The Earth System

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1 Earth in the Solar System

The solar system was created about 4.6 billion years ago (about 9 billion years after the big bang), supposedly after gravitational waves from a supernova produced density anomalies in an interstellar cloud, which acted as condensation centers for the sun and the planets. In addition to hydrogen and helium generated during the big bang higher elements from the ashes of burnt-out stars were present in the cloud. After the sun had formed, its radiation pressure (solar wind) forced the light gases to the edge of the cloud where the large gas planets (Jupiter, Saturn, Uranus, Neptune) formed, whereas the earth-type planets (Mercury, Venus, Earth, Mars) developed in the vicinity of the sun (see Figure 1).

In the beginning Earth was a molten planet that cooled at the surface through thermal radiation, slowly creating a solid crust. Earth consisted (and still consists) mainly of iron (37.4%), oxygen (29.5%), silicon (14.7%) and magnesium (11.2%), which together make up 92.8% of its mass.

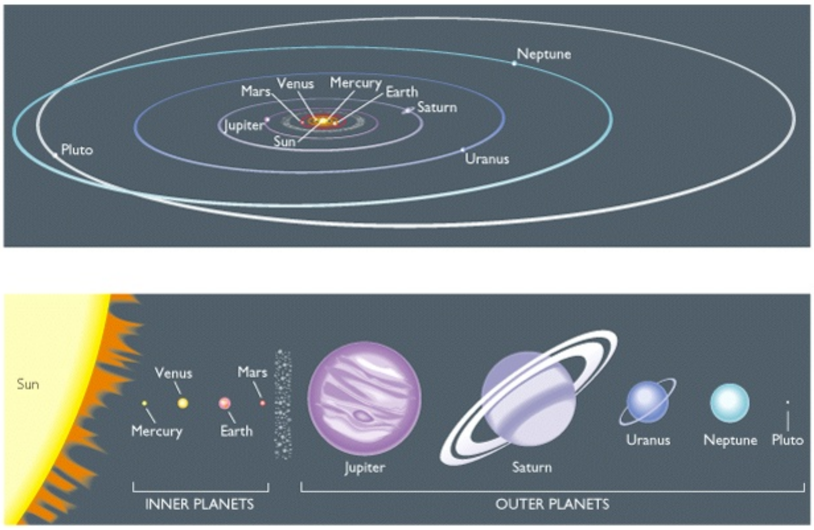


Figure 1: The planets of the Solar System. The upper panel displays the elliptical orbits of the planets around the sun, the lower panel shows the sizes of the planets.

Earth is the largest of the four planets closest to the sun: it differs in many ways from all other planets. Only Earth possesses an atmosphere which supports oxygen-breathing life forms. No other planet has a hydrosphere and living systems which are comparable to our biosphere. The size of the Earth is important because it supports enough gravitational attraction to keep atmospheric gases on the planet. For example, Mercury is too small to prevent the light gases as oxygen and carbon dioxide from escaping while Venus is large enough to keep an atmosphere.

2 Basic Building Blocks of the Earth System

The Earth is subject to constant change. Even the solid body of the Earth or the great polar ice caps are not steady but change over periods of tens to millions of years. These changes are essentially fueled by the sun's energy, the heat stored in the Earth's interior and energy given off through radioactive decay of minerals in the crust and upper-mantle. The living world is also affected by these large-scale processes and is involved in the exchange between various components of the Earth system.

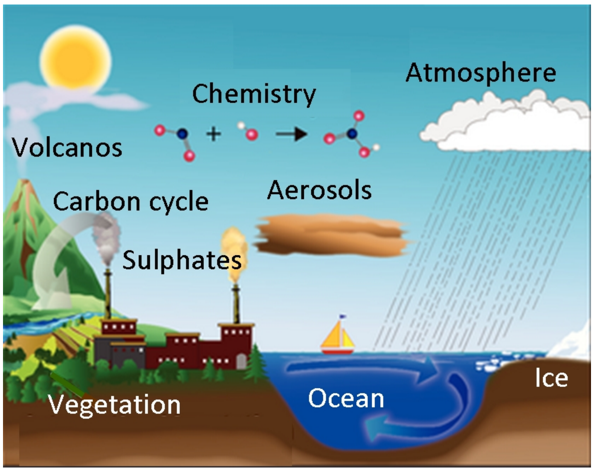


Figure 2: Sketch of the Earth system and some of its components.

The Earth is made up of the following subsystems: geosphere, atmosphere, hydrosphere, the great ice caps, the sea ice in the polar regions and the many mountain glaciers (cryosphere) and the living world (biosphere). On short time scales (years or tens of years) each of these subsystems is in a state of dynamic equilibrium. Consequently, the many different processes of interaction between the various subsystems tend to vary little. If longer periods of time are considered, fluctuations and transitions from one state of equilibrium to another become visible. These delicate states of equilibrium may be permanently disturbed by changes in external conditions. Most of the subsystems obey certain natural laws which will be introduced in the course of the following chapters.

