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Climate Change and Technological Options

Basic facts, Evaluation and Practical Solutions

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List of Abbreviations

Al	Aluminum
AP	Acidification potential
AR4	Forth Assessment Report of IPPC
AT_4	Respiration activity coefficient
BtL	Biomass-to-liquid
CCS	Carbon Capture and Storage
CDM	Clean Development Mechanisms
CDP	Carbon Disclosure Project
CFC	Chlorofluorohydrocarbons
CH_4	Methane
CO	Carbon monoxide
CO_2	Carbon dioxide
CO_2-eq.	Carbon dioxide equivalents
COP	Conference of Parties
Day_{Emit}	Methane emission rate
d.m.	Dry matter
DME	Dimethylether
DSD	Duales System Deutschland
EC	European Commission
EIA	Environmental Impact Assessment
EJ	Exajoule; 10^{18} J
EMIC	Earth model of intermediate complexity
EOR	Enhanced oil recovery
EPA	U.S. Environmental Protection Agency
ETBE	Ethyl-Tertio-Butyl-Ether
EU	European Union
EU-15	European Union (15 member states)
EU-23	European Union (23 member states)
FCCC	Framework Convention on Climate Change
Fe	Iron
FGD	Flue gas desulfurisation
GB_{21}	Gas generation coefficient

GDP	Gross Domestic Product
GE	Gross energy intake
GHG	Greenhouse gas
GNP	Gross National Product
Gt	Gigatons; 10^{12} kg; 10^{9} t
GWP	Global Warming Potential
HDPE	High density polyethylene
HEF	Hydrofluoroether
HFC	Fluorinated hydrocarbons
ICSU	International Council of Scientific Unions
IPCC	Intergovernmental Panel on Climate Change
ISO	International Organization for Standardization
JAMA	Japan Automobile Manufacturer Association
JI	Joint Implementation
K	Kelvin
KAMA	Korean Automobile Manufacturer Association
kg	Kilogramm
LCA	Life cycle assessment
LDPE	Low density polyethylene
LFG	Landfill gas
LLDPE	Linear low density polyethylene
MBP	Mechanical-biological pre-treatment of residual waste
Mio	Million; 10^{6}
MPI	Max Planck Institute
MSW	Municipal solid waste
MTBE	Methyl-Tertio-Butyl-Ether
NADW	North Atlantic Deep Water
NEI	National Emission Inventory
NMVOC	Non methane volatile organic carbon
NP	Nutrition potential
OECD	Organisation for Economic Co-operation and Development
ODP	Ozone depletion potential
PCC	Precipitated calcium carbonate
PCOP	Photochemical oxidation potential
PECVD	Plasma enhanced chemical vapour deposition
PET	Polyethylenetherephthalat
PFC	Perfluorocarbon

ppb	Parts per billion
ppm	Parts per million
RDF	Refuse derived fuel
RFI	Radiative Forcing Index
RFS	Renewable Fuels Standard
RTO	Regenerative thermal oxidation
SAR	Second Assessment Report
SETAC	Society of Environmental Toxicology and Chemistry
SF_6	Sulfur Hexafluoride
SRES	Special Report on Emission Scenarios
SWCC	Second World Climate Conference
t	Ton; 10^3 kg
TAR	Third Assessment Report of IPPC
TOC	Total organic carbon
UNCED	United Nations Conference on Environment and Development
UNEP	United Nations Environmental Programme
UNFCCC	United Nations Framework Convention on Climate Change
VEETC	Volumetric Ethanol Excise Tax Credit
WARM	Waste Reduction Model
WBGU	German Global Change Advisory Council
WCRP	World Climate Research Programme
WMO	World Meteorological Organisation
WSSD	World Summit on Sustainable Development
WtE	Waste to energy

1 Introduction

Climate change has been considered a fact for over a decade, following the proof of rising CO_2 levels, rising Earth's temperatures, melting of glaciers, etc. The consequences can be observed in many regions in daily life, by events such as more frequent or stronger flooding of rivers, increased storms and snowfall, cloudbursts, as well as drought, and desertification. The reason for climate change, natural or anthropogenic, has been under discussion for a long time.

