Chapter 2
Biogeosphere as Environment for Life

The properties of the Earth and especially of the biogeosphere as an environment that has allowed for the development of life and human civilization are discussed in this chapter. The first section describes the position of the Earth in the solar system and the present conditions on Earth as a whole as well in its constituents, e.g. crust, ocean, and atmosphere. The second section deals with the driving forces for changes in the biogeosphere and the resulting developments of the atmospheric composition and the global climate. Finally, the development of life on Earth and of the human civilization are briefly reviewed.

2.1 Planet Earth and the Present Biogeosphere

Earth is part of the solar system and the third of the four so-called inner planets (Fig. 2.1). Characteristic data of the Sun, the planets, as well as of the Moon can be found in Table 2.1. Earth has a mean distance of 149.6×10^6 km from the Sun and a rotational speed of $29.8\,\mathrm{km\,s^{-1}}$ resulting in a rotation period of about 365 d. The average density of the Earth is relatively similar to the values of the other inner planets which all mainly consist of rocks and metals. On the other hand, the four outer planets largely contain light elements and components, e.g. hydrogen, helium, ammonia, and water. As a result, the atmosphere of the outer planets contains mostly hydrogen and helium, while the main atmospheric constituents of the inner planets are nitrogen and carbon dioxide, except for Mercury which has hardly any atmosphere. A unique property of Earth is that its atmosphere contains large quantities of oxygen, a property that has been caused by the evolution of life and decisively determines the conditions on Earth.

The structure of the Earth is depicted in Fig. 2.2. The inner layer is the partly solid and partly liquid core with a radius of about 3470 km that consists mainly of iron and other metals at very high temperature and pressure (cf. Table 2.2). The mantle, located between core and crust, can be considered as an extremely viscous liquid capable of flowing on long timescales. The mantle contains silicate rocks

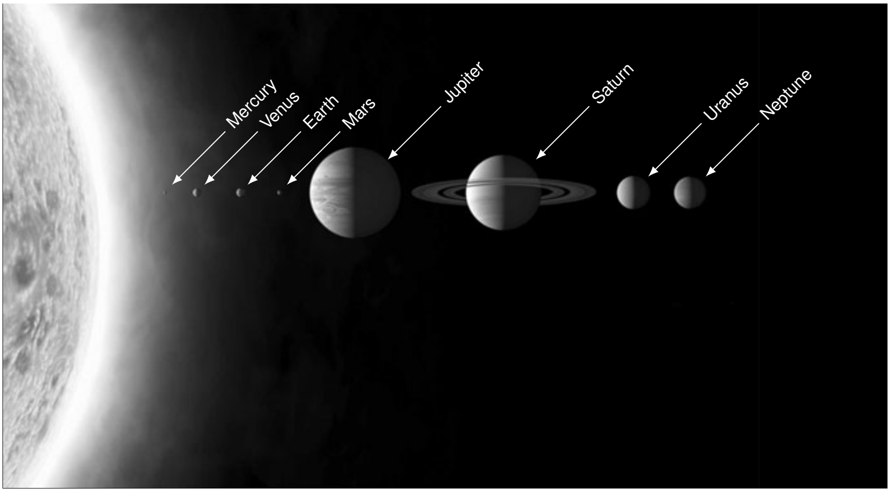

Fig. 2.1 Image of solar system, distances not to scale (http://www.iau.org)

and metals, which results in a higher density than the solid crust. This upper solid layer of the Earth has a thickness of 20 km to 100 km and contributes only a small fraction, 1.2%, to the total mass of the Earth. Additional layers of the Earth are the ocean with an average thickness of 3.7 km, and the atmosphere. As the density of the atmosphere exponentially decreases with height (see Fig. 2.5), 99% of its mass is contained in a layer with a thickness of only about 30 km. The atmosphere and ocean together represent less than 0.025% of Earth's mass.

The *biogeosphere* combines the layers of the Earth where life can exist, i.e. the lower atmosphere, the ocean, and soils and sediments that are part of the crust. Smil (2002) has pointed out that living organisms have invaded the entire ocean, most of the atmosphere – with birds reaching altitudes of more than 10 km and microorganisms even the highest layers of the stratosphere – as well as regions below ground, and the deep-ocean floor down to at least 5 km depth. Although the extent of the biogeosphere is remarkable, these few tens of kilometers form only a very thin layer separating the habitable parts of Earth from the hot interior and outer space. The conditions in the biogeosphere are not only determined by the incoming radiation from the Sun (F_{in}) and the outgoing radiation emitted by Earth's surface (F_{out}) (Fig. 2.2), but also very strongly by the existence of life, as will be shown later.

The average compositions of the whole Earth and of the layers constituting the biogeosphere reveal interesting differences (Table 2.3). While living organisms are mainly composed of the elements carbon, hydrogen, oxygen, nitrogen, sulfur, and phosphorus, it can be seen that some of these elements are only present in minor amounts in the biogeosphere. The Earth crust is composed of silicate rocks with oxygen having the largest mass fraction. The ocean is an aqueous solution of different salts (mostly sodium chloride) with a total concentration of about 3 wt% and

Table 2.1 Characteristic data (mean values) of Sun, planets, and Moon, data from Jacobshagen et al. (2000); Hartmann (1994), unless otherwise noted

	Sun	Mercury	Venus	Earth	Mars
Distance from sun/10^6 km		59.9	108.2	149.6	227.7
Orbital period/a[a]		0.2408	0.6152	1.000	1.881
Rotational speed/km s^{-1}		47.9	35.1	29.8	24.2
Rotation period/d	25.5	58.6	243	1.00	1.02
Escape velocity/km s^{-1}	617.6[c]	4.27	10.3	11.2	5.01
Equatorial diameter/km	1 391 400	4878	12 100	12 756	6786
Mass/kg	1.987×10^{30}	3.3×10^{23}	4.87×10^{24}	5.99×10^{24}	6.44×10^{23}
Density/g cm^{-1}	1.4	5.46	5.23	5.52	3.92
Albedo		0.058	0.71	0.30	0.16
Surface temperature/°C	5800	350	480	15	−23
Surface pressure/bar		2×10^{-15}	90	1	7×10^{-3}
Atmosphere	92% H_2 7.8% He		96% CO_2 96% N_2[c]	77% N_2 21% O_2 1% Ar	95% CO_2 2.7% N_2 1.1% Ar
	Jupiter	**Saturn**	**Uranus**	**Neptune**	**Moon**
Distance from sun/10^6 km	778.3	1429.4	2875.0	4504.3	0.35[b]
Orbital period/a[a]	11.86	29.46	84.01	164.8	27.32 d[b]
Rotational speed/km s^{-1}	13.1	9.64	6.81	5441	
Rotation period/d	0.41	0.43	0.7	0.7	27.3
Escape velocity/km s^{-1}	59.4	35.5	21.4	23.4	2.4
Equatorial diameter/km	142 796	120 000	50 800	46 300	3476
Mass/kg	1.91×10^{24}	5.57×10^{24}	8.66×10^{24}	1.03×10^{24}	7.35×10^{22}
Density/g cm^{-1}	1.31	0.70	1.3	1.66	0.11[c]
Albedo	0.34	0.34	0.34	0.29	−75
Surface temperature/°C	−150	−175	−225	−220	−75
Surface pressure/bar	$\gg$100	$\gg$100	$\gg$100		10^{-14}
Atmosphere	89% H_2 11% He	97% H_2 3% He	85% H_2 15% He		

[a] Except moon
[b] Relative to Earth
[c] Fact sheets on http://nssdc.gsfc.nasa.gov

Table 2.2 Properties of Earth layers, data from Cattermole (2000); Krauskopf (1979)

Layer	Earth	Core	Mantle	Crust	Ocean	Atmosphere
Thickness (radius)/ km	6370	3470	2850	20–100	3.7[a] ($\leq$11)	30[b]
Mean density/ kg m^{-3}	5520	10 700	4500	2800	1027	1.2[c]
Mass/kg	5.98×10^{24}	1.87×10^{24}	3.97×10^{24}	7.08×10^{22}	1.41×10^{21}	5.12×10^{18}
Mass fraction/%	100	31.6	67.2	1.20	0.024	0.000 09
Temperature/°C	–	3000–4000	1000–3000	15–400	15	15[c]
Pressure/bar	–	3.8×10^6[d]	1.4×10^6[d]	1[c]	1[c] ($\leq$1100)	1[c]

