely less than 2°C relative to the period 1861-1880, total CO2 emissions from all anthropogenic sources would need to be *limited to a cumulative budget of about 1000 GtC* [= 3700 GtCO2] since that period.
- About
  - 500 [445 to 585] GtC
  - 1840 (1630 to 2150) GtCO2
- of this budget was already emitted by 2011.
- a lower budget. {12.5.4, Figures 12.45, 12.46, Box 12.2} is required
  - accounting for projected warming effect of non-CO2 forcing,
  - a possible release of GHGs from permafrost or methane hydrates,
  - or requiring a higher likelihood of temperatures remaining below 2°C, all imply

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Quelle des folgenden Textes: IPCC SR15, Chapter 2, pages 103 - 106

Several **feedbacks** of the Earth system, involving
- the carbon cycle,
- non- CO2 GHGs and/or
- aerosols,

may also impact the future dynamics of the coupled carbon–climate system's response to anthropogenic emissions. These feedbacks are caused by the effects of
- nutrient limitation (Duce et al., 2008; Mahowald et al., 2017),
- ozone exposure (de Vries et al., 2017),
- fire emissions (Narayan et al., 2007) and
- changes associated with natural aerosols (Cadule et al., 2009; Scott et al., 2018).

Permafrost

Among these Earth system feedbacks, the importance of the *permafrost feedback's* influence has been highlighted in recent studies. Combined evidence from both
- models (MacDougall et al., 2015; Burke et al., 2017; Lowe and Bernie, 2018) and
- field studies (like Schädel et al., 2014; Schuur et al., 2015)

shows high agreement that permafrost thawing will release both CO2 and CH4 as the Earth warms, amplifying global warming. This thawing could also release N2O (Voigt et al., 2017a, b).
Field, laboratory and modelling studies estimate that
the vulnerable fraction in permafrost is about 5–15% of the permafrost soil carbon (*~5300–5600 GtCO2* in Schuur et al., 2015) [0.05 * 5300 = 265; 0.15 * 5600 = 840] and that
carbon emissions are expected to occur beyond 2100 because of system inertia and the large proportion of slowly decomposing carbon in permafrost (Schädel et al., 2014).

Published model studies suggest that a large part of the carbon release to the atmosphere is in the form of CO2 (Schädel et al., 2016), while the amount of CH4 released by permafrost thawing is estimated to be much smaller than that CO2.
- Cumulative CH4 release by 2100 under RCP2.6 ranges from *0.13 to 0.45 Gt of methane* (Burke et al., 2012; Schneider von Deimling et al., 2012, 2015), with
- fluxes being the highest in the middle of the century because of maximum thermokarst lake extent by mid-century (Schneider von Deimling et al., 2015).

The reduced complexity climate models employed in this assessment do not take into account permafrost or non-CO2 Earth system feedbacks, although the MAGICC model has a permafrost module that can be enabled. Taking the current climate and Earth system feedbacks understanding together, there is a possibility that these models would underestimate the longer-term future temperature response to stringent emission pathways (Section 2.2.2).

pages 104 ff of IPCC SR15, Chapter 2

2.2.2 The Remaining 1.5°C Carbon Budget

The remaining carbon budget calculation presented in the Table 2.2 and illustrated in Figure 2.3 does not consider additional Earth system feedbacks such as permafrost thawing. These are uncertain but estimated to reduce the remaining carbon budget by an order of magnitude of about *100 GtCO2 and more thereafter.* Accounting for such feedbacks would make the carbon budget more applicable for 2100 temperature targets, but would also increase uncertainty (Table 2.2 and see below).

Excluding such feedbacks, the assessed range for the remaining carbon budget is estimated to be
- 840, 580, and 420 GtCO2 for the
- 33rd, 50th and, 67th percentile of TCRE, respectively, with a median non-CO2 warming contribution and starting from 1 January 2018 onward.

Consistent with the approach used in the IPCC Fifth Assessment Report (IPCC, 2013b), the latter estimates use *global near-surface air temperatures both over the ocean and over land* to estimate global surface temperature change since pre- industrial.

The global warming from the pre-industrial period until the 2006–2015 reference period is estimated to amount to *0.97°C with an uncertainty range of about ±0.1°C* (see Chapter 1, Section 1.2.1).

Three methodological improvements lead to these estimates of the remaining carbon budget being about 300 GtCO2 larger than those reported in Table 2.2 of the IPCC AR5 SYR (IPCC, 2014a) (medium confidence).

The AR5 used 15 Earth System Models (ESM) and 5 Earth-system Models of Intermediate Complexity (EMIC) to derive an estimate of the remaining carbon budget. Their approach hence made implicit assumptions about
- the level of warming to date,
- the future contribution of non-CO2 emissions, and
- the temperature response to CO2 (TCRE).

In this report, each of these aspects are considered explicitly.

When estimating *global warming until the 2006–2015* reference period as *a blend of near-surface air temperature over land and sea-ice regions, and sea-surface temperature over open ocean*, by averaging the four global mean surface temperature time series listed in Chapter 1 Section 1.2.1, the global warming would amount to *0.87°C ±0.1°C.*

Using the latter estimate of historical warming and projecting global warming using global near-surface air temperatures from model projections leads to remaining carbon budgets for limiting global warming to 1.5°C of
1080, 770, and 570 GtCO2 for the
33rd, 50th, and 67th percentile of TCRE, respectively.

Note that future research and ongoing observations over the next years will provide a better indication as to how the 2006–2015 base period compares with the long-term trends and might affect the budget estimates. Similarly, improved understanding in Earth system feedbacks would result in a better quantification of their impacts on remaining carbon budgets for 1.5°C and 2°C.

Joeri Rogelj, Piers M. Forster, Elmar Kriegler, Christopher J. Smith & Roland Séférian,
Estimating and tracking the remaining carbon budget for stringent climate targets,
Nature volume 571, pages 335–342 (2019), published: 17 July 2019

for more go to TCRE.rtfd in aeg-ag/topics

A series of studies over the past decade has clarified and quantified why the rise in global average temperature increase is roughly proportional to the total cumulative amount of CO2 emissions produced by human activities since the industrial revolution [4 - 13]. This literature has allowed scientists to *define* the linear relationship between warming and cumulative CO2 emissions as the transient climate response to cumulative emissions of CO2 (TCRE).

Once established, the appeal of this concept became immediately evident: the possibility that the response of an enormously complex system—such as the response of planet Earth to our emissions of CO2—could potentially be reduced to a roughly linear relationship would allow scientists to infer clear and easy-to-communicate implications.

However, additional processes that influence and are influenced by future warming,
- such as the thawing of permafrost, have recently been included in models that simulate the Earth system. These additional processes add uncertainty and may change our understanding of this linear relationship.
- Moreover, global warming is not driven by emissions of CO2 only. Other greenhouse gases (such as methane, fluorinated gases or nitrous oxide) and aerosols and their precursors (including soot or sulphur dioxide) affect global temperatures.

Estimating the remaining carbon budget thus also implies making assumptions about these non-CO2 contributions. This further complicates the relationship between future CO2 emissions and global warming.

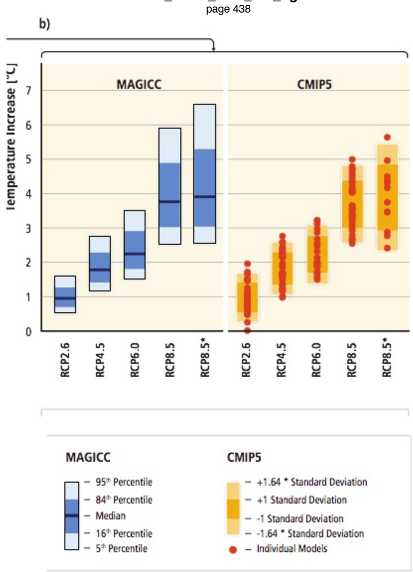
Remaining carbon budget framework

We present in the following equation an estimate of the remaining carbon budget (Blim) for a specific temperature change limit (Tlim) as a function of 5 terms that represent aspects of the geophysical and coupled human–environment system (equation (1):
1. the historical human-induced warming to date (Thist),
2. the non-CO2 contribution to future temperature rise (TnonCO2),
3. the zero-emissions commitment (TZEC),
4. the TCRE, and
5. an adjustment term for sources of unrepresented Earth system feedback (EEsfb).