There is no doubt that mankind contributes to climate change through activities connected with emissions of climatically relevant gases. For example, use of fossil fuels with high emissions of carbon dioxide and other climate gases, especially in transportation and traffic, industrial production and application of substances (which are climate gases of extreme high warming potentials), agricultural activities (such as animal husbandry and rice cultivation) leading to emissions of methane or nitrous oxide, and methane emissions from landfills caused by ineffective waste management, etc.

To control the situation, reduction measures of climate gases and other relevant actions, are urgently necessary on all levels. This is understood by the public and by policy makers. Climate related activities thus are high ranking on the political agenda. They are implemented into the political programmes on UN level, internationally and single countries, but also on communal levels by climate initiatives of cities or NGOs. Examples are the so-called Kyoto Protocol reducing climate gas emissions in industrialized countries, bans of halogenated hydrocarbons, shifting of energy sources from fossil to renewable and international CO_2-emission trading. It is but obvious, that the efforts must be strengthened, to reduce the risks of a dangerous interference with the climate system.

This publication is intended to give a more detailed insight into the problem and the efforts to tackle it, so that the reader is able to develop best climate strategies in practical cases in his own field. In the first part, fundamentals of climate and climate change are discussed, including facts on climate system functioning and its modelling, as well as the effect of climate change on sustainable development and international policy approaches. In the second part, climate and related effects of technology are evaluated, and an overview of effects of industrial and agricultural processes on climate are given, including technological, infrastructural, economic, and socially oriented activities to reduce climate gas emissions.

2 The Climate System

Climate is one of the most important natural resources. Given the size of the planet Earth and its mean distance from the Sun, the three leading climate parameters are solar energy flux density, clouds plus precipitation and land surface characteristics. Asking for the most fundamental parameters for our life we get a very similar answer: energy from the sun, water from the skies and photosynthesis of plants. Hence, climate determines where we can live in larger numbers, what food we get, and how we have to protect ourselves against weather related extremes.

It is therefore obvious that decision makers have to deal with climate whether it is changing because of external forcing or just varying because of internal interaction of climate system components. It has become common practice to speak of the climate system and its components in order to point to its complexity because of the manifold interactions within components and among them. As box 2.1 underlines the components interact at very different timescales from minutes to billions of years, thus creating continuous changes of climate, to which all living beings have to adapt but to which also all living beings have contributed.

2.1 Climate System Components

All parts of the Earth system are important for the climate in a certain area. Therefore, no single place is independent of all others on our globe. The best example of the component interactions are the joint glacials and interglacials of both hemispheres, although the triggering comes from the northern hemisphere with its major landmasses. If the northern hemisphere is closest to the Sun in boreal winter, the declination of the Sun is high (it can vary from 21.8 to 24.5°) and the eccentricity of the Earth's orbit is larger than on average the probability for an inception of a glacial is high. As observations of atmospheric composition, reconstructed from air bubbles in Antarctic ice, confirm, the main long-lived greenhouse gases in the atmosphere, namely carbon dioxide (CO_2), nitrous oxide (N_2O) and methane (CH_4), then start declining and also the southern hemisphere with higher solar radiation flux density will "descend" into a glacial as well. Although the processes leading to this joint glacials are not yet fully understood, it is clear that ocean, atmosphere, biosphere and cryosphere have interacted strongly to create global mean surface temperatures 5°C lower than in interglacials.

Box 2.1: Climate System Components and their Typical Timescales

Climate must change continuously as the components of the climate system interact non-linearly at very different time scales from minutes to billion years (see also table 2.1). And because the radiation flux density of the Sun also varies on time scales from minutes to billions of years. In addition, the Earth's orbit around the Sun varies quasi-periodically through changed positions of the neighbouring major planets (Venus, Jupiter, Saturn). Understanding the Earth system, of which climate is an important part, is therefore a very complex endeavour and far from being in a very mature stage.