2.1 The Geosphere

The Earth's internal structure is subdivided into crust, mantle and core and was formed very early during its development. It was only about 100 years ago that geophysical measurements proved that a chain of ridges totalling 84.700 km in length runs along the bottom of the oceans and that the Earth's crust consists of a mosaic of continental plates. Altogether there are 12 major plates. These crustal segments drift away from or towards each other at rates of up to 3 cm a year (the growth rate of finger nails). The continents are constituent parts of these drifting plates (see e.g. Figure 4). Compared to the Earth radius, the crust is extremely thin, only 4 to 7 km under the oceans and about 100 km under the continents. At the mid-ocean ridges, which can be described as a series of active magma chambers stretched out like a string of pearls, about 2.5 km^3 of new oceanic crustal rock is created each year (see Figure 5). About the same amount of older crust is swallowed up on the active continental margins (the so-called subduction zones) and returned to the Earth mantle. Both processes — the formation of new oceanic crust at the mid-oceanic ridges and the simultaneous subduction of older oceanic

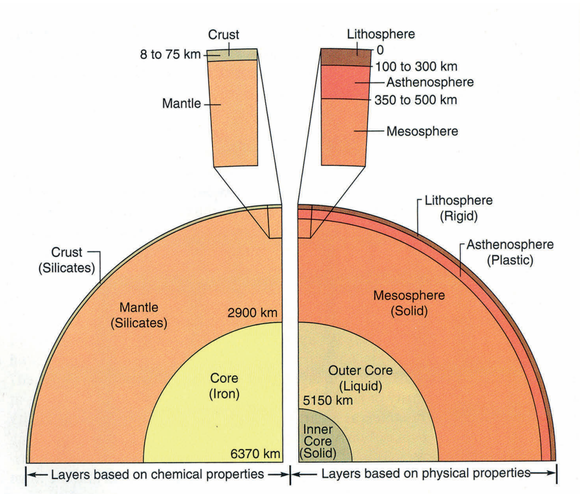


Figure 3: Structure of Earth's interior according to the chemical (left) and physical (right) properties.

crust at the active plate margins — are accompanied by intensive volcanism and increased earthquake activity in these regions. The movement of the plates is the response of the outer crust to convective motion in the Earth mantle in which hot deep material rises and cooler surface material sinks. The formation of mountain ranges as well as the creation and disappearance of ocean basins are the result of plate-tectonic processes. These processes govern the distribution of water and land over the Earth's surface.

The drift of the continents was discovered by the meteorologist ALFRED WEGENER in 1929. He used fossil plants and animals from the old and the new world but also geological structures on both sides of the Atlantic Ocean to support his idea of a large common continent (Pangaea = 'whole earth') which broke off into the American and African continents. Wegener did not live long enough to see the general acceptance of his theory by his colleagues. Only decades later did the theory of continental drift find its proof in the discovery of the plates tectonics.

The global distribution of water and land at the Earth's surface significantly affects the circulations in the ocean and the atmosphere. Thus, plate tectonics contribute to the development of climate and to changes in global environment. Volcanic eruptions, even though local in origin, can affect the Earth system as a whole. They devastate wide areas of land and drastically change the habitat of flora, fauna and man, and — for climate purposes — the volcanic output reflects in the substance composition of the atmosphere. Submarine volcanoes create and destroy groups of islands. Some large volcanic events cause eruptions of volcanic ash reaching the stratosphere, where it remains for many years, substantially influencing the radiation balance of the Earth. Identification of volcanic ash of particular volcanic events in ice cores obtained in the Arctic and the Antarctic provide evidence for the worldwide distribution of volcanic ash in the atmosphere.

The Earth's magnetic field does not remain static in the course of time. Its polarization changes direction by nearly 180° ('field reversal') in a quasi-periodic fashion. Geophysicists have shown that for the last 100 years the Earth's magnetic field has been constantly decreasing and that the next field reversal could take place in approximately 1.500 years. This could have considerable consequences for the biosphere, such as, for example, severe mutations, due to increase in cosmic radiation at the time of the field reversal.