These terms are visualized in Fig. 1 and are described and discussed in turn below.

$B_{lim} = (T_{lim} – T_{hist} – T_{nonCO2} – T_{ZEC})/TCRE – E_{Esfb}$

IPCC_WGIII_AR5_full_fig6.12
page 438



for normally distributed temperatures:
+1.65 standard deviations = 95th percentile
+1 standard deviation = 84th Percentile
median = 50th percentile
-1 standard deviation = 16th Percentile
-1.64 Standard Deviations = 5th Percentile
(see https://www.dummies.com/education/math/statistics/figuring-out-percentiles-for-a-normal-distribution/)
percentiles = 100 * quartiles. Quartiles = cdf. Percentiles and quartiles are defined for a normal distribution

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SYR_AR5_FINAL_full
page 78 of SYR_AR5_FINAL_full

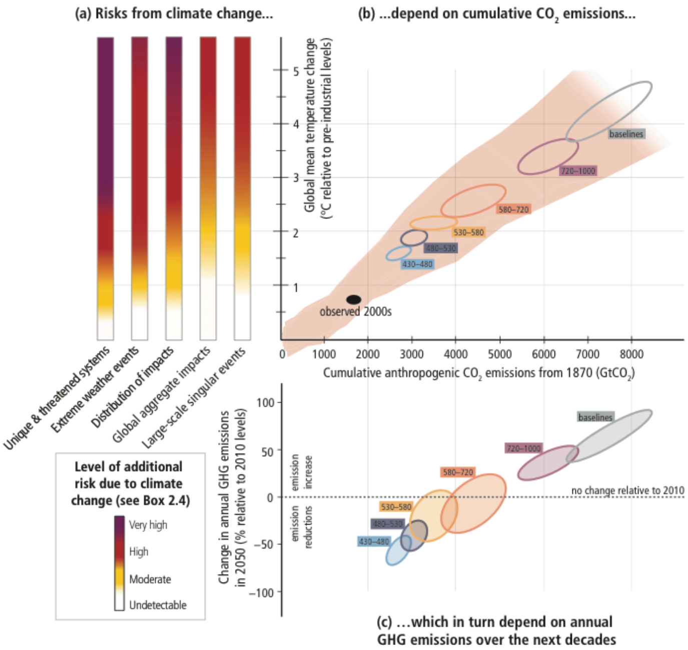

Figure 3.1 | The relationship between risks from climate change, temperature change, cumulative carbon dioxide (CO_2) emissions and changes in annual greenhouse gas (GHG)

Figure 3.1 I The relationship between risks from climate change, temperature change, cumulative carbon dioxide (CO2) emissions and changes in annual greenhouse gas (GHG) emissions by 2050.
Panel b links temperature changes to cumulative CO2 emissions (in GtCO2), from 1870. They are based

- on Coupled Model Intercomparison Project Phase 5 (*CMIP5*) simulations (*pink plume*) and
- on a *simple climate model* (median climate response in 2100) for the baselines and five mitigation scenario categories (*six ellipses*).

Details are provided in Figure 2.3.

Panel c shows the relationship between the cumulative CO2 emissions (in GtCO2) of the scenario categories and their associated change in annual GHG emissions by 2050, expressed in percentage change (in percent GtCO2-eq per year) relative to 2010. The ellipses correspond to the same scenario categories as in Panel b, and are built with a similar method (see details in Figure 2.3).

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page 63 of SYR_AR5_FINAL_full

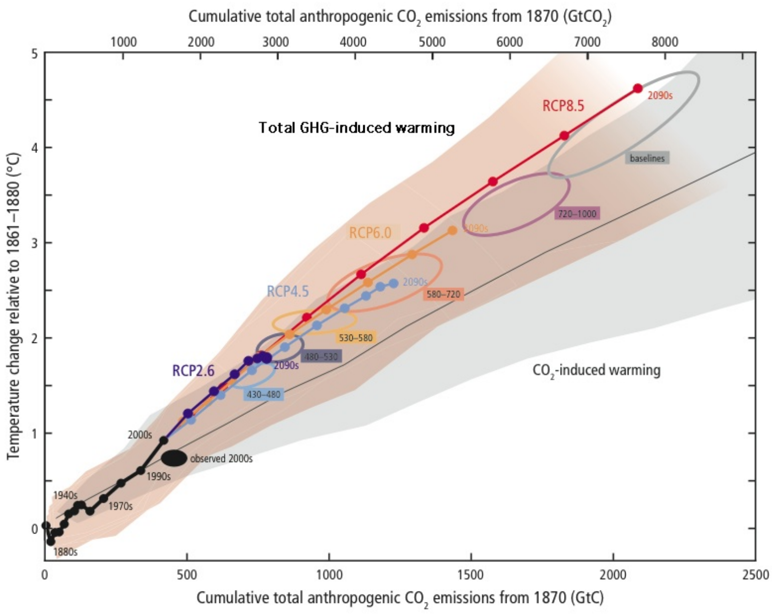

Figure 2.3 I Global mean surface temperature increase as a function of cumulative total global carbon dioxide (CO2 only, no other C-species!) emissions from various lines of evidence.

- *Multi-model results from a hierarchy of climate / carbon-cycle models* for each Representative Concentration Pathway (RCP) until 2100 are shown (*coloured lines*).
- The *coloured plume* illustrates the *multi-model spread over the four RCP scenarios* and fades with the decreasing number of available models in RCP8.5.
  - The multi-model mean and range simulated by CMIP5 models, forced by a CO2 [exclusively CO2] increase of 1% per year (*1% yr–1 CO2 simulations*), is given by the thin black line and grey area (centered around thin black line). For a specific amount of cumulative CO2 emissions, the 1% per year CO2 simulations exhibit lower warming than those driven by RCPs, which include additional non-CO2 forcings.
- Model results over the historical period (1860 to 2010) are indicated in black.
- Dots indicate decadal averages, with selected decades labelled.
- *Ellipses* show total anthropogenic warming in 2100 versus cumulative CO2 emissions from 1870 to 2100 from a simple climate model [*MAGICC*?] (median climate response) under the scenario categories [x-z] used in WGIII.
- Temperature values are always given relative to the 1861–1880 period, and emissions are cumulative since 1870.
- Black filled ellipse shows observed emissions to 2005 and observed temperatures in the decade 2000–2009 with associated uncertainties.

{WGI SPM E.8, TS TFE.8, Figure 1, TS.SM.10, 12.5.4, Figure 12.45, WGIII Table SPM.1, Table 6.3}

Climate Change 2013 The Physical Science Basis
Working Group I Contribution to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change
WGIAR5_all_final, page 28

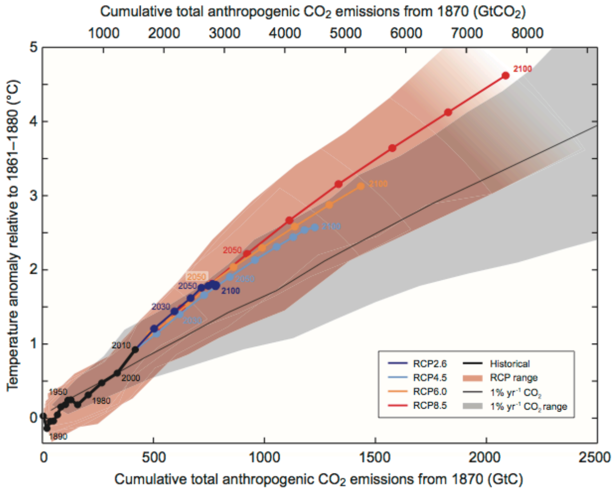

Figure SPM.10 I Global mean surface temperature increase as a function of cumulative total global CO2 emissions from various lines of evidence.