Table 2.1: Climate system components and their typical time scales, together with some climate phenomena

Component	Typical Time-scales	Some Climatically Relevant Phenomena
Atmosphere	Minutes to Millennia	Planetary Boundary Layer Height, Greenhouse Gas Composition, Annual Cycles of Temperature and Precipitation, Storm Tracks
Ocean	Seasons to about 100,000 years	Boundary Currents (e.g. Gulf Stream), Global Conveyor Belt, Single and Multi-year Sea Ice
Biosphere	Days to Millennia	Blooming, Biomass Production, Biome Distribution, Vegetation Cover, High Biodiversity in the Tropics, Vegetation Period, Anthropogenic Monocultures, Algae Blooms, Food Webs in Ocean and on Land
Cryosphere	Days to Millions of Years	Snow Cover, Ice Sheets, Ice Caps, Mountain Glaciers, Permafrost, Frozen Ground, Lake and River Ice, Sea Ice
Lithosphere	Years to Many Million Years	Continental Drift, Subduction of Oceanic Crusts, Formation of Mountain Ranges, Earthquakes, Volcanoes, Fossil Fuel Formation
Pedosphere (Soils)	Decades to Many Millennia	Weathering of Rocks, Humus Formation, Cycling of Elements through Microbiological Processes, Changed Atmospheric Composition by Emissions from Soils

2.2 Observed Climate Variability and Change

One of the most obvious characteristics of climate is its variability, especially in areas with strong gradients of climate zones, e.g. in the semi-arid tropics and in higher mid-latitudes. The mean temperature of one of the coldest days in July and one of the warmest in December in Hamburg do not differ. The rain in parts of the Northern Sahel from one year to the next may differ by more than a factor 3. Therefore climate – as the synthesis of weather – is not only characterized by averages of parameter values but also by their frequency distributions (see figure 2. 1 and box 2.2). Although strong deviations from the average value are rare, they get most of the attention because they represent weather extremes to which our infrastructures are often not well adapted. As Figure 2.1 also clarifies, new extremes on the side to which the distribution is shifted must accompany climate change. The only exception would be the case with a strongly narrowing frequency distribution (what has not been observed). Do we already observe manifestations of climate change? Yes, there are numerous ones, besides the obvious mean global near surface air temperature increase over the recent 150 years (see figure 2. 2). These are (only examples):

- Accelerated mean retreat of mountain glaciers worldwide,
- Strong decrease of multi-year sea ice in the Arctic Ocean (-7 percent per decade since 1979 when satellite observations began),
- Reduced snow cover over North America, less pronounced over Eurasia,
- More rain per event in nearly all areas with slightly decreasing, constant or increasing total precipitation,
- Reduced daily temperature amplitude which can be caused by higher water vapour content, increased cloudiness and higher atmospheric turbidity,
- Mean global sea level rise, about 1.5 to 2.0 mm/a in the 20th century, recently increased to ~3 mm/a, as observed by satellite altimeter measurements since 1991,
- Increased yearly precipitation in most high latitude areas, decreased yearly precipitation in the semi-arid subtropics,
- Decreased temperatures in the stratosphere and mesosphere,
- Increased vegetation period length (about 2 weeks) in the Northern Hemisphere higher latitudes,
- Changed optical properties of clouds caused by air pollution.

In the present rapid climate change era single evaluations of very long time series are therefore partly misleading as the recent decades might have shown a changed frequency distribution of a climate parameter, e.g. rain amounts per event. Therefore subsections of long time series have to be evaluated separately.

Strong climate variability on time-scales up to millennia, as oceans and ice sheets are involved in creating it, makes it difficult to separate climate variability from real climate change. Observations are always the result of variability and change. For more details see section 4.4.