[a] Average value
[b] Contains $\geq$99% of atmosphere mass
[c] At sea level
[d] Maximal values

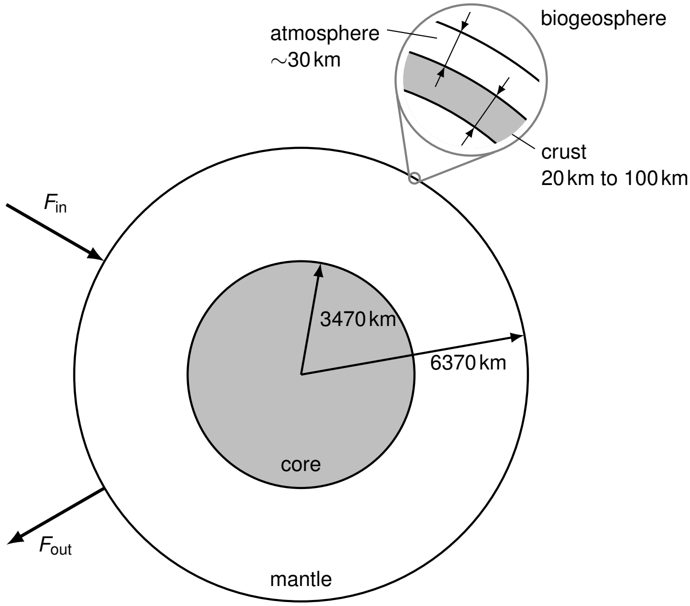

Fig. 2.2 Structure of Earth

contains also trace amounts of dissolved atmospheric gases. The main constituents of the atmosphere are nitrogen and oxygen. These unusually high amounts of free nitrogen and oxygen together with the much lower carbon dioxide fraction than for the other inner planets (Table 2.1) are caused by living organisms, namely through photosynthesis (cf. Sect. 3.4).

Figure 2.3 shows some important interactions between the constituents of the biogeosphere. The *hydrosphere* is the combined mass of water found on Earth, i.e. the ocean, freshwater, groundwater, and ice. The *lithosphere* is the outer rocky shell of the planet, including the crust and the uppermost mantle. The *biosphere* as the entirety of all living organisms interacts with the hydrosphere, lithosphere, and atmosphere. Climate, i.e. the average weather conditions including temperature, precipitation, wind etc. mainly concerns the atmosphere and the hydrosphere. On the other hand, the interaction between atmosphere and lithosphere leads to decomposition and erosion of solid components. Finally, sedimentation and formation of reservoirs mainly takes place at the interface between hydrosphere and lithosphere.

The conditions in the biogeosphere are obviously influenced by the radiative energy that the Earth receives from the Sun (Chap. 3). Physical and chemical processes taking place in the ocean, atmosphere and on the land surface also strongly determine the chemical composition in the different compartments and the energy balance of the Earth. However, the most powerful force for changes during Earth history and for maintaining the beneficial current conditions on our planet has been life, as will be discussed in the following section.

Table 2.3 Composition (mass fractions) of whole Earth (Schlesinger 1997), Earth crust (Krauskopf 1979), ocean (Krauskopf 1979), and atmosphere (Schlesinger 1997, additionally assuming a mean water concentration of 4000 ppm), bold elements are the most important constituents of living organisms (CHONSP)

Rank	Whole Earth	%	Earth crust	%	Ocean	%	Atmosphere	%
1	Iron	35	**Oxygen**	46.4	**Oxygen**	86.0	Nitrogen	75.3
2	**Oxygen**	30	Silicon	28.2	**Hydrogen**	11.0	Oxygen	23.4
3	Silicon	15	Aluminum	8.1	Chlorine	1.88	Argon	1.28
4	Magnesium	13	Iron	5.4	Sodium	1.08	**Hydrogen**	0.03
5	Nickel	2.4	Calcium	4.1	Magnesium	0.13	**Carbon**	0.02
6	**Sulfur**	1.9	Sodium	2.4	**Sulfur**	0.09		
7	Calcium	1.1	Magnesium	2.3	Calcium	0.04		
8	Aluminum	1.1	Potassium	2.1	Potassium	0.03		
9			Titanium	0.50	**Nitrogen**	0.02		
10			**Hydrogen**	0.14				
11			**Phosphorus**	0.11				
12			Manganese	0.10				
13			Fluorine	0.07				
14			Barium	0.05				
15			Strontium	0.04				
16			**Sulfur**	0.03				
17			**Carbon**	0.02				

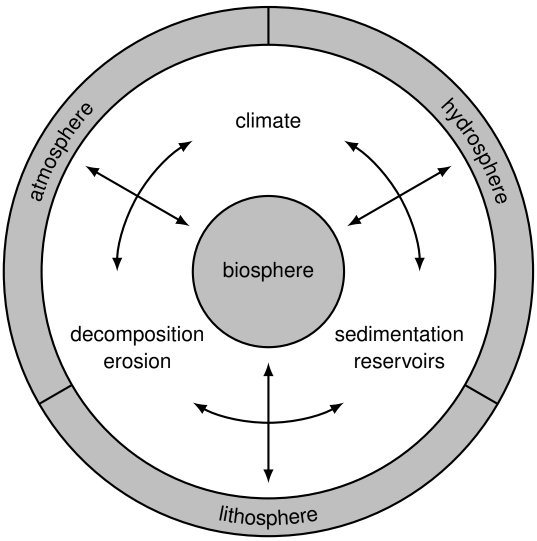

Fig. 2.3 Earth's biogeosphere and the interactions of its constituents, inspired by a brochure of the International Union of Geological Sciences IUGS, http://iugs.org/uploads/images/PDF/12_earthandlife.pdf

2.2 Historical Development of the Biogeosphere

The biogeosphere has undergone a long development over at least 3.5 Ga with drastic changes in the conditions on Earth. These transformations were driven by several factors the most important of which was the evolution of life. The composition of Earth's atmosphere is currently very different from the reconstructed initial state after formation of the Earth and development of the first organisms. At the same time the climatic conditions were subject to alterations as the Earth's energy balance is strongly influenced by the presence of some atmospheric constituents. Life is the key player in the Earth system as it not only continuously alters the global conditions, but has, until now, also been able to adapt itself to the new constraints and to evolve consistently new, higher forms. Recently, man – and especially the modern industrialized civilization – has become an additional driver which has a dramatic impact on global ecosystems and climate at an unprecedented time rate of change.

2.2.1 Formation of Earth and Driving Forces for Change

Earth as a part of the solar system is about 4.5 Ga old (Dalrymple 1991). Thus, it is much younger than our galaxy which has an estimated age of 13.2 Ga (Frebel et al. 2007) and was formed relatively soon after the universe originated in the *Big Bang* some 13.75 Ga ago (Hinshaw et al. 2009). Planets are believed to have grown in the solar nebula from agglomeration of dust and small bodies, so-called *planetesimals* (Schlesinger 1997). The early Earth most probably did not have any atmosphere as the energy released during collisions of planetesimals and by radioactive processes in its interior lead to the melting of the Earth's constituents. Even if there had been an atmosphere, it must have been completely lost as the Moon was formed after collision of the Earth with a body of almost the size of Mars causing the melting of both the impactor and Earth's mantle (Wayne 2009).

After subsequent cooling down, a solid crust was then formed and a new atmosphere mainly consisting of CO_2, N_2 and H_2O developed from outgassing from the inner Earth and from impacting ice-containing bodies such as comets (Wayne 2009). Although the ocean might have appeared as early as 200 Ma after formation of the Earth, it is very likely that repeated vaporization of part or even the entire mass of liquid water was caused by impacts of large bodies until around 3.8 Ga before present (Smil 2002). Only after that period of *heavy bombardment* could life have been formed on Earth, most probably not later than 3.5 Ga ago (Wilde et al. 2001).