- Multi-model results from a hierarchy of climate / carbon-cycle models for each RCP until 2100 are shown with coloured lines and decadal means (dots). Some decadal means are labeled for clarity (e.g., 2050 indicating the decade 2040–2049).
- The coloured plume illustrates the multi-model spread over the four RCP scenarios and fades with the decreasing number of available models in RCP8.5.
- The multi-model mean and range simulated by CMIP5 models, forced by a CO2 increase of 1% per year (1% yr–1 CO2 simulations), is given by the thin black line and grey area (centered around thin black line). For a specific amount of cumulative CO2 emissions, the 1% per year CO2 simulations exhibit lower warming than those driven by RCPs, which include additional non-CO2 forcings.
- Temperature values are given relative to the 1861–1880 base period, emissions relative to 1870. Decadal averages are connected by straight lines.
- Model results over the historical period (1860 to 2010) are indicated in black.
- For further technical details see the Technical Summary Supplementary Material. {Figure 12.45; TS TFE.8, Figure 1}

Chapter 12
page 1033
Climate Stabilization
The principal driver of long-term warming is total emissions of CO2 and the two quantities are approximately linearly related.
The global mean warming per 1000 GtC (transient climate response to cumulative carbon emissions (TCRE)) is likely between *0.8°C to 2.5°C per 1000 GtC*, for cumulative emissions less than about 2000 GtC until the time at which temperatures peak.
To limit the warming caused by anthropogenic CO2 emissions alone to be likely less than 2°C relative to the period 1861-1880,

- total CO2 emissions from all anthropogenic sources would need to be limited to a cumulative budget of about 1000 GtC since that period.
- About half [445 to 585 GtC] of this budget was already emitted by 2011.
- Accounting for projected warming effect of non-CO2 forcing, a possible release of GHGs from permafrost or methane hydrates, or requiring a higher likelihood of temperatures remaining below 2°C, all imply a lower budget. {12.5.4, Figures 12.45, 12.46, Box 12.2}

Some aspects of climate will continue to change even if temperatures are stabilized.

- Processes related to vegetation change,
- changes in the ice sheets,
- deep ocean warming and associated sea level rise and
- potential feedbacks linking for example ocean and the ice sheets

have their own intrinsic long time scales and may result in significant changes hundreds to thousands of years after global temperature is stabilized. {12.5.2 to 12.5.4}

CMIP5 models
Quelle: Paris Climate Agreement: Beacon of Hope, 2017_Book_ParisClimateAgreementBeaconOfH, page 95

1. ACCESS1.0 2. ACCESS3.0 3. BCC-CSM1.1 4. BCC-CSM1.1(m) 5. BNU-CSM

6. CCSM4 7. CESM1(BGC) 8. CESM1(CAM5) 9. CMCC-CESM 10. CMCC-CM 11. CMCC-CMS 12. CNRM-CM5 13. CSIRO-Mk3.6.0 14. CanCM4 15. CanESM2 16. EC-EARTH 17. FGOALS-g2 18. FIO-ESM 19. GFDL-CM2.1 20. GFDL-CM3 21. GFDL-ESM2G

22. GFDL-ESM2M 23. GISS-E2-H 24. GISS-E2-H-CC 25. GISS-E2-R

26. GISS-E2-R-CC 27. HadCM3 28. HadGEM2-CC 29. HadGEM2-ES 30. INM-CM4

31. IPSL-CM5A-LR 32. IPSL-CM5A-MR 33. IPSL-CM5B-LR 34. MIROC-ESM 35. MIROC-ESM-CHEM 36. MIROC4h

37. MIROC5 38. MPI-EMS-LR 39. MPI-ESM-MR 40. MRI-CGCM3 41. NorESM1-M 42. NorESM1-ME

CMIP5 - Coupled Model Intercomparison Project Phase 5 - Overview

At a September 2008 meeting involving *20 climate modeling groups* from around the world, the WCRP's Working Group on Coupled Modelling (WGCM), with input from the IGBP AIMES project, agreed to promote a new set of coordinated climate model experiments. These experiments comprise the fifth phase of the Coupled Model Intercomparison Project (CMIP5). CMIP5 will notably provide a multi-model context for

1. assessing the mechanisms responsible for model differences in poorly understood feedbacks associated with the carbon cycle and with clouds,
2. examining climate "predictability" and exploring the ability of models to predict climate on decadal time scales, and, more generally,
3. determining why similarly forced models produce a range of responses.

It is expected that some of the scientific questions that arose during preparation of the Intergovernmental Panel on Climate Change (IPCC) Fourth Assessment Report (AR4) will through CMIP5 be addressed in time for evaluation in the Fifth Assessment Report (AR5, scheduled for publication in late 2013).

CMIP5 is meant to provide a framework for coordinated climate change experiments for the next five years and thus includes simulations for assessment in the AR5 as well as others that extend beyond the AR5. CMIP5 is not, however, meant to be comprehensive; it cannot possibly include all the different model intercomparison activities that might be of value, and it is expected that various groups and interested parties will develop additional experiments that might build on and augment the experiments described here.

CMIP5 promotes a standard set of model simulations in order to:

- Evaluate how realistic the models are in simulating the recent past
- Provide projections of future climate change on two time scales,
    - near term (out to about 2035) and
    - long term (out to 2100 and beyond)
- And to understand some of the factors responsible for differences in model projections, including quantifying some key feedbacks such as those involving clouds and the carbon cycle

The CMIP5 (CMIP Phase 5) experiment design has been finalized with the following suites of experiments:

- Decadal Hindcasts and Predictions simulations,
- "long-term" simulations,
- "atmosphere-only" (prescribed Surface Sea Temperature, SST) simulations for especially computationally-demanding models.

An overview of CMIP5 and the Experiment Design
Karl E. Taylor, Ronald J. Stouffer, and Gerald A. Meehl

https://journals.ametsoc.org/doi/abs/10.1175/BAMS-D-11-00094.1
Bulletin of the American Meteorological Society 93(4):485-498, November 2011
DOI: 10.1175/BAMS-D-11-00094.1
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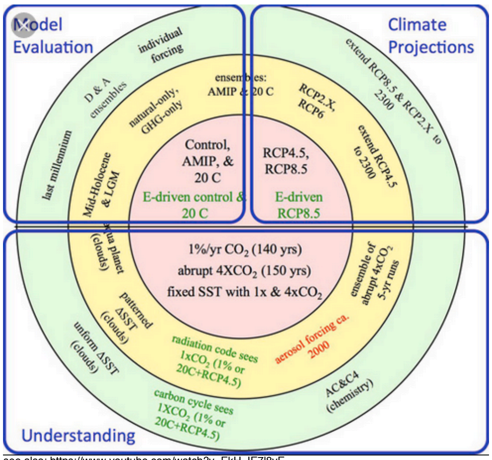

see also: https://www.youtube.com/watch?v=EkH_IE7l8vE

pages 495 - 496
To better characterize projected climate change and, more generally, to separate signal from noise, the CMIP5 experiment design stipulates that modeling groups should perform an ensemble of simulations for some of the experiments. All members of an ensemble are run under identical experiment conditions, but they differ in how they have been initialized. Within a given model's ensemble of historical runs, for example, all members are forced in the same way, but each is initiated from a different point in the preindustrial control run. The different initial conditions produce different climate trajectories, with each realization assumed to be an equally likely outcome. If the observed evolving climate state were to fall within the envelope of the ensemble of model trajectories, then the model would be judged to be consistent with observations. If, however, the observed trajectory strayed far from the ensemble, then the model would be judged to be inconsistent with observations. In general these single-model ensembles of simulations can be used to assess the statistical significance of apparent differences.
...

Multimodel ensemble. The benefits of considering results from the multimodel CMIP5 ensemble is different from the value of the ensembles of simulations produced by individual models.
- The multimodel ensemble represents a variety of best-effort attempts to simulate the climate system. To the extent that these attempts are at least somewhat independent and that the collection of models is not systematically biased on the whole, the ensemble can be used to provide both a consensus representation of the climate system and, based on the spread of model results, provide some measure of how much confidence might be placed in that consensus.

The specific causes of the spread in any set of CMIP5 model simulations will, in general, be difficult to isolate. The variety of model formulations and model resolutions will provide a partial, and often the primary, explanation for differences in simulations. Knowing this fact, however, may not be all that enlightening since models differ in so many respects. There will also be variations in the way that the CMIP5 experiment conditions are applied in different models. ... Finally, some of the differences among the model simulations will be due to climate "noise," which, as discussed earlier, can be quantified using initial condition ensembles produced by individual models.