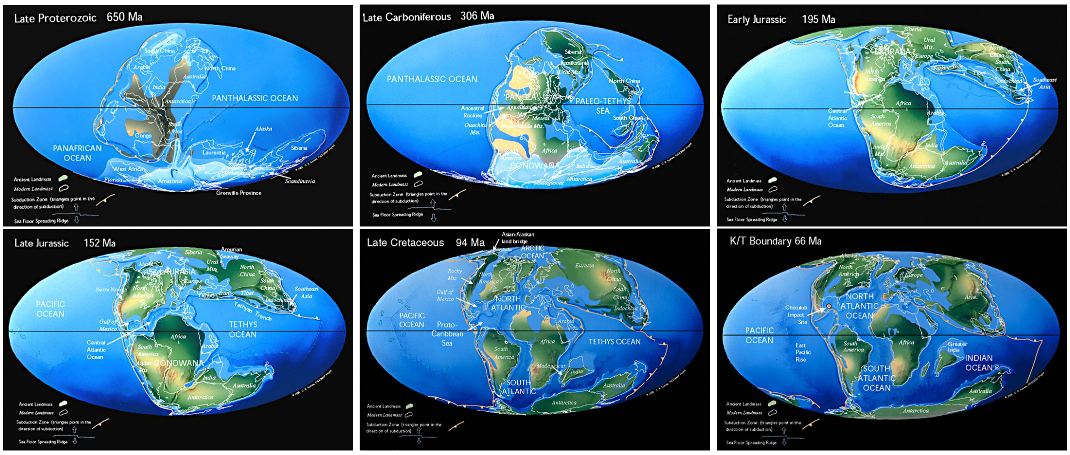


Figure 4: Drift of continents over the last 650 million years. **650 Ma**: illustrates the break-up of the supercontinent, Rodinia, which formed 1100 million years ago. The Late Precambrian was an 'Ice House' World, much like the present-day. **306 Ma**: the continents that make up modern North America and Europe had collided with the southern continents of Gondwana to form the western half of Pangaea. Ice covered much of the southern hemisphere and vast coal swamps formed along the equator. **195 Ma**: south-central Asia had assembled. A wide Tethys ocean separated the northern continents from Gondwana. Though Pangaea was intact, the first rumblings of continental break up could be heard. **152 Ma**: the supercontinent of Pangaea began to break apart in the Middle Jurassic. In the Late Jurassic the Central Atlantic Ocean was a narrow ocean separating Africa from eastern North America. Eastern Gondwana had begun to separate form Western Gondwana. **94 Ma**: the South Atlantic Ocean opened. India separated from Madagascar and raced northward on a collision course with Eurasia. Notice that North America was connected to Europe, and that Australia was still joined to Antarctica. **66 Ma**: The bull's eye marks the location of the Chicxulub impact site. The impact of a 10 mile wide comet caused global climate changes that killed the dinosaurs and many other forms of life. By the Late Cretaceous the oceans had widened, and India approached the southern margin of Asia. From `http://www.scotese.com/credits.htm`.

This map portrays the ages of the ocean floor in different colors (blue for regions created in the Jurassic Period, about 190 million years ago, and red for young ocean floor near the mid-ocean ridges).

The Earth's crust is subject to changes due to the uplift and subsidence of its parts. This gives rise to material being constantly eroded from higher areas by water, ice and air and being deposited again in subjacent areas. The extent of erosion and sedimentation depends on the prevailing topography and climatic conditions. The continual deposition of loose material in sedimentation basins over long geological periods leads to a gradual consolidation of the sedimentary layers. Ultimately, this leads to the formation of sedimentary rocks. These deposits reveal climate fluctuations way back in the past. The oldest sedimentary rocks date back some 3.5 billion years and show signs of weathering.

Soil is a degradation product consisting of rocks and organic substances formed on the surface of the land by the reaction of water, air and organisms in conjunction with environmental influences. It is the basis of life for flora, fauna and man, and an area in which the geosphere, hydrosphere, atmosphere and biosphere interact. Climate history, type of ecosystem and environmental changes can be deduced

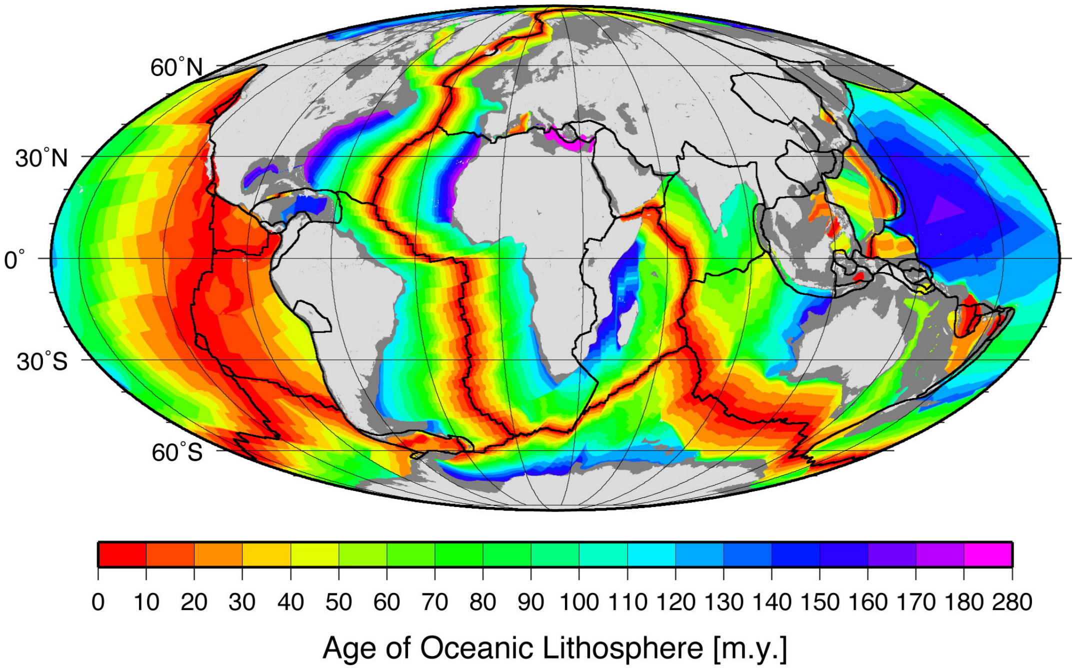


Figure 5: Age of the ocean's floor as indication of crustal movement, from red [10 million years] to purple [280 million years]. The ocean floor is nowhere older than 200 million years. From Müller et al. (2008).

from the properties of soil horizons, which depend on typical local soil-forming factors such as bed rock lithology, climate, relief and living organisms.

2.2 The Hydrosphere

The Earth is a 'water planet'. A good two-thirds of its surface, more specifically 362.000 km^2 of area, is covered with water. The large oceans are an essential prerequisite for the existence of the biosphere. They were the cradle of the first life on Earth and provide an indispensable habitat for numerous organisms. The mean depth of the World Oceans is 3.700 m and thus much larger than the mean elevation of the continents, given by 875 m. The total volume of water in the ocean is about 1.35×10^9km^3 while the and water in frozen state on Earth amounts to only 24.4×10^6km^3 (water in lakes is about 190.000km^3). Ocean water, however, is saline (see the box on p. 7) whereas water on land and specifically in the frozen state in glaciers and ice caps is fresh water. The hydrosphere has a direct influence on weather and climate conditions on Earth, with the worldwide oceanic circulation playing a particularly important role.