However, even after the initial dramatic incidents, conditions on Earth have been subject to considerable changes caused by several different mechanisms (Table 2.4). The most important processes on the early Earth were inorganic chemical reactions of the large amounts of gaseous carbon dioxide with rocks to form carbonates. Before the evolution of photosynthesis, these weathering reactions were the primary mechanism causing the initially very high atmospheric CO_2 partial pressure of about

Table 2.4 Drivers for change of conditions in the biogeosphere

Mechanism	Effects
Inorganic weathering	Conversion of gaseous CO_2 to solid carbonates
Volcanism	Release of gaseous components to the atmosphere
Plate tectonics	Movement of tectonic plates on long time scales
Increasing solar luminosity	Changes of radiative energy balance
Changes in orbital movement and axial position	Periodic alterations of amount and location of solar radiation
Formation of life	Changes in atmospheric composition and global energy balance
Impacts of large space objects	Short-term climate changes, extinction of species
Industrialization	Global impact on land use and massive release of greenhouse gases

10 bar to decrease (cf. Fig. 1.7). On the other hand, volcanoes permanently release gaseous components, the most important of which are H_2O, CO_2, and SO_2, to the atmosphere. The movement of tectonic plates, which is mainly responsible for the volcanic activity, may have had additional effects on the conditions in the biogeosphere. For example, an increased rate of weathering reactions during geologic times with a higher fraction of continents placed in the tropics leads to enhancement of the CO_2 uptake from the atmosphere.

Other driving forces for change are related to the radiative energy received from the Sun. According to standard stellar models, stars like the Sun gradually increase their radiance with time, resulting in a relative intensity of only 70% during the early Earth's history. In addition to this gradual rise of irradiation, the movement of the Earth around the Sun leads to several periodic variations called *Milankovich cycles* which include changes of the Earth's precession, the elliptical orbit and the angle of Earth's axial tilt. These cycles lead to periodic alterations of the overall solar radiation reaching Earth on time scales of tens to hundreds of thousand years.

Finally and most importantly, the formation and further evolution of life has brought about additional changes that include the transformation of the atmospheric conditions as well as the coverage of large parts of the continents with land plants. Although causing only detrimental climate effects on a relatively short time scale, impacts of large extraterrestrial objects may have played an important role during the evolution of life as these incidents not only lead to mass extinction of species but probably also triggered the subsequent development of larger biodiversity levels (Smil 2002). Finally, man has appeared on the global scene and the capabilities of modern societies together with the rapidly growing population (see Sect. 2.2.5) have resulted in ongoing changes of the biogeosphere that now concern the entire Earth.

2.2.2 Atmosphere

The early atmosphere on Earth was in a reduced state and consisted mostly of carbon dioxide, nitrogen, and water together with minor amounts of hydrogen and carbon monoxide. Inorganic weathering reactions like the conversion of diopside to carbonates (React. 2.1) lead to a removal of CO_2 from the atmosphere (Wayne 2009).

$$CaMgSi_2O_6 + CO_2 \longrightarrow MgSiO_3 + CaCO_3 + SiO_2 \qquad (2.1)$$

The first organisms after the formation of life were most probably methanogenic bacteria converting hydrogen with carbon dioxide to methane and water in anaerobic metabolic pathways. The first photosynthetic reactions were based on carbon dioxide and either hydrogen or hydrogen sulfide and did not generate oxygen (*anoxic* photosynthesis).

Free oxygen in the atmosphere before the evolution of life could have been formed only to a minor extent by inorganic photolysis of water vapor. After the development of the oxygen-producing (*oxygenic*) photosynthesis reaction (see Sect. 3.4) the oxygen levels in the atmosphere have risen until present-day levels were eventually reached. However, it took some time before O_2 started to accumulate in the atmosphere as the released oxygen was initially consumed by reduced atmospheric components (CO, H_2), reduced species in the ocean (Fe^{2+}, S^{2-}), and reduced minerals such as pyrite (FeS_2). Figure 2.4 shows that the formed oxygen initially lead to *banded iron formations*, a characteristic type of rock containing hematite (Fe_2O_3) or magnetite (Fe_3O_4). After atmospheric oxygen started to accumulate around 2 Ga before present, or even as early as 2.4 Ga ago according to

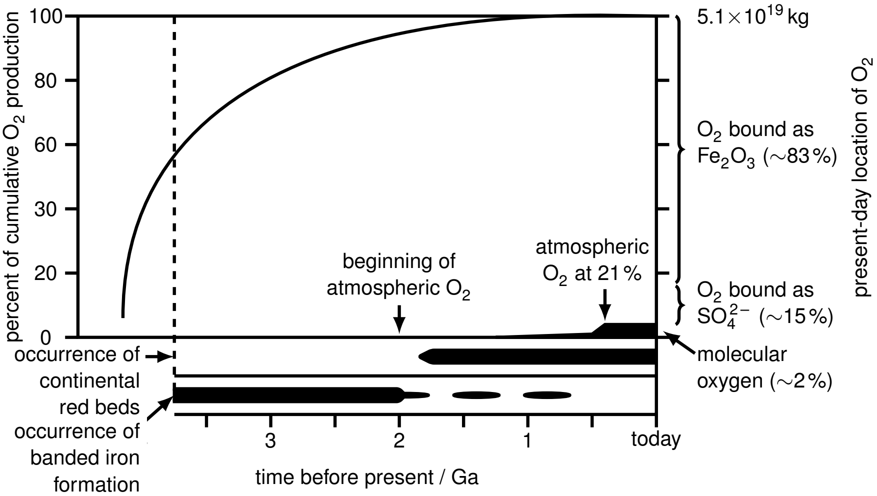

Fig. 2.4 Cumulative history of O_2 released by photosynthesis through geologic time, after Schlesinger (1997)

Buick (2008), so-called *red beds* occurred, iron oxide containing minerals that indicate aerobic terrestrial weathering. This process consumed the major part of O_2 from photosynthesis until the atmospheric oxygen concentration started to rise significantly. Overall, it is believed that 98% of the released oxygen are now bound as iron oxides or sulfate, whereas only 2% remained in the atmosphere.

The structure of the atmosphere is depicted in Fig. 2.5. Gravitational forces keep the gaseous constituents of the atmosphere close to Earth's surface. The atmospheric pressure p strongly decreases with altitude z as the mass of the overlying atmosphere becomes smaller. The hydrostatic equation (Eq. 2.2) describes this relationship.

$$p = p_0 \exp \int_0^z \frac{gM}{RT} \, \mathrm{d}z \tag{2.2}$$

Here, p_0 is the pressure at surface level, g the acceleration of gravity, M the average molar mass of air, R the gas constant ($8.314\,\mathrm{J\,mol^{-1}\,K^{-1}}$) and T the temperature. This equation assumes that the atmosphere behaves like a single gas with a mean molar mass, although in reality several gases with different mass occur. However, the mixing processes in the atmosphere below an altitude of about 100 km are efficient enough to achieve a uniform composition (Coe 2009).

The thermal structure of the atmosphere is relatively complicated (Fig. 2.5). In the lowest layer above the Earth's surface (the *troposphere*), the temperature almost linearly decreases by about $6.5\,\mathrm{K\,km^{-1}}$ until a first minimum (*tropopause*) is reached at a height of 10 km. The *stratosphere* is the second atmospheric layer between 10 and 50 km, where the temperature gradually increases to a maximum of about 0 °C at the *stratopause*. This temperature inversion is caused by the pho-

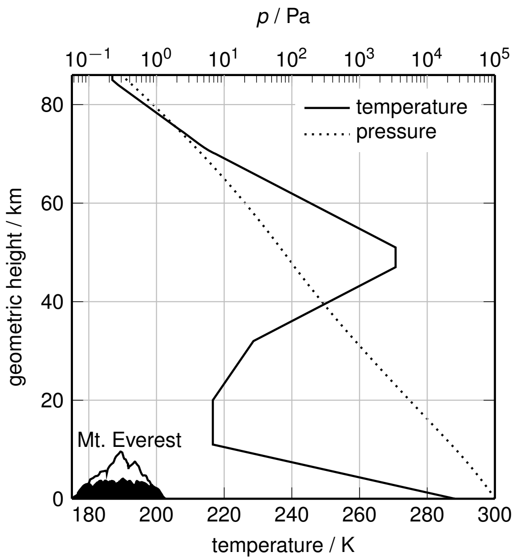

Fig. 2.5 Temperature and pressure profile of the atmosphere to 86 km as defined by the US Standard Atmosphere (1976)

tolytic splitting of O_2 by ultraviolet solar radiation and the resulting formation of ozone (O_3, Reacts. (2.3) and (2.4)).

$$O_2 \longrightarrow 2\,O \tag{2.3}$$

$$2\,O + 2\,O_2 \longrightarrow 2\,O_3 \tag{2.4}$$

This overall reaction effectively absorbs ultraviolet radiation from the Sun (Fig. 3.3) and is thus a protective shield for organisms living on the land surface (Sect. 2.2.4).