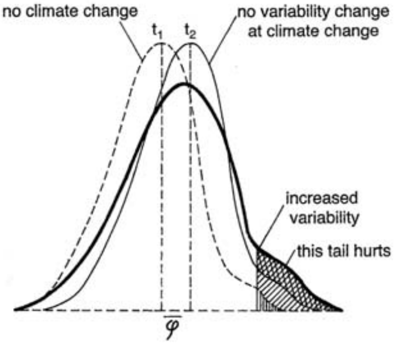

Figure 2.1: **Schematic frequency distribution of climate parameters both for present climate and changed climate. Also a broadened distribution for a changed climate is shown (Grassl, 2002).**

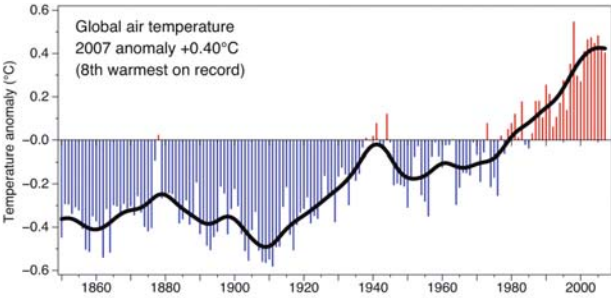

Figure 2.2: **Global mean near surface air temperature since 1856 (Meteorological Office of the United Kingdom)**

Box 2.2: **Climate, its Variability and Change**

The World Meteorological Organization (WMO) in Geneva, a Specialized Agency of the United Nations, defines climate as the synthesis of weather extracted from frequent atmospheric and surface parameter observations over at least 30 years. This synthesis must contain the probability of deviations from the mean, i.e., the number of events deviating for example 3 standard deviations σ from the mean must be known. If mathematical functions are fitted to the observations the frequency distributions turn into probability density functions. If the frequency distribution is close to a Gaussian distribution, like for temperature, a 3 σ-event is close to what most would call a hundred year event, observed only once per century. However, for such long periods the frequency distribution might have changed when climate change has occurred.

Climate change occurs if external parameters change, like solar radiation flux density. It has become customary to speak of climate change also if volcanic eruptions reach the stratosphere or mankind changes atmospheric composition inadvertently, although we and volcanoes are part of the Earth system.

2.3 The Greenhouse Effect of the Atmosphere

If the transmission of solar radiation to the surface of a planet is less attenuated than the emission of thermal (heat) radiation from the surface to space, the surface and the lower atmosphere of the planet warm until emission at the top of the atmosphere balances (in a multi-year average) the amount of solar radiation absorbed by the atmosphere and the surface. For the planet Earth the warming at the surface because of strong absorption of thermal radiation by some atmospheric gases is caused nearly exclusively by minor constituents, i.e. by less than three per mille of the mass of the atmosphere. The warming caused by these minor constituents is about 30°C. The use of the word “about” is due to the fact that we do not know which reflectivity for solar radiation the Earth’s surface would have without these gases, as the ocean might not exist as at present. Since the heat absorbing gases act like glass covering a greenhouse, the warming effect caused by them is called in the rough analogy greenhouse effect.

2.4 Greenhouse Gases

The main constituents of the atmosphere are nitrogen (N_2) with 78.09 percent, oxygen (O_2) with 20.94 percent and Argon (A) with 0.93 percent, constituting already 99.96 percent of the dry atmosphere. The minor constituents absorbing strongly thermal infrared (heat) radiation are (if ranked according to importance in the undisturbed pre-industrial atmosphere):

1. Water vapour (H_2O), responsible for nearly two-thirds of the greenhouse effect;
2. Carbon dioxide (CO_2), responsible for about 20 percent;
3. Ozone (O_3), responsible for about 7 percent;
4. Nitrous oxide (N_2O), contributing only about 3 percent;
5. Methane (CH_4) contributing less than 3 percent.

Some other naturally occurring gases, like carbon monoxide (CO), are weak greenhouse gases but are neglected here.