2.2.1 The World Ocean

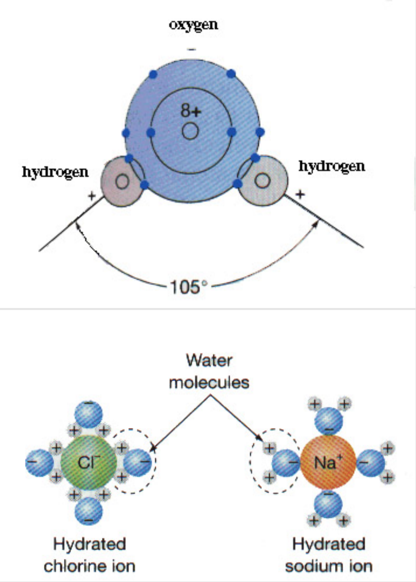
It is generally accepted that the oceanic circulation has a profound influence on the mean state of the Earth's climate and on climate changes on decadal and longer time scales. Large-scale transports of heat and fresh water by ocean currents are key climate parameters. The stratification and circulation in the upper ocean is crucial for the penetration of heat and substances into the ocean. Watermass for-

1: Water

Life on Earth is made possible by water. This is because water has a number of unusual properties, such as its high heat capacity, or its dissolving capability. Most of these properties are rooted in the molecular structure of water.

A water molecule consists of hydrogen atoms that are each bound to a central oxygen atom by sharing an electron in one of four sp^3 hybrid orbits of the oxygen atom. The two H-O bonds form an angle of 105 degrees, i.e. the three atoms are not aligned along a line but rather form a triangle. The charge of the molecule is not evenly distributed, i.e. it is polar and acts as a little dipole with the negative end closer to the oxygen atom and the positive end between the two H atoms.

Because of this polarity water is attracted both to anions and cations. When a salt dissolves in water its ions are hydrated, i.e. surrounded with water molecules. This hydration sphere is held together by attraction between the charged ion and one of the polar ends of the water molecules. Also because of its polarity, water has a tendency to form hydrogen bonds between individual water molecules; even in liquid water the individual molecules do not act independently, but tend to form clusters of molecules held together by hydrogen bonds. This 'supra-molecular structure of water' is responsible for most of its unusual properties, such as its high heat capacity, its high heat of evaporation, the density maximum above its freezing point of pure water.



Structure of a single water molecule. Dissolved ions in water are surrounded by water molecules in a so-called 'hydration sphere'. From

Water has the highest heat capacity of all solids and liquids, except liquid NH_3. This means that water has a large thermal buffer capacity. The oceans therefore act as a climate thermostat, and ocean currents can carry huge amounts of heat.

Water has the highest heat of evaporation of all liquids. This additionally creates thermostating capacity.

Water has the highest dielectric constant of all substances except H_2O_2 and HCN.

Many substances can be dissolved in water making the basic chemical reactions of life possible.

One important consequence of the hydrogen bonds between individual water molecules is that water has a much higher freezing and boiling point than would be expected from the size and weight of the molecule alone. If the hydrogen bonding would not exist, water would freeze at -110 °C and boil at -80 °C , and no liquid water would exist on Earth.

mation processes in high latitudes are an important controlling factor for the oceanic uptake of carbon dioxide through the sea surface and thus directly influence the radiative forcing in the atmosphere.

The circulation is determined by the structure and strength of the wind systems, the regional distribution of precipitation patterns, and the heat exchange with the atmosphere. The shape of the sea floor, particularly the great deep-sea basins, also has a decisive influence on ocean current systems. On a global scale, one can roughly divide the ocean currents into large, mostly horizontal gyres (see Figure 6), circulating in the ocean basins, and an overturning circulation (see Figure 7) in the meridional-vertical realm, simplified as a huge 'conveyor belt', which constantly redistributes heat, nutrients, sediments and chemical trace constituents over the World Ocean.

The World Ocean plays a twofold role in the Earth's climate system. On the one hand climate fluctuations are caused by long-term changes in the heat distribution of the ocean. On the other hand the thermal 'inertia' of the great water masses slows down climatic changes. The close link between ocean and atmosphere is also effective on shorter time scales. This is seen by the close correspondence between the surface temperature of the ocean and the air temperature close to the

2: *Ocean Salinity*

The distinct property of seawater is that it is salty. The definition of salinity is the total mass of dissolved material per mass of seawater. It is therefore a dimensionless quantity (mass/mass). Seawater has a typical salinity around 34.7 g kg^{-1} with most seawater having values between 33 and 36 g kg^{-1}. It contains a mixture of several dissociated salts, with NaCl as the most important, but with a significant contribution from other salts. Except for a number of minor constituents, the ions of the salt material occur in constant proportion.

The reason for the almost constant composition of the salts in seawater is that the *residence time* of these salts in the ocean is on the order of millions of years. This is much longer than it takes an average water molecule to travel from the surface of the ocean into the deep sea and back, which is on the order of thousands of years. The residence time is an estimate for the average time that a salt ion that enters the ocean remains in the ocean before it leaves it again, e.g. by the formation of salt deposits or salt spray. On the timescales of million years the ocean should therefore be well mixed. This, however, is true only in a coarse sense: there are significant local variations of salinity due to the presence localized sources of salt (by evaporation of water and ice freezing; in both processes, the salt remains in the water; see also the box on p. 10) and freshwater (by precipitation).

ground. The surface winds also strongly contribute to changes in the oceanic circulation and thus regional weather conditions. Since such changes prevail for longer times in the oceans compared to the atmosphere, the ocean can be regarded as a long-term memory which imposes its 'knowledge' from previous climate conditions on future weather and climate.