The third layer of the atmosphere is called *mesosphere*, which extends to about 90 km above surface level. Here, the temperature decreases again. The thermal structure of the troposphere is also responsible for the global circulation patterns of the atmosphere (Fig. 2.6). Due to the large amounts of solar radiation received at the equator (see Sect. 3.3), warm air masses that contain much water vapor rise there. Upon cooling at higher altitudes, precipitation occurs and the now relatively dry air moves away from the equator. At approximately 30N and 30S latitude, the air masses sink to the surface and form characteristic direct patterns, so-called *Hadley* cells. Similar patterns also occur in the polar regions, and the two direct tropical and polar cells drive an indirect circulation pattern known as *Ferrel* cell at 30N–60N and 30S–60S. As a result of these intensive circulation processes, the tropospheric air in the Northern and Southern Hemisphere mixes within a few months (Schlesinger 1997).

Table 2.5 summarizes the average concentrations of atmospheric constituents, their total mass, and their mean residence time. Most of these species are quite uniformly distributed in the atmosphere. This is the case for the main atmospheric components, nitrogen and oxygen, and all other gases with a residence time of at least a few years. The behavior of water vapor is very different as it has a residence time of only about 10 days (Schlesinger 1997). Therefore, the water vapor concentration shows large spatial and temporal variations. Additionally, the upper parts of the atmosphere above 10 km contain only minor amounts of water due to

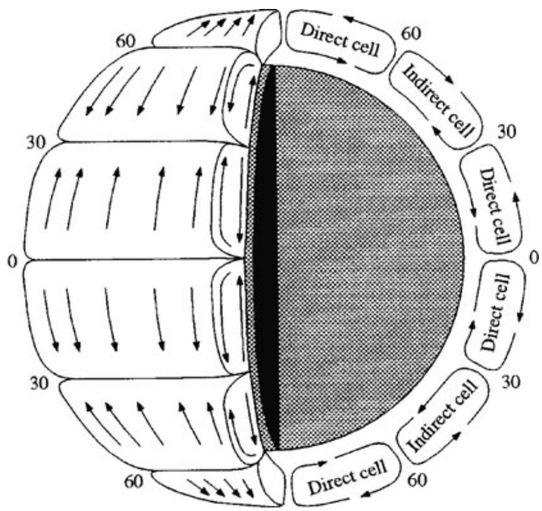

Fig. 2.6 Global patterns of circulation showing surface patterns (*left hand side*) and vertical patterns (*right hand side*), from Schlesinger (1997), reproduced with permission

Table 2.5 Global average concentrations of atmospheric constituents, data from Schlesinger (1997) unless otherwise noted

Compounds	Formula	Concentration[a, b]	Residence time/a	Total mass/kg
Major constituents/%				
Nitrogen	N_2	77.698	2.4×10^{7}[d]	3.87×10^{18}
Oxygen	O_2	20.863	4000[d]	1.19×10^{18}
Argon	Ar	0.930		6.59×10^{16}
Water	H_2O	0.4	0.025	1.3×10^{16}[a]
Parts-per-million constituents/ppm $= 10^{-6}$				
Carbon dioxide	CO_2	378[f]	3.6[d]	2.95×10^{15}
Neon	Ne	18.1		6.49×10^{13}
Helium	He	5.22		3.70×10^{12}
Methane	CH_4	1.76[f]	12[c]	5.02×10^{12}
Krypton	Kr	1.14		1.69×10^{13}
Parts-per-billion constituents/ppb $= 10^{-9}$				
Hydrogen	H_2	508		1.82×10^{11}
Ozone	O_3	390		3.3×10^{12}[e]
Nitrous oxide	N_2O	319[f]	114[c]	2.49×10^{12}
Xenon	Xe	87		2.02×10^{12}
Parts-per-trillion constituents/ppt $= 10^{-12}$				
Methyl chloride	CH_3Cl	620	1.0[c]	5.53×10^{9}
CFC 12	CCl_2F_2	540[f]	100[c]	3.12×10^{10}
Carbonyl sulfide	COS	500		5.30×10^{9}
CFC 11	CCl_3F	250[f]	45[c]	6.79×10^{9}
Ammonia	NH_3	100[e]		3×10^{10}[e]
Methyl bromide	CH_3Br	11	0.7[c]	1.84×10^{8}

[a] Original values assuming dry atmosphere with molecular weight of 28.97 g mol^{-1} modified taking into account mass of water vapor (Trenberth and Smith 2005) corresponding to average water concentration of 0.4 Vol. %
[b] Volume fractions
[c] IPCC (2007)
[d] Own estimates based on reservoirs and transfer flows (cf. Chap. 4)
[e] Hartmann (1994)
[f] Updated 2006

their relatively low temperatures. Another example of a component with significant variations is ozone, which develops a characteristic profile as a function of altitude and may decline strongly at certain locations due to anthropogenic activities (see Sect. 4.7).

Table 2.5 also contains values for several trace gases with relevance for Earth's radiative energy balance (Sect. 3.2). The concentration of some of these components has strongly risen during the last decades (e.g. CO_2, CH_4, N_2O). Others are produced synthetically and did not occur in the pre-industrial atmosphere (chlorofluorocarbons such as CCl_2F_2). The latter species are chemically inert in the troposphere and are able to mix into the stratosphere, where they contribute to ozone depletion by catalytic action.

In addition to gases, large quantities of small solid particles or liquid droplets, so-called *aerosols*, are present in the atmosphere (Table 2.6). These particles, which

Table 2.6 Global emissions of aerosols, from Schlesinger (1997), after Jonas et al. (1995)

Natural sources	Flow/Mt a^{-1}	Anthropogenic sources	Flow/Mt a^{-1}
Primary aerosols		Primary aerosols	
Soil dust	1500	Industrial particles	100
Sea salt	1300	Soot	20
Volcanic dust	33	Particles from forest fires	80
Organic particles	50		
Secondary aerosols		Secondary aerosols	
Sulfates from organic sulfides	90	Sulfates from SO_2	140
Sulfates from SO_2	12	Nitrates from NO_x	36
Organic condensates	55	Organic condensates	10
Nitrates from NO_x	22		
Sum natural sources	3070	Sum anthropogenic sources	390

are often transported over long ranges, can be subdivided into primary and secondary aerosols. *Primary* aerosols are particles that are emitted to the atmosphere as solid particles, e.g. soil dust by wind erosion, dust from volcanoes, or industrial particles especially from coal-fired power plants. *Secondary* aerosols are formed in the atmosphere from volatile components. One example is the natural formation of sulfates from gaseous organic sulfides such as dimethyl sulfide ($(CH_3)_2S$). These sulfate aerosols play an important role as cloud condensation nuclei (see Sect. 4.5).

2.2.3 Climate

Climate is the average state of the atmosphere (temperature, precipitation, pressure, wind speed etc.) observed over long time periods, e.g. several years or decades. In contrast, weather comprises the short-term atmospheric conditions relevant for hours or days. The *climate system* consists of the atmosphere, the ocean, the cryosphere (ice on land and ocean), the land surface, and the biosphere. This complex system is determined by several factors the most important of which are the incoming solar radiation and the composition of the atmosphere, especially regarding species able to absorb infrared radiation (Chap. 3). Solar radiation gradually increases over very long time periods, while periodic fluctuations occur due to the movement of the Earth around the Sun. The composition of the atmosphere is – as previously discussed – influenced by inorganic reactions, biotic processes, and most recently through anthropogenic activities.