For the first time in CMIP, these traditional long-term experiments will be performed by ESMs, as well as by AOGCMs and EMICs.
- The ESMs, which include at least a full representation of the carbon cycle, will in some experiments be driven by *prescribed concentrations of CO2* so that their results can be compared directly to the AOGCMs.
- Additional ESM simulations will be driven by *prescribed emissions of CO2*.
- Both types of experiments can be used to study carbon feedbacks on climate change and the impacts of climate change on terrestrial and marine ecosystems.

University of British Columbia
Climate Literacy Courses (in cache)

Module 1: Climate in the Public Sphere
Climate change is a pervasive and challenging phenomenon that can be viewed through a multitude of lenses. A scientific lens, for instance, reveals altered ecosystems and climatic tipping

Module 2: Introduction to the Climate System
n this module of the science section of the course, we'll look at the big picture of Earth's climate system. What are the parts? What are some of the major interactions among the parts?
2.2 Energy Basics and Earth's Climate Sensitivity
2.4 Our Geologic Backdrop: Ice Age Cycles
Milankovitch Cycles generate a resonance in system thus generating glacier cycles with periods 20 000, 40 000 and 100 000 years (see also Abe-Ouchi, 2013: Modeling the 100,000-year Glacial-interglacial Cycles: Forcing and Feedback)

Module 4: The Carbon Cycle
we'll look at stocks and flows of carbon. The atmosphere, biosphere, hydrosphere, and geosphere all exchange carbon with one another. Some flows are large and fast; others are small and slow. Humans, particularly through deforestation and fossil fuel use, have a significant impact on the planetary carbon cycle. This module explores the natural carbon cycle, the perturbations in carbon stocks and flows from human activities, and the climate system's response to human perturbations.
4.1 The Unperturbed Carbon Cycle: Stocks and Flows
CO2 cycles
- The vegetation breathes (annual cycles of CO2
- The ocean breathes ((20, 40, 100) ky cycles): together with Milankowitch cycles generate glacier cycles (CLIMBER, look here)
- The rocks breathe (100 10^6 years cycles): GEOCARB (look here)

Module 5: Climate Models
5.1 Introducing Climate Modeling
5.2 Choices Climate Modelers Make
5.3 Climate Model Output
"Models can produce ranges of possibilities, and that information can be useful for human communities to plan and implement mitigation and adaptation strategies."

IPCC WGIII AR5 full
Pages 438ff
6.3.2.6 The link between concentrations, radiative forcing, and temperature

The assessment in this chapter focuses on
(*) scenarios that result in alternative CO2eq concentrations by the end of the century. However,
(*) temperature goals are also an important consideration in policy dis-cussions.

This raises the question of how the scenarios assessed in this chapter relate to possible temperature outcomes.
(*) One complica-tion for assessing this relationship is that scenarios can follow differ-ent concentration pathways to the same end-of-century goal (see Section 6.3.2.2), and this will lead to different temperature responses.
(*) A second complication is that several uncertainties con-found the relationship between emissions and temperature responses, including uncertainties about the

(*) carbon cycle,
(*) climate sensitivity, and the
(*) transient climate response (see WG I, Box 12.2).

This means that the temperature outcomes of different concentra-tion pathways assessed here (see Section 6.3.2.1) are best expressed in terms of a range of probable temperature outcomes

(see Chapter 2 and Section 6.2.3 for a discussion of evaluating scenarios under uncertainty).

For this assessment, the method described by Rogelj et al. (2012) and Schaeffer et al. (2014) is used, which employs the MAGICC model based on the *probability distribution* of input parameters from Meinshausen (2009) (see also Meinshausen et al., 2011c).

MAGICC was run 600 times for each scenario.

Probabilistic temperature statements are based on the resulting distributions (see also the Methods and Metrics Annex; and the underlying papers cited).

Because the temperature distribution of these runs is based on a single probability distribution in a single modelling framework, resulting probabilistic temperature statements should be regarded as indicative.

An important consideration in the evaluation of this method is the consistency between the distributions of key parameters used here and the outcome of the WG I research regarding these same parameters.

Carbon cycle parameters in the **Model for the Assessment of Greenhouse-gas Induced Climate Change** (**MAGICC**) model used in this chapter are based on

(*) Earth-System **Coupled Model Intercomparison Project (CMIP)** 4 model results from AR4,

and a probability density function (PDF) for climate sensitivity is assumed that corresponds to the assessment of IPCC AR4 (Meehl et al., 2007; Rogelj et al., 2012, Box 10.2).

The MAGICC output based on this approach has been shown to be consistent with the output of the CMIP5 Earth-System models (see also WG I Sections 12.4.1.2 and 12.4.8). The MAGICC model captures the temperature outcomes of the CMIP5 models reasonably well, with median estimates close to the middle of the CMIP5 uncertainty ranges (see panels a and b in Figure 6.12).

page 438

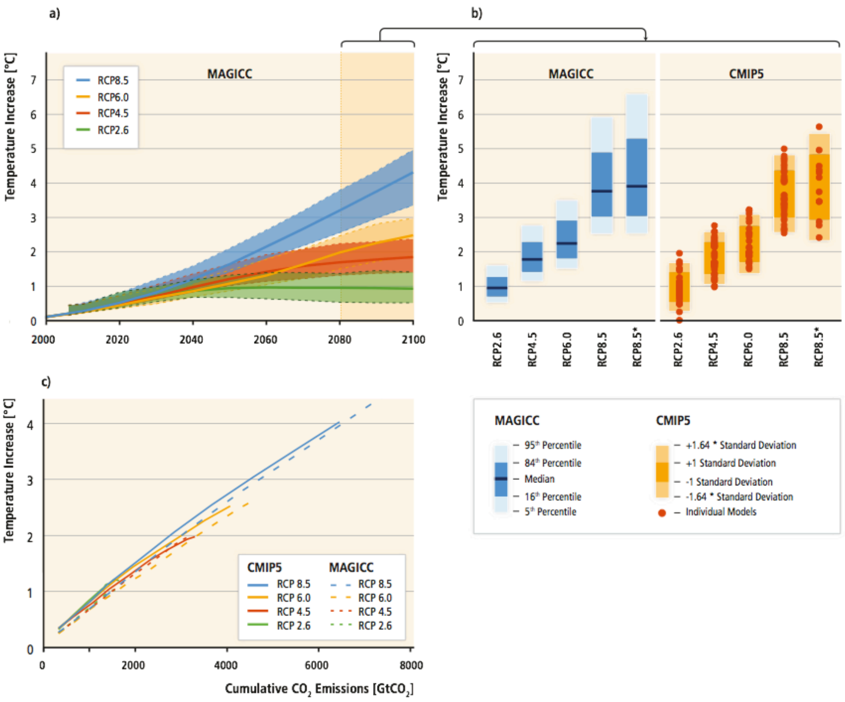

Figure 6.12 I Comparison of CMIP5 results (as presented in Working Group I) and MAGICC output for global temperature increase. Note that temperature increase is presented relative to the 1986 - 2005 average in this figure (see also Figure 6.13).

- Panel a) shows concentration-driven runs for the RCP scenarios from **MAGICC (lines)** and **one-standard deviation ranges from CMIP5 models**.
- Panel b) compares 2081 - 2100 period projections from MAGICC with CMIP5 for scenarios driven by prescribed RCP concentrations (four left-hand bars of both model categories) and the RCP8.5 run with prescribed emissions (fifth bar; indicated by a star).
- Panel c) shows temperature increases for the concentration-driven runs of a subset of CMIP5 models against cumulative CO2 emissions back-calculated by these models from the prescribed CO2 concentration pathways (full lines) and temperature increase projected by the MAGICC model against cumulative CO2 emissions (dotted lines) (based on WGI Figure SPM.10). Cumulative emissions are calculated from 2000 onwards.