There is, however, also another factor which underlines the importance of the ocean for the global climate system. The ocean forms one of the largest carbon reservoir on Earth. Owing to its relatively large surface area compared with that of the land masses, it plays an important role in the carbon cycle

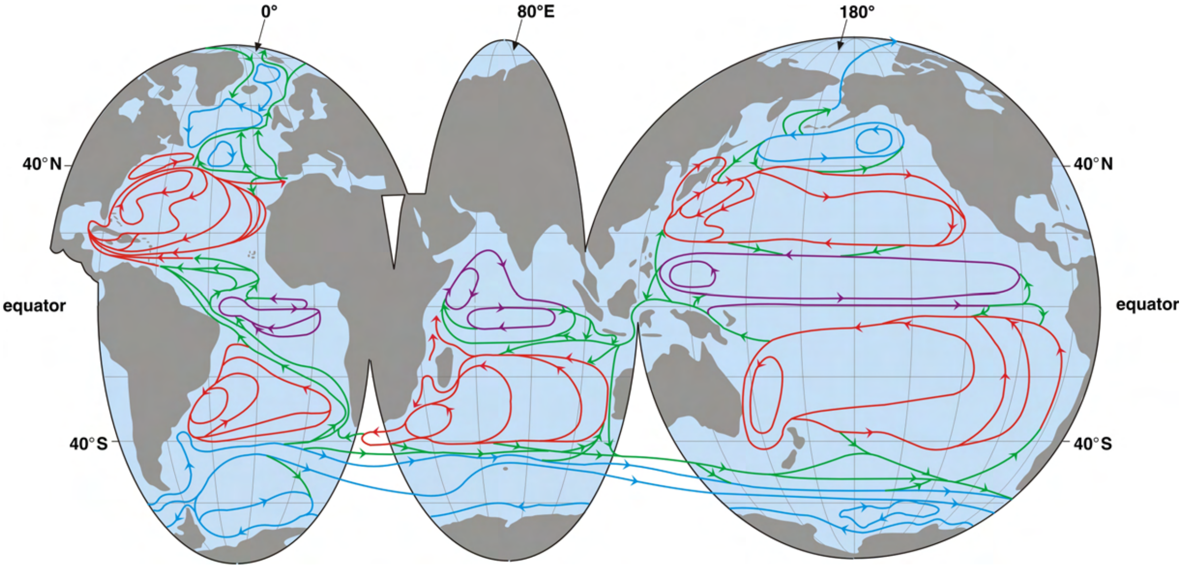


Figure 6: A schematic view of the near-surface ocean circulation (**?**). Subtropical gyres are represented with red, subpolar and polar gyres with blue, the equatorial gyres with magenta lines. The Antarctic Circumpolar Current is also blue. The green lines represent exchange between basins and gyres.

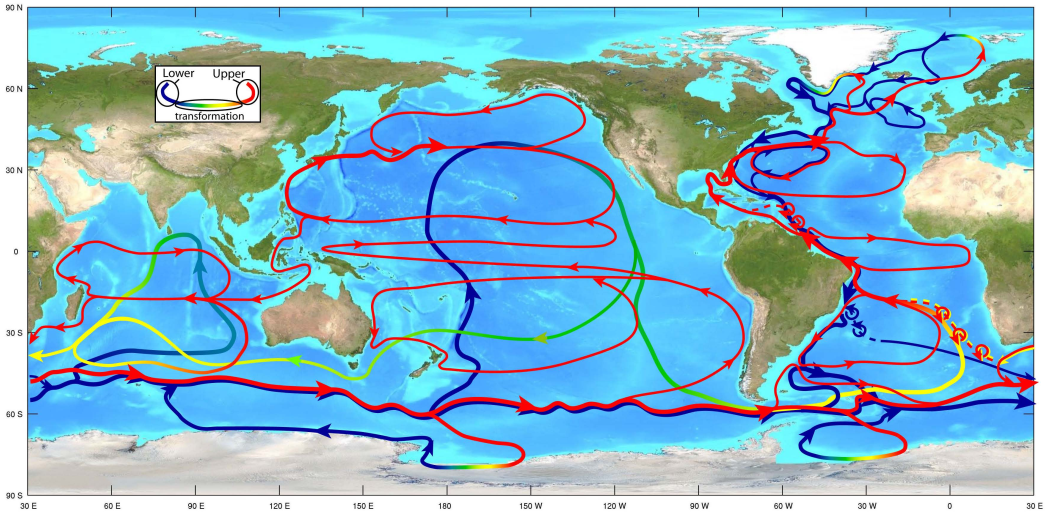


Figure 7: A schematic of the global meridional overturning circulation and some of its recirculation loops according to Rick Lumpkin (pers. communication; see also **?**). The surface currents are colored in red, while yellow, green and blue colors depict the deeper circulation (see the inlet positioned on Asia). Directions of the currents are given by arrows. The surface currents are basically those of Figure **??**. Note the large eddies in the South Atlantic, indicating that the associated transports are not achieved by continuous large-scale currents.

through biological and chemical exchange processes. A small quantity of this carbon is deposited on the sea floor through dead organisms and their calcific shells. A much larger part of this carbon is given off again into the atmosphere. The ocean reacts relatively inertly to an increase in the carbon dioxide concentration in the atmosphere. However, the carbon dioxide content in the water close to the surface remains in a quasi-equilibrium with the atmosphere. Carbon dioxide is only withdrawn permanently from the atmosphere when the carbon, which is chemically or biologically bound in the surface water, sinks to lower levels in the ocean (biological pump) and is buried in the sediments.