It is important to note that two of these five greenhouse gases are short-lived, namely water vapour and ozone, with lifetimes of about 9 days and hours to months, respectively. The other three gases are all called long-lived, although they differ strongly in their lifetimes. Methane needs about 12 years and nitrous oxide 120 years until their concentration would have fallen to about 37 percent, i.e. 1/e, if no emissions occurred. For carbon dioxide no single number can be given as the uptake into the ocean is a complex process that involves several time scales, e.g. sedimentation of organisms. About 200 years are needed to reach 1/e for the additional (anthropogenic) load.

Table 2.2 Recent changes of naturally occurring long-lived greenhouse gases due to human activities (IPCC, 2007a)

Species	**Concentration**		
Year	1750	2005	Change since 1998
CO_2 (ppm)	280	379 ± 0.65	+ 13
CH_4 (ppb)	730	1,774 ± 1.8	+ 11
N_2O (ppb)	270	319 ± 0.12	+ 5

The assessment of the consequences of an enhanced greenhouse effect (for concentration changes see table 2.2.) is made more complicated by the strong temperature dependence of the water cycle including the dominant greenhouse gas water vapour (see box. 2.3). Radiative transfer calculations with fixed atmospheric composition, except a doubling of carbon dioxide concentration, and allowing so-called convective adjustment in the troposphere, give a 1.2°C average warming of near surface air temperature. If water vapour reacts, like in so-called equilibrium models of general atmospheric circulation, the warming roughly doubles mainly due to two positive feedbacks, one by water vapour (already mentioned) and the other by the snow/ice-albedo[1]/temperature feedback. The big uncertainty still remaining for the sensitivity of the climate system to an enhanced greenhouse effect is due to the less well known feedback of clouds, where even the sign of the global mean effect is not known, although locally it is clear that more low, optically thick water clouds would

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[1] Albedo is the ratio between backscattered and incoming solar radiation flux density. Therefore it is zero for a black body and unity for a completely backscattering or reflecting surface. Typical values of natural surfaces like forests and grassland vary from about 10 to 20 percent, but can reach 90 percent for fresh powder snow.

dampen the enhanced greenhouse effect (negative feedback) and that cold but thin cirrus (ice clouds) in the upper troposphere would enhance it.

Box 2.3 Known Positive Feedbacks in the Water Cycle

The dominant cycle for the climate system is the water cycle. This dominance is due to several positive and potentially also negative feedbacks. Two positive feedbacks have to be named here caused by:

- The Clausius-Clapeyron equation
- The differences between the albedo of snow/ice and liquid water

Feedback 1: Assuming chemical equilibrium and the second law of thermodynamics we get for the change of water vapour pressure in the atmosphere dp_s at saturation for a temperature change dT

$$\frac{dp_s}{dT} \approx \frac{L}{vT^2}$$

with

L = latent heat of evaporation
v = specific volume of water vapour
T = absolute temperature (K)

For atmospheric temperatures between +25°C at saturation (base of a tropical cumulus cloud) and -80°C at saturation (tropical cirrus cloud top) the saturation pressure p_s increases from 6 to 20 percent per °C temperature change following this equation. Hence the water vapour pressure varies by up to four orders of magnitude between cloud base and cloud top of a severe tropical cumulonimbus. In other words: Nearly all water vapour in this column (~ 60 mm of precipitable water) will fall out as rain, for a convergent flow even more.

Therefore, the dominant greenhouse gas water vapour will show a positive feedback (i.e. it will amplify) when a warming is stimulated by a greenhouse gas concentration increase.

Feedback 2: The brightest and the darkest natural surface are composed of water: Fresh powder snow “reflects” (in reality mainly backscatters) about 85 percent of incoming solar radiation flux density while the ocean absorbs about 96 percent at blue skies and high sun; hence reflecting only 4 percent. Consequently the disappearance of snow or sea ice warms the lower atmosphere which leads to further melting nearby. This positive feedback is the key feedback in glacial cycles and is still important at present, as large parts of the Northern Hemisphere land and ocean are seasonally and smaller parts permanently covered by snow or snow on sea ice. This positive so-called snow/ice-albedo/temperature feedback is also fundamental for the inception of a glacial.

