Working Group I: The Scientific Basis

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C.1 Observed Changes in Globally Well-Mixed Greenhouse Gas Concentrations and Radiative Forcing Over the millennium before the Industrial Era, the atmospheric concentrations of greenhouse gases remained relatively constant. Since then, however, the concentrations of many greenhouse gases have increased directly or indirectly because of human activities.

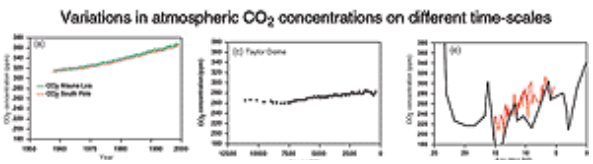
Table 1 provides examples of several greenhouse gases and summarises their 1750 and 1998 concentrations, their change during the 1990s, and their atmospheric lifetimes. The contribution of a species to radiative forcing of climate change depends on the molecular radiative properties of the gas, the size of the increase in atmospheric concentration, and the residence time of the species in the atmosphere, once emitted. *The latter – the atmospheric residence time of the greenhouse gas – is a highly policy relevant characteristic. Namely, emissions of a greenhouse gas that has a long atmospheric residence time is a quasi-irreversible commitment to sustained radiative forcing over decades, centuries, or millennia, before natural processes can remove the quantities emitted.*

Table 1: *Examples of greenhouse gases that are affected by human activities. [Based upon Chapter 3 and Table 4.1]*

	CO_2 (Carbon Dioxide)	**CH_4 (Methane)**	**N_2O (Nitrous Oxide)**	**CFC-11 (Chlorofluoro-carbon-11)**	**HFC-23 (Hydrofluoro-carbon-23)**	**CF_4 (Perfluoro-methane)**
Pre-industrial concentration	about 280 ppm	about 700 ppb	about 270 ppb	zero	zero	40 ppt
Concentration in 1998	365 ppm	1745 ppb	314 ppb	268 ppt	14 ppt	80 ppt
Rate of concentration change **b**	1.5 ppm/yr **a**	7.0 ppb/yr **a**	0.8 ppb/yr	-1.4 ppt/yr	0.55 ppt/yr	1 ppt/yr
Atmospheric lifetime	5 to 200 yr **c**	12 yr **d**	114 yr **d**	45 yr	260 yr	>50,000 yr

a Rate has fluctuated between 0.9 ppm/yr and 2.8 ppm/yr for CO_2 and between 0 and 13 ppb/yr for CH_4 over the period 1990 to 1999.
b Rate is calculated over the period 1990 to 1999.
c No single lifetime can be defined for CO_2 because of the different rates of uptake by different removal processes.
d This lifetime has been defined as an –adjustment time– that takes into account the indirect effect of the gas on its own residence time.

Carbon dioxide (CO_2) *The atmospheric concentration of CO_2 has increased from 280 ppm[5] in 1750 to 367 ppm in*



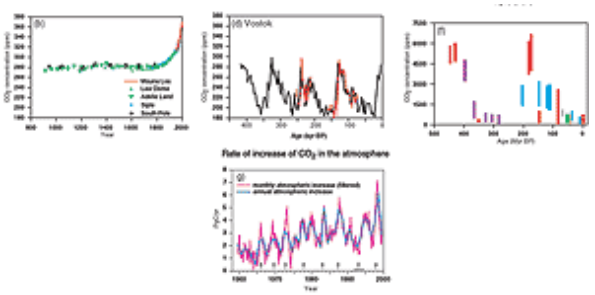


Figure 10: Variations in atmospheric CO_2 concentration on different time-scales. (a) Direct measurements of atmospheric CO_2. (b) CO_2 concentration in Antarctic ice cores for the past millenium. Recent atmospheric measurements (Mauna Loa) are shown for comparison. (c) CO_2 concentration in the Taylor Dome Antarctic ice core. (d) CO_2 concentration in the Vostok Antarctic ice core. (Different colours represent results from different studies.) (e to f) Geochemically inferred CO_2 concentrations. (Coloured bars and lines represent different published studies) (g) Annual atmospheric increases in CO_2. Monthly atmospheric increases have been filtered to remove the seasonal cycle. Vertical arrows denote El Niño events. A horizontal line defines the extended El Niño of 1991 to 1994. [Based on Figures 3.2 and 3.3]

1999 (31%, Table 1). Today's CO_2 concentration has not been exceeded during the past 420,000 years and likely not during the past 20 million years. The rate of increase over the past century is unprecedented, at least during the past 20,000 years (Figure 10). The CO_2 isotopic composition and the observed decrease in Oxygen (O_2) demonstrates that the observed increase in CO_2 is predominately due to the oxidation of organic carbon by fossil-fuel combustion and deforestation. An expanding set of palaeo-atmospheric data from air trapped in ice over hundreds of millennia provide a context for the increase in CO_2 concentrations during the Industrial Era (Figure 10). Compared to the relatively stable CO_2 concentrations (280 ± 10 ppm) of the preceding several thousand years, the increase during the Industrial Era is dramatic. The average rate of increase since 1980 is 0.4%/yr. The increase is a consequence of CO_2 emissions. Most of the emissions during the past 20 years are due to fossil fuel burning, the rest (10 to 30%) is predominantly due to land-use change, especially deforestation. As shown in Figure 9, CO_2 is the dominant human-influenced greenhouse gas, with a current radiative forcing of 1.46 Wm^{-2}, being 60% of the total from the changes in concentrations of all of the long-lived and globally mixed greenhouse gases.