The different processes in the ocean run on a broad range of time scales. Although the interactive processes in the upper part of the ocean, the so-called mixed layer, take place within a matter of days, weeks or months, the redistribution processes between the warm equatorial water masses and the cold water of the polar regions in the deep ocean take decades or centuries (see also Figure **??**).

2.2.2 The link between ocean, atmosphere and sea ice

Sea ice is an important element in the Earth's climate system, in addition to the atmosphere and ocean. The ocean in the polar regions of the Earth is covered with ice extending over 17 to 27 million square kilometers depending on the season. This corresponds to about 10% of the Earth's surface. Since ice reflects solar energy much more efficiently than open water, the radiation balance of the Earth is significantly affected by the presence of sea ice. In contrast to temperature latitudes, in which moisture and heat are exchanged directly between the ocean and atmosphere through evaporation and precipitation, it is the seasonal freezing and melting of sea ice which brings about the exchange in the polar regions. The formation of ice causes sea water to release most of the salts it contains. Some of the resulting heavier surface water sinks to the sea floor. In response, warmer, less heavier water

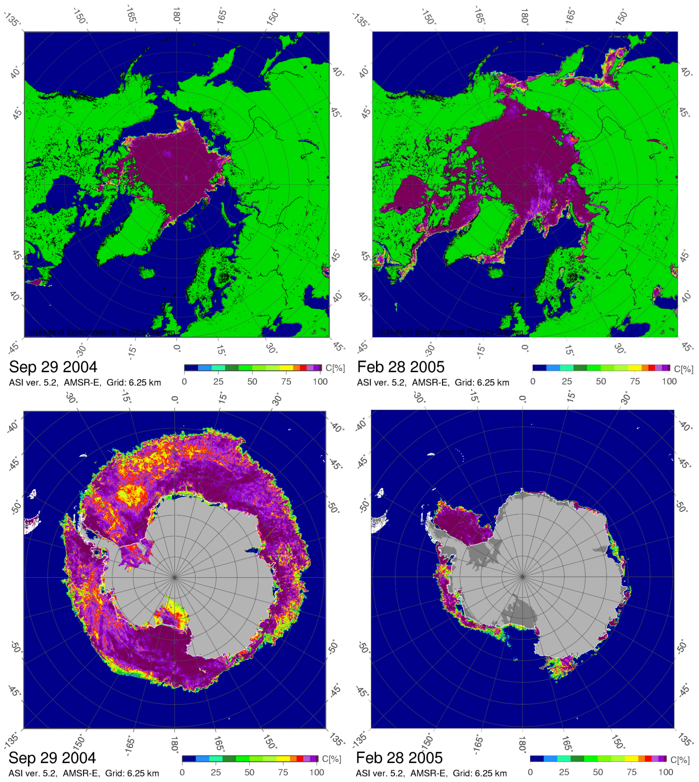


Figure 8: Sea ice concentration in the Arctic Ocean (upper panels) and in the Southern Ocean (lower panels) for September 2004 and February 2005 from satellite data.

from the deeper ocean layers rises to the surface. Thus there is an exchange between surface and bottom leading to the formation of deep water in the polar oceans. Traces of this water can be found throughout the world ocean. It supplies the surrounding water with oxygen and nutrients. Hence the polar oceans can be called the ’lungs’ of the world ocean. This is where the large overturning circulation, ventilating the Word Ocean, has its origin.

2.2.3 Water on land

On land, water occurs in liquid form as surface water, i.e. , lakes, rivers and streams and also as soil moisture and ground water. In solid form it creates glacial ice or ground ice in permafrost areas. Some of this water is available as fresh water and constitutes the basis for life on land. However, its availability to man, animals and plants is only limited. The usable fresh water reservoirs are very unevenly distributed over the Earth. This is primarily due to climatic, geological and morphological differences. Only those arid regions where ground water reservoirs have formed, dispose of a constant fresh water supply.

The type and distribution of vegetation depend to a large extent on the supply of water. A decrease in the amount of precipitation can result in the drying out of surface water, a reduction in soil moisture and a drop in water tables. This leads to a change in the vegetation types of the Earth’s surface in the areas affected. As this has consequences for the albedo, these changes also alter the climate on regional and larger scales.

3: Snow and Ice on Earth

Presently, ice covers 11% (15.7×10^6 km^2) of the land surface, and on an annual average approximately 6.5% (23.0×10^6 km^2) of the oceans. In spite of its larger area, the volume of sea ice relative to that of ice sheets is only 1:600. Ice shelves, mostly present in Antarctica, cover 1.4×10^6 km^2, which is far less than the area of sea ice. The ice shelf volume is approximately 0.5×10^6 km^3, ten times the volume of sea ice. All mountain glaciers amount to 0.24×10^6 km^3, a little less than 10% of the Greenland ice sheet. Because of their small area, the climatic impact is rather minor. Snow covers in winter — in addition to sea and land ice — approximately 50% of the land surface in the Northern Hemisphere. The snow volume is, on the other hand, rather small, it amounts to only 2.5×10^3 km^3.

Snow has the highest albedo (up to 0.9 for dry snow). This high reflectivity for solar radiation is the most important climate property of snow. In addition snow has a rather low heat conductivity, thereby reducing the upward heat flux from the Earth or ice surfaces.

Sea ice has also a relatively high albedo and acts in the climate system as an energy sink. The most important impact of sea ice on the ocean is the formation of deep and bottom water. The salinity of sea water is on average 34.7 g/kg, the salt content of sea ice, on the other hand is only 5 g/kg. Hence, during the freezing process a substantial amount of salt is released into the ocean. Cooling and brine rejection in polar regions are the main processes driving the global thermohaline circulation.