Source: WGI_AR5 (Section 12.5.4.2, Figure 12.46, TFE.8 Figure 1) and MAGICC calculations (RCP data (van Vuuren et al., 2011a), method as in Meinshausen et al., 2011c).

enter these lines (MAGICC and CMIP5) into my Mathematica plots with ISAM RCPs

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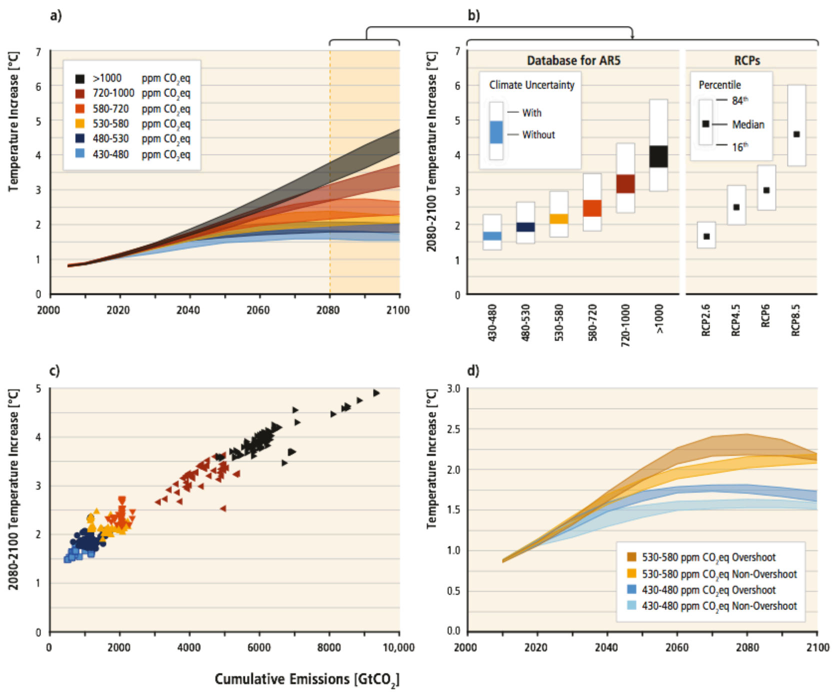


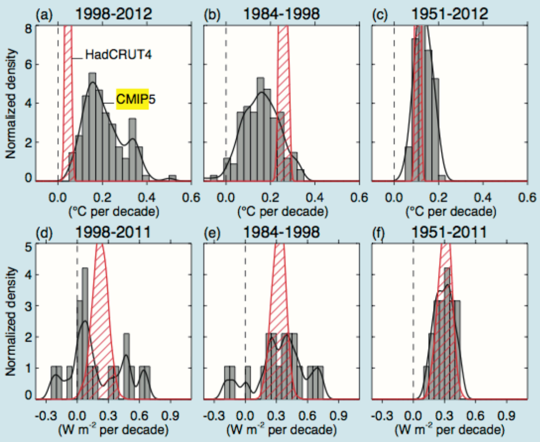
Figure 6.13 I Changes in global temperature for the scenario categories above 1850 - 1900 reference level as calculated by **MAGICC**. (Observed temperatures in the 1985 - 2006 period were about 0.61 deg C above the reference level ,Äì see e. g. WG1 Table SPM.2).

- Panel a) shows temperature increase relative reference as calculated by MAGICC (10th to 90th percentile for median MAGICC outcomes).
- Panel b) shows 2081 - 2100 temperature levels for the scenario categories and RCPs for the MAGICC outcomes.
  - The bars for the scenarios used in this assessment include both
    - the 10th to 90th percentile range for median MAGICC outcomes (colored portion of the bars) and
    - the 16th to 84th percentile range of the full distribution of MAGICC outcomes from these scenarios, which also captures the Earth-System uncertainty.
  - The bars for the RCPs are based on the 16th to 84th of MAGICC outcomes based on the RCP emissions scenarios, capturing only the Earth-System uncertainty.
- Panel c) shows relationship between cumulative CO2 emissions in the 2011 - 2100 period and median 2081 - 2100 temperature levels calculated by MAGICC.
- Panel d) indicates the median temperature development of overshoot (> 0.4 W / m2) and nonovershoot scenarios for the first two scenario categories (25th to 75th percentile of scenario outcomes).

Source: WG III AR5 Scenario Database (Annex II.10).

Man macht also MAGICC calcs. from scenarios und verwendet
(*) manchmal nur die median results
(*) manchmal die median results plus Streuung (percentiles)
(*) manchmal the full range of the results und schaut nach dem percentile range.

Darin spiegelt sich wider
(*) earth system uncertainties (as reflected in parameter uncertainties?)
(*) uncertainties in the input, i.e. the emissions



Box TS.3, Figure 1 | (Top) Observed and simulated GMST trends in °C per decade, over the periods 1998–2012 (a), 1984–1998 (b), and 1951–2012 (c). For the observations, 100 realizations of the Hadley Centre/Climatic Research Unit gridded surface temperature data set 4 (HadCRUT4) ensemble are shown (red, hatched). The uncertainty displayed by the ensemble width is that of the statistical construction of the global average only, in contrast to the trend uncertainties quoted in Section 2.4.3, which include an estimate of internal climate variability. Here, by contrast, internal variability is characterized through the width of the model ensemble. For the models, all 114 available CMIP5 historical realizations are shown, extended after 2005 with the RCP4.5 scenario and through 2012 (grey, shaded). (Bottom) Trends in effective radiative forcing (ERF, in W m^{-2} per decade) over the periods 1998–2011 (d), 1984–1998 (e), and 1951–2011 (f). The figure shows AR5 best-estimate ERF trends (red, hatched) and CMIP5 ERF (grey, shaded). Black lines are smoothed versions of the histograms. Each histogram is normalized so that its area sums up to one. {2.4.3, 8.5.2; Box 9.2; Figure 8.18; Box 9.2, Figure 1}

Quelle: WGI_AR5_all_final, page 63

Tab.'4.1 page 323 Overview of chs 5 - 16

Übergangsraten nach David-Archer-2009-Lecture #20
7 Gt C/a emissions from industry
2.5 Gt C/a goes into land plants
2.5 Gt C/a goes into ocean

increase in atmosphere: 4 Gt C/a

inventories:
Coal 5000 Gt C
living C on land surface 500 Gt C
in soils (mostly dead C) 1500 Gt C

the ocean has like 50 times as much C as the atmosphere

after we introduced CO2 into the atmosphere, 25% of it still is there after 1000 years, 10% of it stays there for half a million years.

coursera: why co2 matters
temp. as function of co2 partial pressure
temp. goes up as the log of the co2-concentration, due to band saturation effect - asymptotic increase

(abzissa: T, ordinate: sea level) diagram
frage: sind die von ISAM berechneten Werte für temp. und sea level die bei der erreichten CO2 Konz. stabilen (Gleichgewichts-) Werte oder verändern sie sich nach 2100 weiter, ähnlich wie David Archer in seiner lecture #20 für sea level (am Ende bei 39 Minuten) sagt.
antwort wahrscheinlich: Gleichgewicht des sea level mit Temperatur stellt sich sehr langsam ein, sea level folgt nicht so schnell wie Temperatuf der CO2-Konzentration.

the temperature has a stronger tail because of the band saturation effect (at high CO2 concentrations thermal backradiation by CO2 ceases not as much as atmospheric CO2 concentration decreases).

scenario categories (ppm) vs. RCPs (W/m2)
550 CO2eq (3.7 W / m2) between 2040 and 2050, (550/3.7 = 149)
450 CO2eq (2.6 W / m2) between 2020 and 2030 (450/2.6 = 173)

The emissions pathways for all of the emissions from the scenarios collected for this assessment were run through a common version of the MAGICC model to obtain estimates of CO2eq concentrations (Section 6.3.2)

(*) page 430
a standard reduced-form climate model called MAGICC (see Meinshausen et al., 2011a; b; c; Rogelj et al., 2012). For each scenario, MAGICC was run multiple times using a distribution of Earth-System parameters, creating an ensemble of MAGICC runs. The resulting median concentration from this distribution was used to classify each scenario (see Section 6.3.2.6 for more on this process and a discussion of temperature outcomes).

Global Warming Potential (GWP)

Figure 6.6 | Total radiative forcing (W/m2) or CO2 concentrations (ppm) vs. time (left panel) and cumulative carbon emissions since 1751 (right panel) vs time in baseline scenario literature compared to RCP scenarios

WGIAR5_all_final.pdf
page 90
There is very high confidence that globally averaged changes over land will exceed changes over the ocean at the end of the 21st century by a factor that is likely in the range 1.4 to 1.7. In the absence of a strong reduction in the Atlantic Meridional Overturning, the Arctic region is projected to warm most (very high confidence) (Figure TS.15).
... It is virtually certain that, in most places, there will be more hot and fewer cold temperature extremes as global mean temperatures increase.