2.5 The Carbon Cycle and Atmospheric Carbon Dioxide

Besides the water cycle also the carbon cycle is fundamental for the Earth's climate. All Earth system components contain carbon and exchange it rapidly or slowly causing major changes of climate. The most active part of the carbon cycle is the exchange between the atmosphere and the biosphere, both on land and in the sea. As figure 2.3 shows the reservoir atmosphere with about 760 GtC looses about 120 ± 70 GtC per year because carbon dioxide (CO_2) is

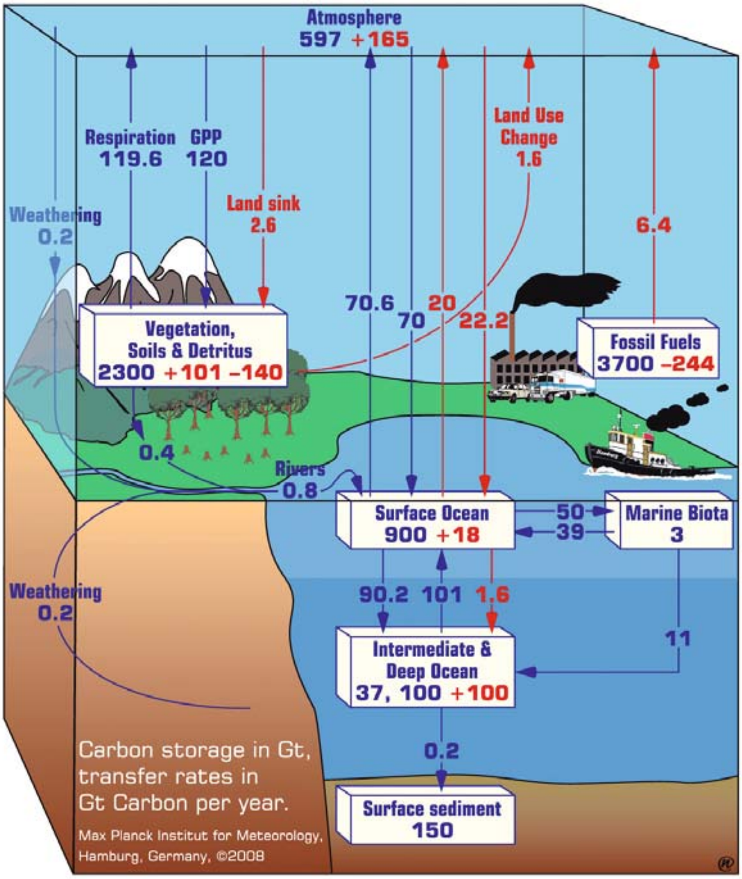

Figure 2.3: **Carbon fluxes between the reservoirs in GtC and GtC/a, respectively (IPCC, 2007a)**

taken up by terrestrial plants or enters the sea, where part of it is used by algae for biomass production. Nearly the same amount is going back to the atmosphere because of out-gassing from the ocean and respiration by plants, animals and humans. Thus, the undisturbed carbon cycle is nearly balanced, as only 0.2 GtC/a are buried in sea sediments and a still not well known small portion (0.4 GtC/a) enlarges peat bogs or is emanating from or buried in deep soils. From the above we learn that the lifetime of carbon dioxide in the atmosphere is rather short, about seven years, and the question arises "Why is there a problem with additional CO_2 as "only" about 8 GtC/a, roughly one percent of the reservoir content, are emitted by human activities?" As Table 2.3 clarifies 4.1 ± 0.1 GtC/a of these emissions remain in the atmosphere, hence increase the atmospheric carbon reservoir by about half a percent per year. Only 2.2 Gt of the anthropogenic carbon enter the ocean per year and thus are taken away for hundreds of years. Would we stop emissions only about 15 percent of all former anthropogenic emissions will in the long-run stay in the atmosphere. Table 2.3 contains a further astonishing fact: In the 1990s the existing terrestrial biosphere grew, by about 2.6 ± 1.7 GtC/a, more than the emissions from deforestation and other land use change that reached 1.6 ± 1.1 GtC/a. Overall, the carbon stored in the biosphere increased in recent years.