The simplified reconstructed development of the average global temperature since the formation of Earth as well as a projection for the future are shown in Fig. 2.7. The early Earth was very hot, but rapid cooling occurred and liquid water was formed 4 Ga ago or earlier. Although the solar radiation at that time was lower than today, the temperatures remained higher than at present, most probably caused by very high carbon dioxide concentrations that trapped infrared radiation. CO_2

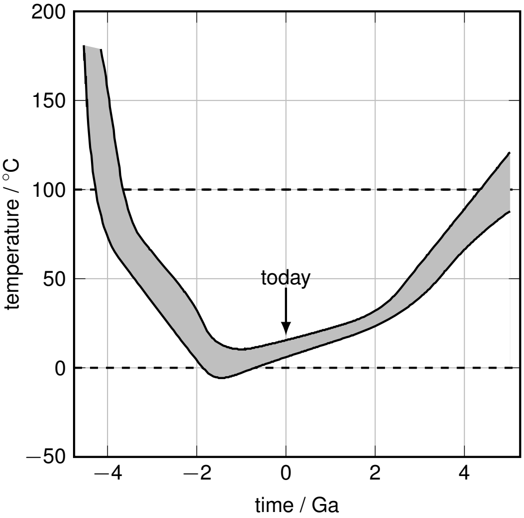

Fig. 2.7 Estimated development of temperature at sea level since the formation of Earth and future prediction, after Schönwiese (2008)

consuming processes (weathering, photosynthesis) lead to a significant decrease of the global temperature until glaciations – supposedly even worldwide – occurred for certain periods of time. Since about 1 Ga before present, the temperature has shown a rising tendency, probably caused by the increasing solar irradiation at already relatively low carbon dioxide concentration levels. For the long-term development, one can therefore expect the global temperature to rise significantly, especially since there is little capacity for further cooling through reduction of CO_2 concentrations (Wayne 2009).

The temperature depicted in Fig. 2.7 is to a large extent based on geophysical models and only partly on experimental observations. On shorter time scales, a broad range of paleoclimatological methods allows for the relatively precise reconstruction of climatic conditions. These methods are comprised of the investigation of sediments and ice cores, chemical signatures of certain elements in minerals, isotopic ratios (especially of oxygen), investigation of fossil soil and organisms, as well as tree rings from living plants for the very recent developments. Figure 2.8 shows average atmospheric surface temperatures in the Northern Hemisphere for the last million years and the last ten thousand years, respectively. One can see that strong temperature fluctuations of up to 7 K occurred during the last million years and that temperature changes took place within a period of only a few thousands of years. Overall, the climate in the Northern Hemisphere was much colder than today, with massive glaciations periodically covering large parts of North America and northern Europe. It has been estimated that northern Germany, which was predominantly ice-covered during the *last glacial maximum* about 18 000 a ago, had an

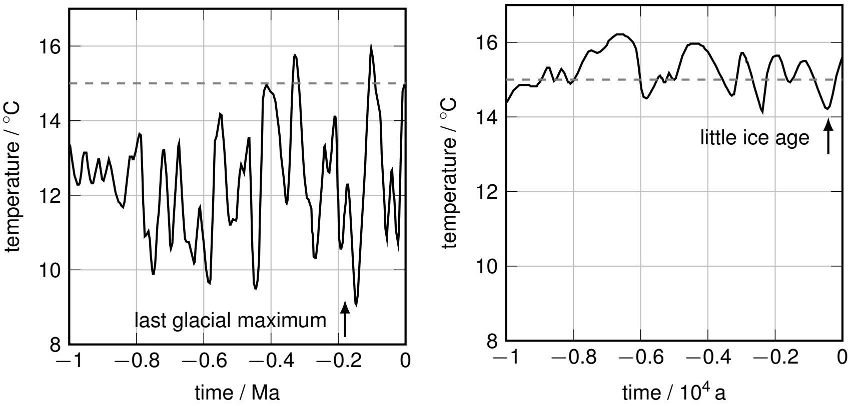

Fig. 2.8 Reconstruction of average surface temperatures in the Northern Hemisphere during the last million years (*left*) and the last ten thousand years (*right*), *dashed lines*: current average global surface temperature, data from Schönwiese (2008)

average yearly temperature of around –20 °C (Schönwiese 2008), more than 25 K lower than today.

In contrast, the temperatures during the last 10 000 years appear to have remained relatively constant around 15 °C (Fig. 2.8, right). Nevertheless, the observed temperature variations of no more than ±1 K were responsible for quite significant local climate changes. During the *medieval climate optimum*, around 1000 a before present, it was possible to colonize the south of Greenland. However, the following *little ice age* – the period between the 14th and the 19th century – brought much colder climates to Europe and North America with crop failure and long, harsh winters. It has to be noted that these considerable climate changes correspond to average surface temperature differences in the Northern Hemisphere of less than 1.5 K.

The systematic study of climatic trends through direct observations started after the development of instruments, e.g. for temperature and pressure measurements. Today, a global network of meteorological stations is available which are assisted by satellite-based measurements. These observations allow for the precise assessment of climatic alterations both locally and as a global average. Figures 2.9 and 2.10 show the development of average summer air temperatures and summer precipitation in Europe between 1901 and 2000 as examples. It can be seen that the regions with the strongest warming (>1.5 K) are located in the south of France, Spain, and around Austria. On the other hand, a slight temperature decrease occurred in some regions of Russia. The temperature trends of the European winter temperature are relatively similar to these patterns. The development of the average summer precipitation (Fig. 2.10) shows that some regions like Portugal, Spain, and Poland received less rainfall while precipitation increased in northern Europe, Southern Italy, and Greece. On the contrary, the corresponding trend for winter (not shown) reveals slightly increased rainfall for Central Europe.

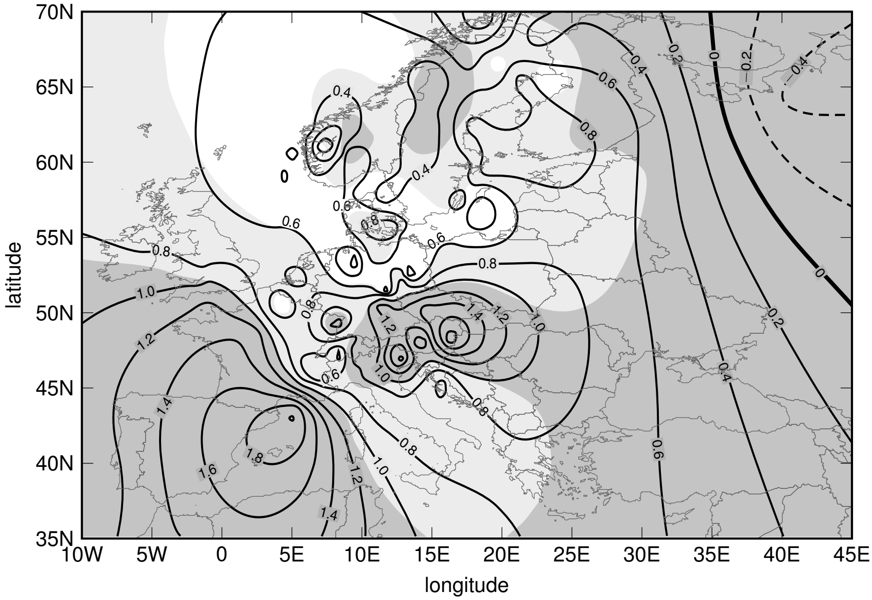

Fig. 2.9 Linear trends of average summer air temperatures in K at sea level in Europe between 1901 and 2000 (Schönwiese 2008), *gray*: >99% significance, *lightgray*: >85% significance, *dashed lines*: temperature decrease

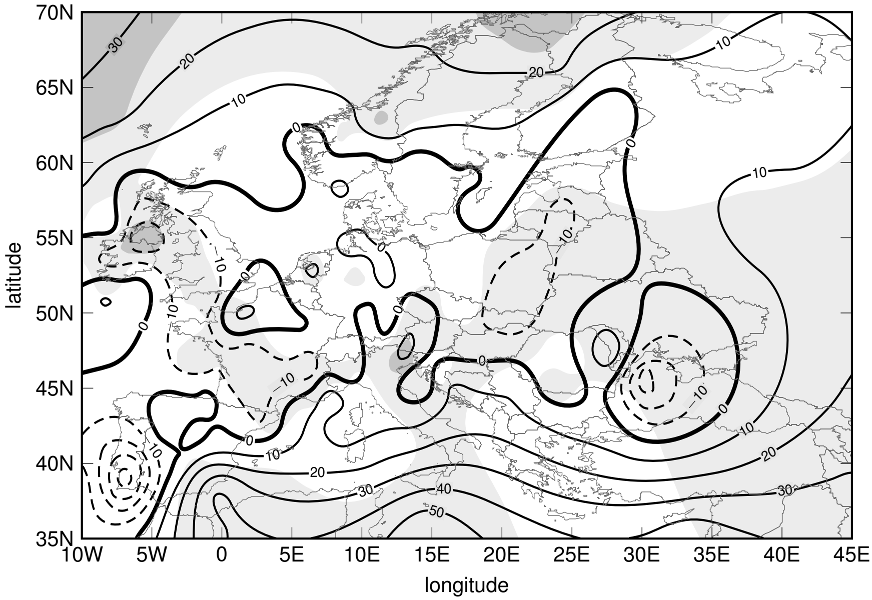

Fig. 2.10 Linear trends (in %) of average summer precipitation in Europe between 1901 and 2000 (Schönwiese and Janoschitz 2008), *gray*: >95% significance, *lightgray*: >70% significance, *dashed lines*: decreased precipitations

The climate system of the Earth shows a complex spatio-temporal behavior. Even during phases with relatively constant average global conditions, significant local variations can occur. In addition to the factors summarized in Table 2.4, the climate is also influenced by atmospheric (see Fig. 2.6) and oceanic circulation. Warm water masses in the *gulf stream* and its extension towards Europe are responsible for higher temperatures in coastal areas of Ireland, Great Britain, and Norway than would exist in the absence of this ocean current. Although the resulting temperature differences might be only on the order of 1 K, the effects on vegetation, agriculture and overall habitability of the respective region are quite noticeable. One should keep these facts in mind for the later discussion of the current and predicted future impact of anthropogenic activities on the climate of the Earth.