- These changes are expected for events defined as extremes on both daily and seasonal time scales.
- Increases in the frequency, duration and magnitude of hot extremes along with heat stress are expected;
- however, occasional cold winter extremes will continue to occur.

Twenty-year return values of low-temperature events are pro- jected to increase at a rate greater than winter mean temperatures in most regions, with the largest changes in the return values of low temperatures at high latitudes.
Twenty-year return values for high- temperature events are projected to increase at a rate similar to or greater than the rate of increase of summer mean temperatures in most regions.

Under RCP8.5 it is likely that, in most land regions, a current 20-year high-temperature event will occur more frequently by the end of the 21st century

- (at least doubling its frequency,
- but in many regions becoming an annual or 2-year event)
- and a current 20-year low-temperature event will become exceedingly rare (See also TFE.9). {12.4.3}

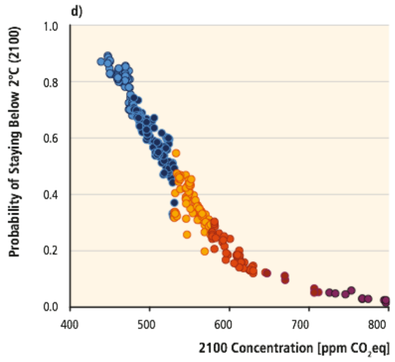


Figure 6.14 I The probability of staying below temperature levels for the different scenario categories (colors, 430-480, 480-530, 530-580, 580-650, 650-720 ppm_{CO2eq}) as assessed

by the **MAGICC** model, representing the statistics of 600 different climate realizations for each emission scenario.

Relationship between 2100 concentration and the probability of exceeding 2 °C in 2100. Source: WG III AR5 Scenario Database (Annex II.10).
Source: page 440 of ipcc_wg3_ar5_full

Table TS.1 | Key characteristics of the scenarios collected and assessed for WGIII AR5. For all parameters, the 10th to 90th percentile of the scenarios is shown.[1, 2] [Table 6.3]

CO_2eq Concentrations in 2100 [ppm CO_2eq] Category label (concentration range)[9]	Subcategories	Relative position of the RCPs[5]	Cumulative CO_2 emissions[3] [$GtCO_2$]		Change in CO_2eq emissions compared to 2010 in [%][4]		Temperature change (relative to 1850–1900)[5, 6]				
			2011–2050	2011–2100	2050	2100	2100 Temperature change [°C][7]	Likelihood of staying below temperature level over the 21st century[8]			
								1.5 °C	2.0 °C	3.0 °C	4.0 °C
< 430	Only a limited number of individual model studies have explored levels below 430 ppm CO_2eq										
450 (430–480)	Total range[1, 10]	RCP2.6	550–1300	630–1180	−72 to −41	−118 to −78	1.5–1.7 (1.0–2.8)	*More unlikely than likely*	*Likely*	*Likely*	*Likely*
500 (480–530)	No overshoot of 530 ppm CO_2eq		860–1180	960–1430	−57 to −42	−107 to −73	1.7–1.9 (1.2–2.9)	*Unlikely*	*More likely than not*		
	Overshoot of 530 ppm CO_2eq		1130–1530	990–1550	−55 to −25	−114 to −90	1.8–2.0 (1.2–3.3)		*About as likely as not*		
550 (530–580)	No overshoot of 580 ppm CO_2eq		1070–1460	1240–2240	−47 to −19	−81 to −59	2.0–2.2 (1.4–3.6)		*More unlikely than likely*[12]		
	Overshoot of 580 ppm CO_2eq		1420–1750	1170–2100	−16 to 7	−183 to −86	2.1–2.3 (1.4–3.6)				
(580–650)	Total range	RCP4.5	1260–1640	1870–2440	−38 to 24	−134 to −50	2.3–2.6 (1.5–4.2)				
(650–720)	Total range		1310–1750	2570–3340	−11 to 17	−54 to −21	2.6–2.9 (1.8–4.5)		*Unlikely*	*More likely than not*	
(720–1000)[2]	Total range	RCP6.0	1570–1940	3620–4990	18 to 54	−7 to 72	3.1–3.7 (2.1–5.8)	*Unlikely*[11]		*More unlikely than likely*	
>1000[2]	Total range	RCP8.5	1840–2310	5350–7010	52 to 95	74 to 178	4.1–4.8 (2.8–7.8)		*Unlikely*[11]	*Unlikely*	*More unlikely than likely*

Table 6.3 | Key characteristics of the scenarios categories introduced in Table 6.2. For all parameters, the 10th to 90th percentile of the scenarios are shown.[1] Source: WG III AR5 Scenario Database (Annex II.10).

CO_2-equivalent concentration in 2100 (ppm CO_2eq)[2]	Subcategories	Cumulative CO_2 emissions[3] ($GtCO_2$)		CO_2eq. emissions in 2050 relative to 2010 (%)[4]	CO_2eq emissions in 2100 relative to 2010 (%)	Concentration (ppm)[5]		Temperature (relative to 1850–1900)[6, 7]				
		2011–2050	2011–2100			CO_2 in 2100	Peak CO_2eq.	2100 Temperature (°C)	Probability of Exceeding 1.5 °C (%)	Probability of Exceeding 2 °C (%)	Probability of Exceeding 3 °C (%)	Probability of Exceeding 4 °C (%)
430–480	Total range	550–1300	630–1180	−72 to −41	−118 to −78	390–435	465–530	1.5–1.7 (1.0–2.8)	49–86	12–37	1–3	0–1
	Overshoot < 0.4 W/m²	*550–1030*	*630–1180*	*−72 to −49*	*−94 to −78*	*390–435*	*465–500*	*1.5–1.7 (1.0–2.6)*	*49–72*	*12–22*	*1–2*	*0–0*
	Overshoot > 0.4 W/m²	*920–1300*	*670–1180*	*−66 to −41*	*−118 to −103*	*400–435*	*505–530*	*1.6–1.7 (1.1–2.8)*	*76–86*	*22–37*	*1–3*	*0–1*
480–530	Total range	860–1600	960–1550	−57 to 4[8]	−179 to −127	425–460	505–575	1.7–2.1 (1.2–3.3)	80–96	32–61	3–10	0–2
	Overshoot < 0.4 W/m²	*870–1240*	*960–1490*	*−57 to −42*	*−103 to −76*	*425–460*	*505–560*	*1.8–2.0 (1.2–3.2)*	*81–94*	*32–56*	*3–10*	*0–2*
	Overshoot > 0.4 W/m²	*1060–1600*	*1020–1500*	*−54 to 4[8]*	*−179 to −98*	*425–460*	*530–575*	*1.8–2.1 (1.2–3.3)*	*86–96*	*38–61*	*3–10*	*1–2*
	No exceedance of 530 ppm CO_2eq	*860–1180*	*960–1430*	*−57 to −42*	*−107 to −73*	*425–455*	*505–530*	*1.7–1.9 (1.2–2.9)*	*80–87*	*32–40*	*3–4*	*0–1*
	Exceedance of 530 ppm CO_2eq	*1130–1530*	*990–1550*	*−55 to −25*	*−114 to −90*	*425–460*	*535–575*	*1.8–2.0 (1.2–3.3)*	*88–96*	*39–61*	*4–10*	*1–2*
530–580	Total range	1070–1780	1170–2240	−47 to 7	−184 to −59	425–520	540–640	2.0–2.3 (1.4–3.6)	93–99	54–84	8–19	1–3
	Overshoot < 0.4 W/m²	*1090–1490*	*1400–2190*	*−47 to −12*	*−86 to −60*	*465–520*	*545–585*	*2.0–2.2 (1.4–3.6)*	*93–96*	*55–71*	*8–14*	*1–2*
	Overshoot > 0.4 W/m²	*1540–1780*	*1170–2080*	*−7 to 7*	*−184 to −98*	*425–505*	*590–640*	*2.1–2.2 (1.4–3.6)*	*95–99*	*63–84*	*8–19*	*1–3*
	No exceedance of 580 ppm CO_2eq	*1070–1460*	*1240–2240*	*−47 to −19*	*−81 to −59*	*450–520*	*540–575*	*2.0–2.2 (1.4–3.6)*	*93–95*	*54–70*	*8–13*	*1–2*
	Exceedance of 580 ppm CO_2eq	*1420–1750*	*1170–2100*	*−16 to 7*	*−183 to −86*	*425–510*	*585–640*	*2.1–2.3 (1.4–3.6)*	*95–99*	*66–84*	*8–19*	*1–3*
580–650	Total range	1260–1640	1870–2440	−38 to 24	−134 to −50	500–545	585–690	2.3–2.6 (1.5–4.2)	96–100	74–93	14–35	2–8
650–720	Total range	1310–1750	2570–3340	−11 to 17	−54 to −21	565–615	645–710	2.6–2.9 (1.8–4.5)	99–100	88–95	26–43	4–10
720–1000	Total range	1570–1940	3620–4990	18 to 54	−7 to 72	645–780	765–935	3.1–3.7 (2.1–5.8)	100–100	97–100	55–83	14–39
> 1000	Total range	1840–2310	5350–7010	52 to 95	74 to 178	810–975	1075–1285	4.1–4.8 (2.8–7.8)	100–100	100–100	92–98	53–78