Direct atmospheric measurements of CO_2 concentrations made over the past 40 years show that year to year fluctuations in the rate of increase of atmospheric CO_2 are large. In the 1990s, the annual rates of CO_2 increase in the atmosphere varied from 0.9 to 2.8 ppm/yr, equivalent to 1.9 to 6.0 PgC/yr. Such annual changes can be related statistically to short-term climate variability, which alters the rate at which atmospheric CO_2 is taken up and released by the oceans and land. The highest rates of increase in atmospheric CO_2 have typically been in strong El Niño years (Box 4). These higher rates of increase can be plausibly explained by reduced terrestrial uptake (or terrestrial outgassing) of CO_2 during El Niño years, overwhelming the tendency of the ocean to take up more CO_2 than usual.

Partitioning of anthropogenic CO_2 between atmospheric increases and land and ocean uptake for the past two decades can now be calculated from atmospheric observations. Table 2 presents a global CO_2 budget for the 1980s (which proves to be similar to the one constructed with the help of ocean model results in the SAR) and for the 1990s. Measurements of the decrease in atmospheric oxygen (O_2) as well as the increase in CO_2 were used in the construction of these new budgets. Results from this approach are consistent with other analyses based on the isotopic composition of atmospheric CO_2 and with independent estimates based on measurements of CO_2 and $13CO_2$ in seawater. The 1990s budget is based on newly available measurements and updates the budget for 1989 to 1998 derived using SAR methodology for the IPCC Special Report on Land Use, Land-Use Change and Forestry (2000). The terrestrial biosphere as a whole has gained carbon during the 1980s and 1990s; i.e., the CO_2 released by land-use change (mainly tropical deforestation) was more than compensated by other terrestrial sinks, which are likely located in both the northern extra-tropics and in the tropics. There remain large uncertainties associated with estimating the CO_2 release due to land-use change (and, therefore, with the magnitude of the

residual terrestrial sink).

Process-based modelling (terrestrial and ocean carbon models) has allowed preliminary quantification of mechanisms in the global carbon cycle. Terrestrial model results indicate that enhanced plant growth due to higher CO_2 (CO_2 fertilisation) and anthropogenic nitrogen deposition contribute significantly to CO_2 uptake, i.e., are potentially responsible for the residual terrestrial sink described above, along with other proposed mechanisms, such as changes in land-management practices. The modelled effects of climate change during the 1980s on the terrestrial sink are small and of uncertain sign.

Table 2: *Global CO_2 budgets (in PgC/yr) based on measurements of atmospheric CO_2 and O_2. Positive values are fluxes to the atmosphere; negative values represent uptake from the atmosphere. [Based upon Tables 3.1 and 3.3]*

	SAR [a],[b]	**This Report [a]**	
	1980 to 1989	***1980 to 1989***	***1990 to 1999***
Atmospheric increase	3.3 ± 0.1	3.3 ± 0.1	3.2 ±0.1
Emissions (fossil fuel, cement) [c]	5.5 ± 0.3	5.4 ± 0.3	6.3 ± 0.4
Ocean-atmosphere flux	-2.0 ± 0.5	-1.9 ± 0.6	-1.7 ± 0.5
Land-atmosphere flux [d]	-0.2 ± 0.6	-0.2 ± 0.7	-1.4 ± 0.7

a Note that the uncertainties cited in this table are ±1 standard error. The uncertainties cited in the SAR were ±1.6 standard error (i.e., approximately 90% confidence interval). Uncertainties cited from the SAR were adjusted to ±1 standard error. Error bars denote uncertainty, not interannual variability, which is substantially greater.
b Previous IPCC carbon budgets calculated ocean uptake from models and the land-atmosphere flux was inferred by difference.
c The fossil fuel emissions term for the 1980s has been revised slightly downward since the SAR.
d The land-atmosphere flux represents the balance of a positive term due to land-use change and a residual terrestrial sink. The two terms cannot be separated on the basis of current atmospheric measurements. Using independent analyses to estimate the land-use change component for 1980 to 1989, the residual terrestrial sink can be inferred as follows: Land-use change 1.7 PgC/yr (0.6 to 2.5); Residual terrestrial sink -1.9 PgC/yr (-3.8 to 0.3). Comparable data for the 1990s are not yet available.