2.2.4 Life

Life on Earth comprises all living species such as microorganisms, fungi, plants, and animals. All of these very different living systems have the ability to respond to outer stimuli, to grow, develop and reproduce, to maintain themselves in a stable, favorable state, and to adapt – through natural selection – to their changing environment over successive generations. Organisms are open systems that exchange energy and matter with their surroundings. Viruses are organisms at the edge of life as they have no metabolism of their own and are not able to reproduce autonomously without the aid of a host organism.

The smallest unit of a living system is a cell and organisms can be classified into unicellular and multicellular types. Depending on the kind and complexity of cells, simpler *prokariotic* and more evolved *eukariotic* organisms, the cells of which have a nucleus and so-called organelles, can be distinguished. Prokaryotes are in most cases unicellular organisms such as bacteria and archea. Eukaryotes have a cell nucleus which contains the genetic material and several other cellular substructures, mostly surrounded by membranes i.e. layers with tailored permeability for molecules and/or ions. These organisms appear as unicellular microorganisms but also as multicellular fungi, plants, and animals.

The energy and mass balance of organisms can be driven by a remarkably broad variety of metabolic pathways. Basically, one can distinguish between *autotrophic* and *heterotrophic* organisms. Autotrophs employ energy from the environment either from sunlight (photoautotrophs) or from simple inorganic compounds (chemoautotrophs) and use it to produce more complex and energy-rich carbon-containing molecules. These mechanisms are the core of primary production of organic molecules and the basis of all food chains. Heterotrophs rely on organic carbon substrates produced by autotrophs. Photoheterotrophs use energy from sunlight, but require organic carbon for growth, whereas chemoheterotrophs such as fungi and animals need carbon-containing molecules both as energy and carbon source.

The metabolism is the overall chemistry taking place in organisms to maintain life. It can be grouped into metabolic pathways i.e. complex series of chemical reactions often accelerated and controlled by organic catalysts, so-called enzymes. Key components in metabolic pathways are comprised of proteins, carbohydrates, lipids, nucleotides, and many other macromolecules. The central unit of intracellular energy transfer is adenosine triphosphate (ATP) which releases high amounts of energy during hydrolysis to adenosine diphosphate (ADP) and water. Probably the most important development during the evolution of life on Earth was oxygen-producing photosynthesis. This process allows organisms to obtain carbohydrates (e.g. glucose $C_6H_{12}O_6$) from carbon dioxide and water under irradiation of sunlight. The energy contained in glucose is employed via *glycolysis*, another central metabolic pathway taking place in almost all organisms, to build up ATP and other energy carriers.

The myriad of chemical processes necessary for maintaining life, growth of organisms, and their reproduction requires the storage of information and mechanisms for its transmission. All these instructions are encoded in deoxyribonucleic acid (DNA), a long nucleotide-based polymer in form of a double-stranded helix. Remarkably, this type of molecule is composed of only four structural elements, adenine, cytosine, guanine, and thymine. These nucleobases form the DNA macromolecule together with sugar and phosphate groups and the sequence of the four bases contains the genetic information. Decoding takes place via various types of ribonucleic acid (RNA), a macromolecule similar to DNA, but single-stranded and containing uracil rather than thymine as the fourth nucleobase. As a result, all proteins composed of 20 amino acids can be synthesized, which is necessary for the proper function and reproduction of organisms.

Changes in the DNA sequence, caused by errors occurring during DNA replication, by radiation, chemicals, or viruses, are called *mutations*. Depending on the position and severity of the alterations, mutations may have either no effect or give rise to modifications of the cellular chemistry. As many of the mutations have detrimental effects, organisms have developed repair mechanisms to maintain their functionalities. However, mutations can also have positive effects on organisms and are the basis for continuous *evolution* of life. In a changing environment, some mutations of organisms are preferred over others by natural selection. Apparently, these adaptive processes are extremely efficient as life has encountered not only dramatic alterations of environmental conditions during Earth's history, but has also come close to extinction during several occasions such as severe global glaciations and impacts of large extraterrestrial bodies (Smil 2002).

There is general consensus that life has developed over long time spans from primitive beginnings to more evolved and intricate forms. Darwin was among the first to describe this evolution as *tree of life* visualizing the common origin and subsequent branching of species through time. Today, modern classifications of this type are called *phylogenetic* trees which are based on the genetic information contained in organisms. Figure 2.11 shows such a diagram proposed by Woese et al. (1990) who defined archea as a new domain of life independent of bacteria.

This genetically based analysis successfully supports the traditional way to reconstruct the historic evolution of life based on the fossil record. Despite tremendous research effort, there is still no generally accepted theory explaining how life

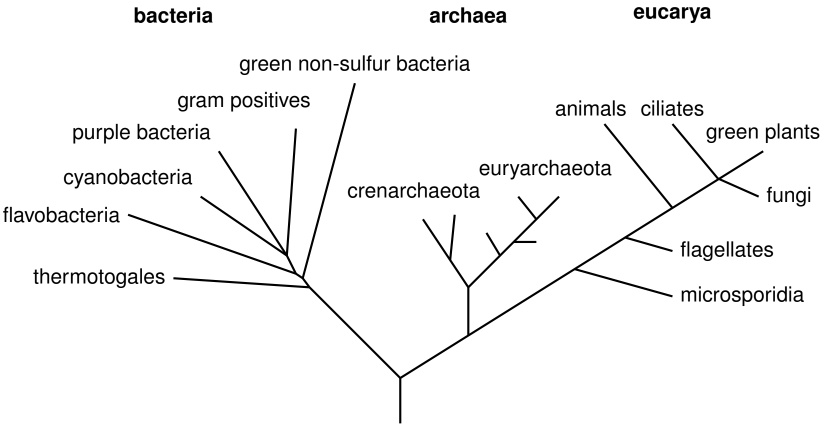

Fig. 2.11 Universal phylogenetic tree based on RNA sequence comparisons, after Woese et al. (1990), simplified

on Earth could have formed from inanimate matter. Although elements of the overall process such as the formation of organic molecules and membrane-like structures are quite well understood, there is no consensus about how self-replicating processes might have evolved. Nevertheless, life must have been formed relatively early in Earth's history (Fig. 2.12) as the oldest fossil objects are believed to be microorganisms generated 3.5 Ga before present (Wilde et al. 2001). These already quite complex living organisms must have required some time for development, thus life probably occurred soon after the end of the heavy bombardment about 3.8 Ga ago. During the Archean, simple life forms dominated the biosphere with methanogens, and other species employing several variations of photosynthesis, being present. At the beginning of the Proterozoic, cyanobacteria were already the most important species (Smil 2002). Thus, the oxygen concentration in the atmosphere began to rise soon (Buick 2008).

The appearance of free oxygen in the atmosphere (the *great oxygenation event*) was a milestone in Earth's history when a change from reducing to oxidizing conditions in the biosphere occurred. This had dramatic consequences for those species relying on anaerobic metabolic pathways, like methanogenic bacteria or photosynthetic sulfur bacteria, which were poisoned by O_2 and could survive only in niche habitats. On the other hand, atmospheric oxygen allowed for the development of the ozone layer which protects life from harmful ultraviolet radiation outside the ocean. Moreover, more complex eukariotic cells appeared around 1.8 Ga before present which were the basis for superior multicellular life forms (Schlesinger 1997). At the end of the Proterozoic, algae and first animals such as sponges already existed.