Source: page 431 of ipcc_wg3_ar5_full

1. Italicized text in blue shows results of the subset of the scenarios from column one. One subcategory distinguishes scenarios that have a large overshoot (i.e. a maximum forcing during the 21st century that is > 0.4 W/m2 higher its 2100 forcing) from those that do not have a large overshoot. The second set of subcategories shows whether a scenario exceeds the maximum equivalent concentration level of its category somewhere before 2100. For categories above 580 ppm CO2eq, the information in the row 'total range' refers to the 10th to 90th percentiles for the total set of scenarios in the category. For the categories below 580 ppm CO2eq, the total range is based on the 10th to 90th percentiles of the subcategories (the lowest and highest values from the subcategories).
2. The CO2eq concentration includes the forcing of all GHGs including halogenated gases and tropospheric ozone, as well as aerosols and albedo change (calculated on the basis of the total forcing from a simple carbon cycle/climate model MAGICC).
3. For comparison of the cumulative CO2 emissions estimates assessed here with those presented in WGI AR5,
   - an amount of
     - 515 [445 to 585] GtC corresponding to
     - 1890 [1630 to 2150] GtCO2,
   - was already emitted by 2011 since 1870 (WGI Section 12.5).
   - Note that cumulative CO2 emissions are presented here for different periods of time (2011–2050 and 2011–2100) while cumulative CO2 emissions in WGI AR5 are presented as total compatible emissions for the RCPs (2012–2100) or for total compatible emissions for remaining below a given temperature target with a given likelihood. (WGI Table SPM.3, WGI SPM.E.8)
4. The global 2010 emissions are 31 % above the 1990 emissions (consistent with the historic GHG emission estimates presented in this report). CO2eq emissions include the basket of Kyoto gases (CO2, CH4, N2O as well as F-gases).
5. The assessment in WGIII AR5 involves a large number of scenarios published in the scientific literature and is thus not limited to the RCPs. To evaluate the CO2eq concentration and climate implications of these scenarios, the MAGICC model was used in a probabilistic mode (see Annex II). For a comparison between MAGICC model results and the outcomes of the models used in WGI AR5, see WGI Sections 12.4.1.2, 12.4.8 and Section 6.3.2.6 of this report. Reasons for differences with WGI AR5 SPM Table.2 include the difference in reference year (1986–2005 vs. 1850–1900 here), difference in reporting year (2081–2100 vs 2100 here), set-up of simulation (CMIP5 concentration-driven versus MAGICC emission-driven here), and the wider set of scenarios (RCPs versus the full set of scenarios in the WGIII AR5 scenario database here).
6. Temperature change in 2100 is provided for a median estimate of the MAGICC calculations, which illustrates differences between the emissions pathways of the scenarios in each category. The range of temperature change in the parentheses includes in addition also the carbon cycle and climate system uncertainties as represented by the MAGICC model (see 6.3.2.6 for further details). The temperature data compared to the 1850–1900 reference year was calculated by taking all projected warming relative to 1986–2005, and adding 0.61 °C for 1986–2005 compared to 1850–1900, based on HadCRUT4, as also applied in WGI Table SPM.2. Temperature change is reported for the year 2100, which is not directly comparable to the equilibrium warming reported in WGIII AR4 (see Table 3.5; see also Section 6.3.2). For the 2100 temperature estimates, the transient climate response (TCR) is the most relevant system property.
   - The assumed 90 % range of the TCR for MAGICC is 1.2–2.6 °C (median 1.8 °C).
   - This compares to the 90 % range of TCR between 1.2–2.4 °C for CMIP5 (WGI Section 9.7) and an
   - assessed likely range of 1–2.5 °C from multiple lines of evidence reported in the WGI AR5 (Box 12.2 in Section 12.5).
7. The high estimate is influenced by multiple scenarios from the same model in this category with very large net negative CO2eq emissions of about 40 GtCO2eq/yr in the long term. The higher bound CO2eq emissions estimate, excluding extreme net negative emissions scenarios and thus comparable to the estimates from the other rows in the table, is about – 19 % in 2050 relative to 2010.

Table TS.1 I Projected change in global mean surface air temperature and global mean sea level rise for the mid- and late 21st century relative to the reference period of 1986–2005. {12.4.1; Tables 12.2,13.5}

		2046–2065		2081–2100	
	Scenario	Mean	*Likely* range[c]	Mean	*Likely* range[c]
Global Mean Surface Temperature Change (°C)[a]	RCP2.6	1.0	0.4 to 1.6	1.0	0.3 to 1.7
	RCP4.5	1.4	0.9 to 2.0	1.8	1.1 to 2.6
	RCP6.0	1.3	0.8 to 1.8	2.2	1.4 to 3.1
	RCP8.5	2.0	1.4 to 2.6	3.7	2.6 to 4.8
	Scenario	Mean	*Likely* range[d]	Mean	*Likely* range[d]
Global Mean Sea Level Rise (m)[b]	RCP2.6	0.24	0.17 to 0.32	0.40	0.26 to 0.55
	RCP4.5	0.26	0.19 to 0.33	0.47	0.32 to 0.63
	RCP6.0	0.25	0.18 to 0.32	0.48	0.33 to 0.63
	RCP8.5	0.30	0.22 to 0.38	0.63	0.45 to 0.82

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Box TS.6 I The use of scenarios in this report
Scenarios of how the future might evolve capture key factors of human development that influence GHG emissions and
(*) our ability to respond to climate change.

Scenarios cover a range of plausible futures, because human development is determined by a myriad of factors including human decision making. (Binney: human behaviour follows pattern, is extremely structured).

Scenarios can be used to integrate knowledge about the drivers of GHG emissions,
(*) mitigation options,
(*) climate change, and
(*) climate impacts.

One important element of scenarios is the projection of the level of human interference with the climate system.
(*) To this end, a set of 4 "representative concentration pathways" (RCPs) has been developed.
(*) These RCPs reach
(-) radiative forcing levels of 2.6, 4.5, 6.0, and 8.5 Watts per square meter (W / m2)
(-) (corresponding to concentrations of 450, 650, 850, and 1370 ppm CO2eq), respectively, in 2100,
(-) 450 ppm / 2.6 W/m2 = 174 ppm / (W/m2)
(-) 650 ppm / 4.4 W/m2 = 148 ppm/(W/m2)
(-) 850 ppm / 6.0 W/m2 = 142 ppm/(W/m2)
(-) 1370 ppm / 8.5 W/m2 = 161 ppm/(W/m2)

covering the range of anthropogenic climate forcing in the 21st century as reported in the literature.
(*) The four RCPs are the basis of a new set of climate change projections that have been assessed by WGI AR5. [WGI 6.4, WGI 12.4]

Scenarios of how the future develops without additional and explicit efforts to mitigate climate change ("baseline scenarios") and with the introduction of efforts to limit GHG emissions ("mitigation scenarios"), respectively, generally include
(*) socio-economic projections in addition to
(*) emission,
(*) concentration, and
(*) climate change information.