Ice shelves are a characteristic feature of the Antarctic ice sheet. Ice shelves are floating, with thicknesses of 200 m at their northern edge and 1000 m at the grounding line near the continent. Ice shelves play a important role, because, particularly in the Weddell Sea, deep and bottom water is produced by melting and freezing processes at their base.

Ice sheets grow through accumulation and compression of snow. There are two large ice sheets on Earth: the Greenland Ice Sheet with a height of approximately 3000 m, and the Antarctic Ice Sheet with an elevation of more than 4000 m. They have a significant impact on the global energy balance through the high albedo of the high–elevation, cold and snow covered ice masses, and influence the global wind pattern. The equilibrium of the great ice caps depends on their mass and spatial extent.

2.3 The Cryosphere

The significance of the ice masses in the cryosphere with respect to the global climate has been mentioned above. Like a thermal power engine, the Earth's atmosphere and world ocean transport heat from the tropics to the polar regions, where this energy surplus is compensated for by the negative balance between solar radiation and heat emission. The energy balance in the polar regions, which has a strong influence on the temperature gradient between the equator and the poles, controls the weather in the mid latitudes. Much of what we experience as our daily weather is considerably influenced by these heat transport processes and is kept going by them.

The cryosphere forms the Earth's most important fresh water reservoir, of which the inland ice of Antarctica currently accounts for about 80%. This was not always the case. During the last great ice age, about 20.000 years ago, large areas of North America and northern Europe, including a large part of northern Germany, were covered by ice, and after melting, the gloabel sea level rose by 120 m.

There is a close correlation between the state and stability of the Earth's great ice caps and global sea level. When the current great masses of ice on Greenland and Antarctica would melt, the sea level rose all over the world by roughly 70 m. Via a series of feedback mechanisms, sea level is, in turn, linked to developments in the Earth's atmosphere. The Earth's mountain glaciers play a particularly important role because they act both as regional water reservoirs and as sensitive indicators of global changes.

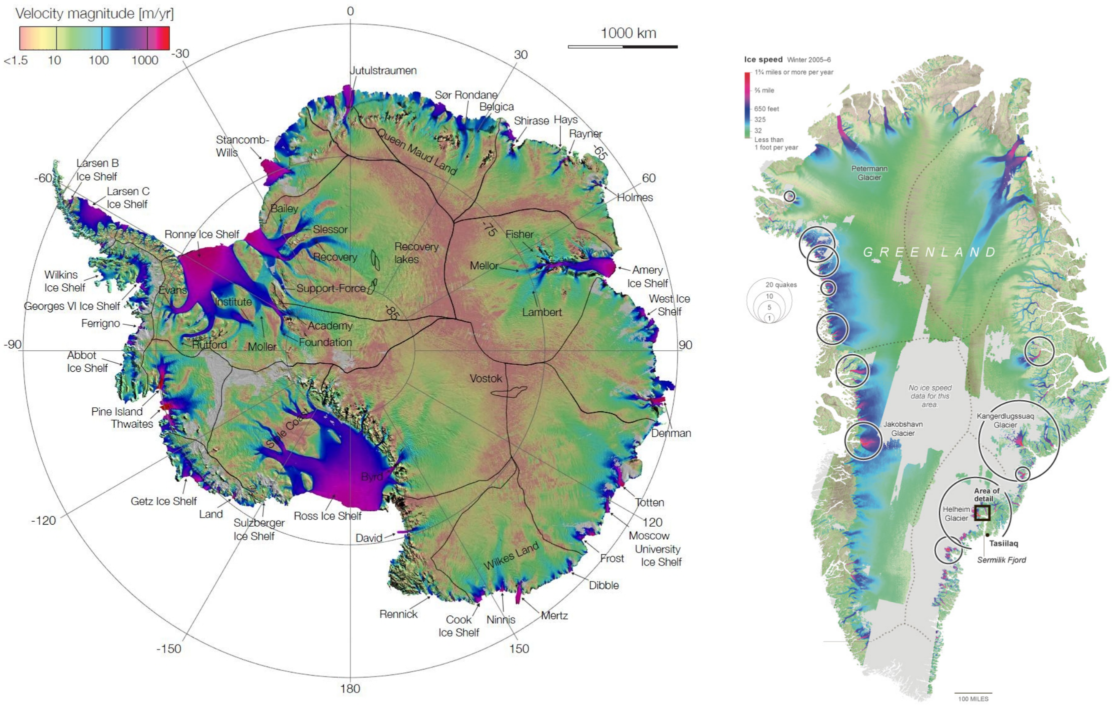


Figure 9: Left: Antarctic ice sheet. The map shows the speed and direction of ice flow, derived from radar interferometric data from the Japan Aerospace Exploration Agency's ALOS PALSAR, the European Space Agency's Envisat ASAR and ERS-1/2, and the Canadian Space Agency's RADARSAT-2 spacecraft. The thick black lines delineate major ice divides. Subglacial lakes in Antarctica's interior are also outlined in black. Thick black lines along the coast indicate ice sheet grounding lines. Right: same for Greenland. Here dotted lines highlight the boundaries between major ice drainage basins. Note that the color scale is different for the maps, left in meter per year, right in miles per year.