The Phanerozoic, the current eon in the geologic timescale, started about 540 Ma ago with the relatively sudden appearance of many new life forms during the *Cambrian explosion*. Land plants, complex multicellular eukaryotes obtaining their en-

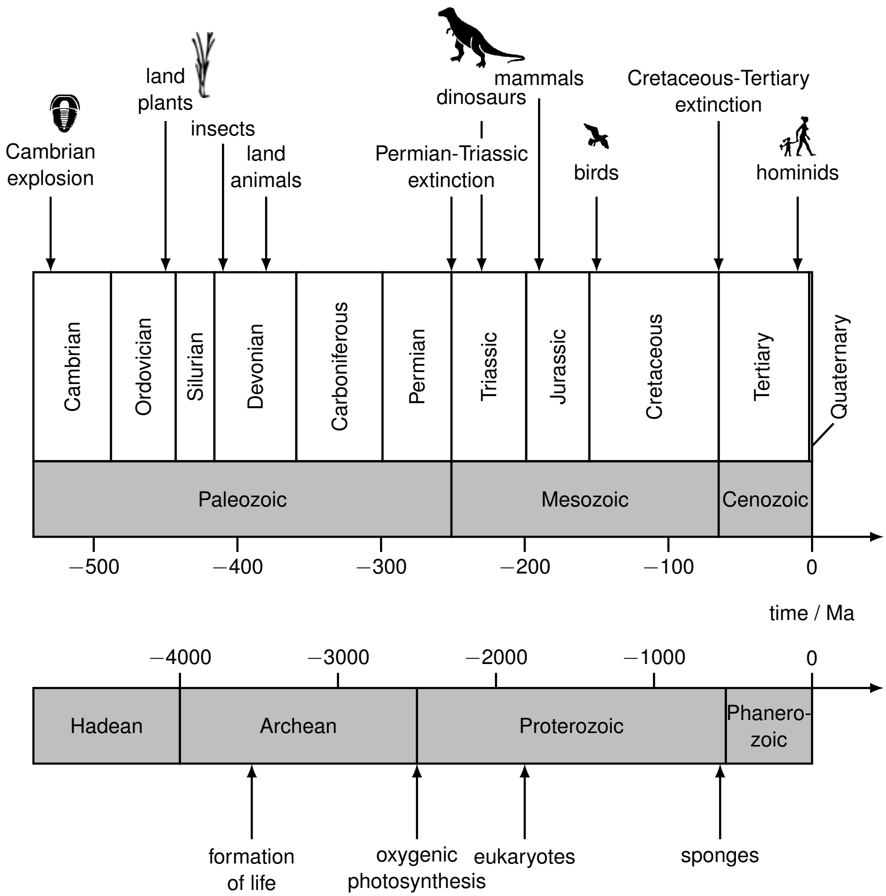

Fig. 2.12 Divisions of geologic time and major stations during development of life on Earth

ergy from photosynthesis, started to occupy terrestrial habitats some 450 Ma ago (Smil 2002). These species dramatically intensified the overall production of oxygen and the transfer of carbon from the atmosphere to soils and sediments. Land animals followed during the Devonian and the Permian already saw a rich diversity of terrestrial life. Many species died out during the severe Permian-Triassic (250 Ma ago) and the Cretacious-Tertiary (65 Ma ago) extinction events but life resisted these dramatic incidents – which might have been caused by climatic changes, enhanced volcanic activity or impacts of huge meteorites – and recovered relatively quickly. Mammals that appeared 195 Ma before present eventually evolved hominids around 20 Ma ago (Smil 2002). These great apes are believed to be the ancestors of the species *homo sapiens*, the modern humans which appeared in Africa about 200 000 years ago and subsequently spread to other continents.

2.2.5 Civilization

Modern civilization arose during the *Neolithic revolution* when early societies transformed from hunting and gathering to agriculture and settlement in villages and towns. Foraging societies with population densities of up to only a few humans per km^2 could not evolve functional specialization and social stratification (Smil 1994). Plant and animal domestication in agriculture allowed for enhanced and more reliable food production. Agricultural techniques ranging from burning or clearing the natural vegetation over the use of irrigation, fertilization and draft animals to the development of cropping cycles were invented in several regions of the world with Mesopotamia and Egypt being among the first centers of the emerging civilization.

Intensification of agriculture and food production was achieved through partial replacement of human labor by work done by animals, e.g. oxen, buffaloes, and horses, used for plowing. Since biomass growth through photosynthesis is directly linked to the availability of water (cf. Sects. 3.4 and 4.3) with one kilogram of important crops typically requiring up to 1000 kg water, irrigation is essential in many regions. Gravity-driven irrigation using canals or dams has a relatively low energy demand, but in many cases it was necessary to lift water over considerable heights by human or animal power, often assisted by mechanical devices. Finally, cropping lead to deficits in nutrients – especially of nitrogen – and thus ways to recycle these indispensable materials had to be developed.

Once sufficiently advanced agricultural techniques had been developed, higher population densities that ultimately lead to the formation of more complex societies living in cities became possible. Building the *great pyramid* of Giza, with a mass of over 6 Mt which was completed within 20 years around 2550 BCE, required planning, logistics, supervision of tens of thousands of workers, and technical skills, all on very high levels. It is interesting to note that the world population at that time of these admirable achievements is believed to have been less than 20 million (Fig. 2.13).

Before the advent of the industrialized civilization driven by fossil fuels, the energy required for agricultural needs and the erection of buildings was obtained through human and animal labor, kinetic energy of water and wind, as well as chemical energy stored in biomass. Humans can only deliver mechanical power of the order of 100 W to 200 W over longer periods of time, whereas a horse (1 horsepower $=$ 735 W) is much stronger. On the other hand, the Roman watermill complex located at Barbegal in Southern France was already able to deliver some 30 kW (Smil 1994). Since energy supply was limited and yields from agricultural production remained relatively constant, the world population did not strongly increase from the time of the early Roman empire (400×10^6 at the beginning of the common era) until the 17th century (545×10^6 at 1650).

England was the first country to employ coal as an additional energy source on large scale. By 1650, the coal production had already amounted to more than 2 Mt (Smil 1994). Coal replaced wood in household heating, was used as reducing agent in steel production, and allowed for the invention of the steam engine, a machine

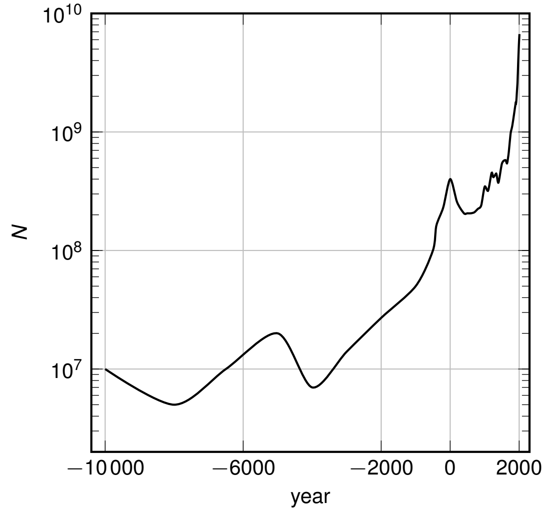

Fig. 2.13 Upper estimates of historical world population between 10000 BCE and 2008, data from US Census Bureau

able to transform the chemical energy in coal into mechanical energy. Around 1800, steam engines outperformed both watermills and windmills and could also be employed to drive large ships and locomotives (see Fig. 2.14). When the first oil fields were detected after 1850, a convenient liquid fuel with high energy content became available. These liquid hydrocarbons are highly suitable to drive internal combustion engines which became available before 1900 and are the basis for transportation in automobiles and airplanes. At about the same time, steam turbine rotating generators for the production of electrical energy were developed and quickly utilized for lighting, electric railroads, and the beginning telecommunications industry.