How long will this favourable situation last? No answer can be given yet but coupled carbon cycle and climate models, forerunners of the emerging Earth system models, show at least that there is the possibility for a sign change in the latter part of the 21st century. Then climate change impacts are much stronger and the carbon dioxide fertilization effect draws down carbon dioxide levels in the atmosphere less as climate change puts more pressure on terrestrial and marine ecosystems, which then reduce the CO_2-uptake. The lesson from this section: the net fluxes into the ocean interior count and not gross primary production on land or fluxes from the atmosphere across the ocean surface. While the carbon cycle was nearly balanced before industrialization, it is strongly imbalanced now with a "hangover" of more than 3 GtC/a for the atmosphere.

Table 2.3: Present anthropogenic carbon emissions and heat fluxes; all in GtC/a (IPCC, 2007a)

	Period		
	1980s	1990s	2000 – 2005
Atmospheric increase	3.3 ± 0.1	3.2 ± 0.1	4.1 ± 0.1
Emissions (fossil + cement)	+5.4 ± 0.3	+6.4 ± 0.4	+7.2 ± 0.3
Net flux ocean/atmosphere	-1.8 ± 0.8	-2.2 ± 0.4	-2.2 ± 0.5
Net flux land/atmosphere	-0.3 ± 0.9	-1.0 ± 0.6	-0.9 ± 0.6
Land use change flux	+1.4 (0.4 to 2.3)	+1.6 (0.5 to 2.7)	n.a.
Residual terrestrial sink	-1.7 (-3.4 to 0.2)	-2.6 (-4.3 to -0.9)	n.a.

2.6 Aerosols, their Direct and Indirect Climate Effects

Although greenhouse gases and cloud droplets and cloud ice are dominant constituents of the atmosphere determining to a large extent the radiation budget of the planet Earth, also aerosol[2] particles play a major role for our planet. These tiny particles suspended in air in the size range from about 1 nanometer (nm) to about 10 micrometers (µm) radius are either emitted from the Earth's surface or form in the atmosphere from precursor gases like sulphur dioxide (SO_2). While the small ones (< 0.01 µm radius) often get attached to other larger particles or surfaces by the molecules' Brownian motion, the larger ones, called coarse particles, with $r > 1\mu m$, settle through gravity. Therefore, maximum spectral concentration (particles per unit volume per unit of radius) is often close to $r = 0.01$ µm and typical lifetime in the free troposphere reaches weeks for particles in the size range around 0.1 µm. Their main sink process is activation as a cloud condensation nucleus and subsequent rain-out, and much less below cloud scavenging. As any cloud droplet needs an aerosol particle as a condensation nucleus, it is clear that the aerosol particles can strongly influence the optical properties of clouds and can exert an indirect effect besides the direct one, which anybody can see through atmospheric turbidity, the result of scattering of visible light by aerosol particles.

2.6.1 Direct aerosol particle effects

All aerosol particles scatter, absorb and emit radiation. Depending on their size extinction (scattering plus absorption) of solar radiation is often much more important than emission of thermal infrared radiation. Often the latter is neglected, which is only valid for particles with radii < 0.1 µm. Especially when the particles have grown with relative humidity, this neglection is not justified. As most of them are soluble and hygroscopic, i.e. they deliquesce like sodium chloride (NaCl) at about 80 percent relative humidity, turbidity of air increases strongly at high relative humidity. Hence attenuation or extinction of solar radiation by aerosol particles is not only depending on chemical composition but also on relative humidity. Via air pollution we thus change radiative transfer in the cloud free atmosphere. Main effects are:

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[2] An aerosol is a mixture of air and small particles suspended in air. Often the term aerosol is used for the particles only. Here the term aerosol particles will be preferred.