WGIII AR5 has assessed the full breadth of baseline and mitigation scenarios in the literature. To this end,
(*) it has collected a database of more than 1200 published mitigation and baseline scenarios.

In most cases, the underlying socio-economic projections reflect the modelling teams" individual choices about how to conceptualize the future in the absence of climate policy.

The baseline scenarios show a wide range of assumptions about
(*) economic growth (ranging from threefold to more than eightfold growth in per capita income by 2100),
(*) demand for energy (ranging from a 40 % to more than 80 % decline in energy intensity by 2100) and other factors, in particular
(*) the carbon intensity of energy. Assumptions about
(*) population are an exception: the vast majority of scenarios focus on the low to medium population range of 9 to 10 billion people by 2100.

Although the range of emissions pathways across baseline scenarios in the literature is broad, it may not represent the full potential range of possibilities (Figure TS.7). [6.3.1]

The concentration outcomes of the baseline and mitigation scenarios assessed by WGIII AR5 cover the full range of RCPs. However, they provide much more detail at the lower end, with many scenarios aiming at concentration levels in the range of 450, 500, and 550 ppm CO2eq in 2100. The climate change projections of WGI based on RCPs, and the mitigation scenarios assessed by WGIII AR5 can be related to each other through the climate outcomes they imply. [6.2.1]

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meine deutsche Übersetzung der Seiten 103 - 104 des Chapter 2
Mitigation Pathways Compatible with 1.5°C in the Context of Sustainable Development
IPCC Special Report "Global Warming of 1.5 Degrees Celsius"

engl. Original:
These feedbacks are caused by the effects of
- *nutrient limitation (Duce et al., 2008; Mahowald et al., 2017),*
- *ozone exposure (de Vries et al., 2017),*
- *fire emissions (Narayan et al., 2007) and*
- *changes associated with natural aerosols (Cadule et al., 2009; Scott et al., 2018).*

Among these Earth system feedbacks, the importance of the permafrost feedback's influence has been highlighted in recent studies.

Combined evidence from both
- *models (MacDougall et al., 2015; Burke et al., 2017; Lowe and Bernie, 2018) and*
- *field studies (like Schädel et al., 2014; Schuur et al., 2015)*

shows high agreement that permafrost thawing will release both CO2 and CH4 as the Earth warms, amplifying global warming.

This thawing could also release N2O (Voigt et al., 2017a, b).

Field, laboratory and modelling studies estimate
- *that the vulnerable fraction in permafrost is about 5–15% of the permafrost soil carbon (~5300–5600 GtCO2 in Schuur et al., 2015) and*
- *that carbon emissions are expected to occur beyond 2100 because of system inertia and the large proportion of slowly decomposing carbon in permafrost (Schädel et al., 2014).*

Published model studies suggest that a large part of the carbon release to the atmosphere is in the form of CO2 (Schädel et al., 2016), while the amount of CH4 released by permafrost thawing is estimated to be much smaller than that CO2.
- *Cumulative CH4 release by 2100 under RCP2.6 ranges from 0.13 to 0.45 Gt of methane (Burke et al., 2012; Schneider von Deimling et al., 2012, 2015), with fluxes being the highest in the middle of the century because of maximum thermokarst lake extent by mid-century (Schneider von Deimling et al., 2015).*

Unter diesen Erdsystemrückkopplungen wurde in jüngsten Studien die Bedeutung des Einflusses der Permafrostrückkopplung hervorgehoben.

Kombinierte Evidenz aus
- sowohl Modellen (MacDougall et al., 2015; Burke et al., 2017; Lowe und Bernie, 2018)
- als auch Feldstudien (wie Schädel et al., 2014; Schuur et al., 2015)

zeigen in hoher Übereinstimmung, dass Permafrostböden beim Auftauen sowohl CO2 als auch CH4 freisetzten werden. Das wird die globale Erwärmung verstärken.

Dieses Auftauen könnte auch N2O freisetzen (Voigt et al., 2017a, b).

Feld-, Labor- und Modellstudien schätzen, dass von dem Permafrostboden-Kohlenstoffinventar von ~ 5300–5600 GtCO2 nach Schuur et al., 2015) etwa

(*) 5–15% = 265 - 840 GtCO2 freigesetzt werden kann,

und dass Kohlenstoffemissionen voraussichtlich erst nach 2100 auftreten werden wegen der Systemträgheit und des hohen Anteils von sich langsam [mikrobiell] zersetzendem Kohlenstoff [von CH4 nach CO2?] im Permafrostboden (Schädel et al., 2014).

Veröffentlichte Modellstudien legen nahe, dass ein Großteil der Kohlenstoffabgabe an die Atmosphäre in Form von CO2 erfolgt (Schädel et al., 2016), während die Menge an CH4, die durch das Auftauen von Permafrost freigesetzt wird, viel geringer ist als dieses CO2. Die kumulative CH4-Freisetzung bis 2100 unter RCP2.6 (RCP2.6 ist das niedrigste Emissions-Szenario, das das IPCC für repräsentativ hält) reicht

(*) von 0,13 bis 0,45 Gt Methan (Burke et al., 2012; Schneider von Deimling et al., 2012, 2015),

wobei die Methan-Zuflüsse in die Atmosphäre in der Mitte dieses Jahrhunderts die höchsten sind.

Ergänzung:
Klimawirksamkeit von Methan: 21 x Klimawirksamkeit von CO2
Halbwertszeit von Methan in der Atmosphäre: 9 - 15 Jahre.

Zur Erklärung der Bedeutung der Halbwertszeit
Bei konstanter Emission von Methan bleibt -grob gesagt- nur das in der Atmosphäre, was innerhalb von 9 - 15 Jahren emittiert wird. Das ist bei CO2 anders: Alles von uns emittierte CO2 bleibt über Jahrhunderte in der Atmosphäre. Man geht man daher davon aus, dass für die Klimaerwärmung die insgesamt emittierte CO2-Menge zählt, nicht der Zeitraum, in der sie emittiert wurde. Eine Begrenzung der Klimaerwärmung (seit 1860) auf 1.5 Grad Celsius entspricht daher eine Begrenzung der seit 1860 emittierten CO2-Menge auf ein Budget von etwa 4000 Gt CO2. Von diesem Budget haben wir bis heute etwa die Hälfte aufgebraucht (s. Abb. 2.3 auf Seite 105 im oben verlinkten IPC Special Report.)

How does a climate model work?

With respect to **temporal scales**: at each model time step, a new state of the Earth's atmosphere and oceans is calculated and then used as the initial state for the next time step. By this method the model is 'stepped forward' in time. The simulated climate can then be inferred by the 'statistics' (averages, extremes etc) from multi-decadal simulations. Typical global climate model time steps are *30 minutes up to 3 hours* – meaning that processes that happen on shorter time scales are not captured per se but must be parameterised (or approximated).

This is similar for **spatial scales**: with typical *spatial resolution of 200km* (for the atmosphere) for each **grid cell of the model**, processes that are smaller in scale (e.g. condensation of water vapour into cloud droplets), are not simulated per se but are parameterised. Physical aspects are complemented by other empirical equations that describe other elements of the Earth system and how they interact, for example the effect of vegetation cover.

more models
R.S. Smith, C. Dubois, J, Marotzke, Global Climate and Ocean Circulation on an Aquaplanet Ocean–Atmosphere General Circulation Model, Journal of Climate 19(18) · September 2006

more literature

Oxford Research Encyclopedia of Climate Science
free abstracts, full articles by subscription (150 pounds/year, 50 pounds/3months)

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	Geoengineering	Statistics

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Bob Trenwith Global Warming Science
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.... 1.2 Paleoclimate
.... 1.3 Instrumental Record of Earth's Climate, Composition of Atmosphere
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.... 2.3 Atmospheric Circulation
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.... 2.5 Oceans and Climate
.... 2.6 The Carbon Cycle, Geochemistry of Radiatively Active Trace Gases
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"The interactions between climate change and the carbon cycle and the future we choose".
Corinne Le Quere
Queen`s Lecture 2019, *TU-Berlin, 11.11.2019*
https://www.youtube.com/watch?v=XWxni9BjYew

How climate-related tipping points can trigger mass migration and social chaos
By Perry World House, November 8, 2019