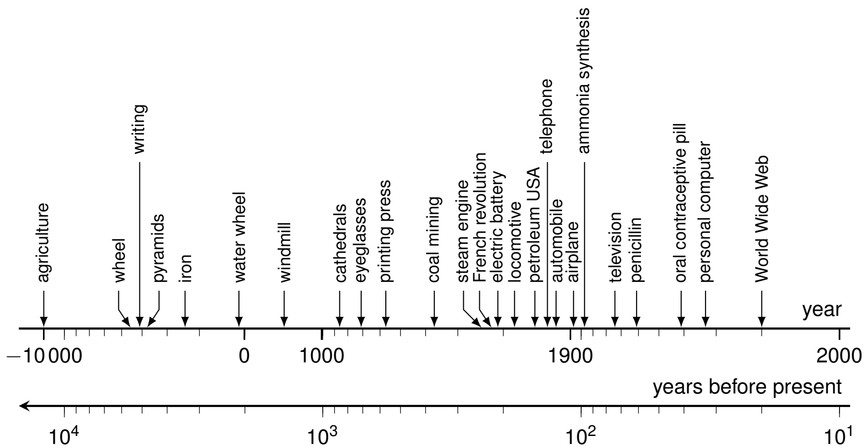

Fig. 2.14 Chronology of selected achievements during development of human civilization, from Smil (1994) and other sources

Another fundamental breakthrough was related to the development of fertilizers. Phosphates became available by treatment of phosphate rocks with sulfuric acid, while progress in mining resulted in the discovery of potassium carbonate and chloride deposits. The supply of nitrogen was improved by nitrate deposits, ammonia recovered from coke ovens or synthetically manufactured in the cyanamide process and the later developed, much more energy-efficient Haber–Bosch process (see Sect. 4.4). These artificial fertilizers and progress in the development of chemicals for protecting crops made it possible to nourish a strongly expanding world population that had reached its first billion shortly before the year 1800 and is expected to reach 7 billion by 2012 (Box 2.1 and Fig. 2.15).

Box 2.1: Expected Development of the World Population

Data for the development of the World Population since 1950 as well as the predicted future numbers until 2050 are shown in Fig. 2.15. Mathematically, the development of the number of individuals N with time t can be approximated by (Eq. 2.5),

$$\frac{\mathrm{d}N}{\mathrm{d}t} = k(t)N \tag{2.5}$$

where k is the growth rate of the population that can be calculated with the birth rate b and the death rate d according to (Eq. 2.6).

$$k(t) = \frac{b(t) - d(t)}{N(t)} \tag{2.6}$$

Early attempts to describe the population dynamics by Malthus assumed a constant growth rate and predicted an exponential increase of the number of individuals (Eq. 2.7).

$$N(t) = N_0 \mathrm{e}^{k(t-t_0)} \tag{2.7}$$

Figure 2.15 reveals that this is unrealistic as the actual growth rate has been decreasing from around 2% a^{-1} in 1970 to less than 1.2% a^{-1} after 2000 and is expected to decline further. A more realistic growth model according to Verhulst assumes a limited growth until a capacity K has been reached and results in the following development of growth rate and number of individuals as a function of time (Eqs. 2.8 and 2.9).

$$k(t) = k_0 \left(1 - \frac{N(t)}{K}\right) \tag{2.8}$$

$$N(t) = \frac{K N_0 \mathrm{e}^{k_0 t}}{K + N_0(\mathrm{e}^{k_0 t} - 1)} \tag{2.9}$$

The values calculated with a capacity of 11×10^9 cap depicted in Fig. 2.15 show a quite good agreement with the predicted development of the world population according to the US Census Bureau.

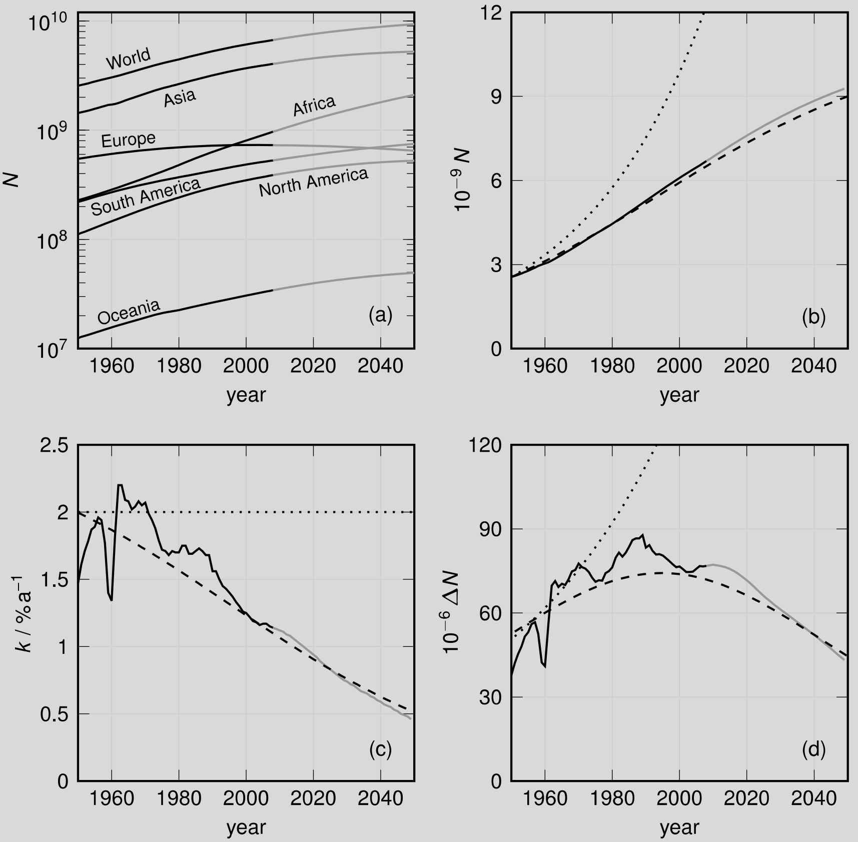

Fig. 2.15 **a** Development of regional and world population between 1950 and 2050, **b** world population, **c** world population growth rate, **d** annual population change, data from US Census Bureau, September 2009, *black lines*: data until 2008, *gray lines*: projections for time after 2008, *dotted lines*: exponential growth (calculated with $k = 2\%\,\mathrm{a}^{-1}$), *dashed lines*: logistic growth (calculated with $k_0 = 2.6\%\,\mathrm{a}^{-1}$, $K = 11 \times 10^9$)

The United Nations attempt to assess the overall status of the development in different countries and the world through the Human Development Index (HDI, see Table 7.1) which takes into account (i) the life expectancy at birth, (ii) the overall education by the adult literacy rate and the gross enrollment ratio and (iii) the per-capita gross domestic product (GDP) as a measure of the standard of living.

In the 2009 report, 38 countries having a HDI of more than 0.9 were listed with life expectancies close to or more than 80 a, very high literacy rate and GDP values above 18 000 US $\$\,\mathrm{cap}^{-1}\,\mathrm{a}^{-1}$. Figure 2.16 shows as an example that the life expectancy in Germany has more than doubled since 1875. The least developed 23 countries with HDI values below 0.5 corresponding to life expectancies around 50 a,

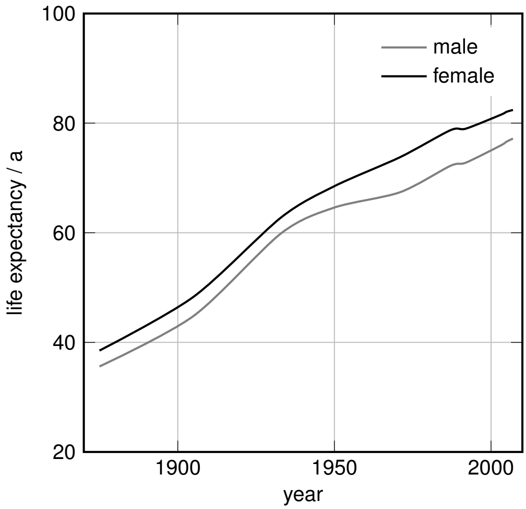

Fig. 2.16 Development of life expectancy at birth for Germany between 1875 and 2007, data from the German Federal Statistical Office

literacy rates of 30 to 70%, and a GDP of not more than 1700 US $ cap^{-1} a^{-1} are mainly located in Africa. It will be of utmost importance to improve the conditions in these regions of the world. On the other hand, the relatively comfortable conditions in the developed countries are to a large extent based on the availability of moderately priced fossil fuels which are by far the most important drivers of industrialized economies. The limits for anthropogenic energy and material flows as well as the implications for the future development of mankind will be discussed in Chaps. 6 and 7.

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Energy Flows, Material Cycles and Global Development
A Process Engineering Approach to the Earth System
Schaub, G.; Turek, Th.
2011, XII, 204 p., Hardcover
ISBN: 978-3-642-12735-9