2.4 The Atmosphere

The composition of the atmosphere has changed fundamentally in the course of the Earth's history due to a number of different biological, chemical and physical processes. The early atmosphere of the Earth consisted mainly of nitrogen and carbon dioxide. Thus, it was similar to the present atmospheres of the planets Venus and Mars. Only with the emergence of life and biochemical processes lasting several billion years did the current atmosphere of about 78% nitrogen, 21% oxygen and 1% other gases evolve. This development of the Earth has been possible due to a number of fortunate circumstances, the most important one being the distance of the Earth from the sun, which enabled the formation of a proto-ocean at an early state in its evolution. Any change in orbit parameters might have led to completely different conditions. For the present-day Earth this could have meant perpetual cold, like the conditions on Mars, or oppressive heat as on Venus.

The Earth's atmosphere provides only a thin protective cover from outer space. The thickness of the entire atmosphere is about one twentieth of the Earth's radius. The atmosphere is subdivided into four layers of varying heights, based on the mean vertical temperature distribution: the troposphere between the surface of the Earth and an altitude of 11 km, the stratosphere between 11 km and 50 km,

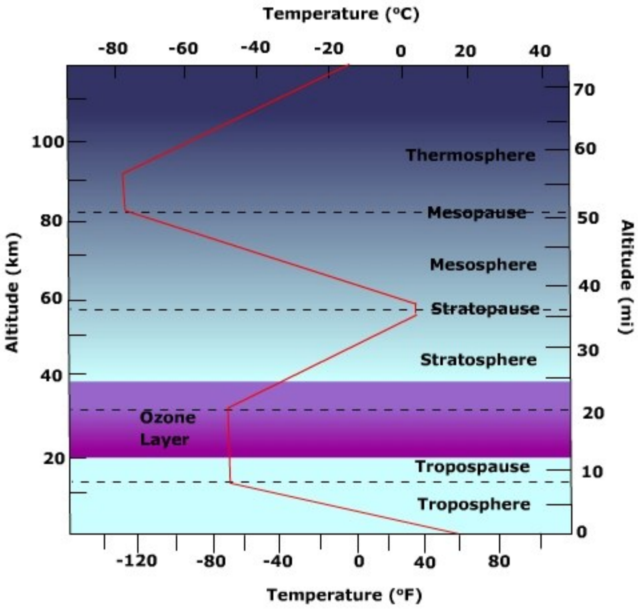


Figure 10: Vertical temperature profile of the ICAO (International Civil Aviation Organization) Standard Atmosphere. Each layer is characterized by a uniform change in temperature with increasing altitude. In some layers there is an increase in temperature with altitude, whilst in others it decreases with increasing altitude. The top or boundary of each layer is denoted by a 'pause', where the temperature profile abruptly changes.

the mesosphere between 50 km and 85 km, and the thermosphere from 85 km to about 300 km (see Figure 10).

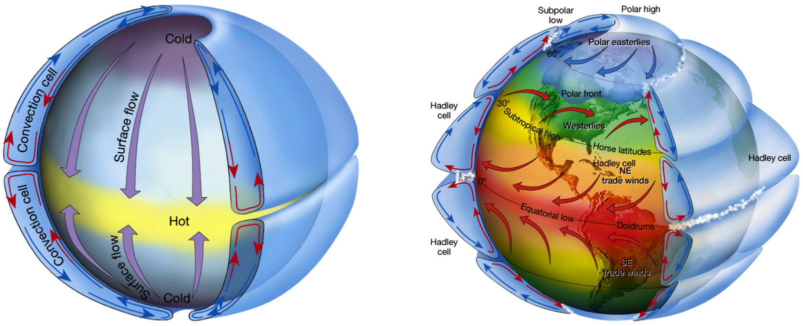
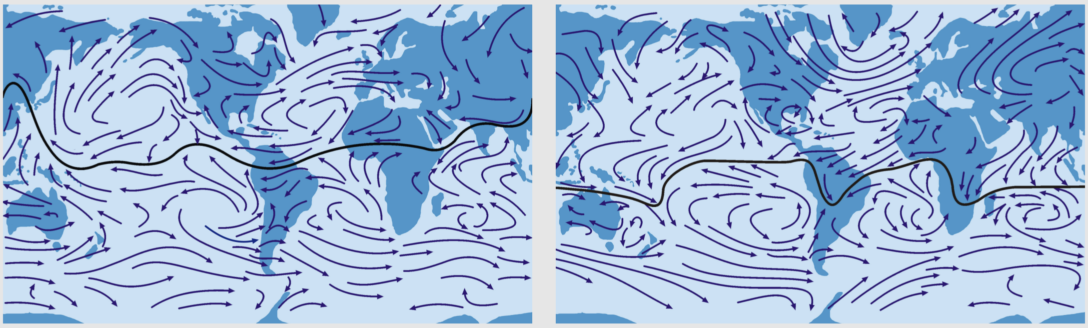


Figure 11: The circulation of the atmosphere. The left panel is for idealized, non-rotating planet where only the Hadley cell exists. The right panel is for the real Earth with Hadley and Ferrel cells. The corresponding surface winds are shown schematically. From: The Atmosphere, by Lutgens and Tarbuck, 2001.

The two lowest layers of the atmosphere, the troposphere and stratosphere, are particularly important for climate issues. The troposphere, containing about 90% of the mass of the atmosphere and almost all the water vapor, only takes up about two thousandth of the Earth's radius. At the ground,

4: *The Global Wind System*

The figure below (redrawn after **?**) shows the prevailing surface winds for the situation in the northern summer (left panel) and the northern winter (right panel). Unlike in the ocean, the circulation in the atmosphere is relatively unconstrained in zonal (east-west) direction. The large mountain ranges deflect the winds somewhat, but to a first approximation they are independent of longitude. There is a clear pattern of westward (easterly) blowing trade winds on both sides of the equator, eastward blowing (westerly) winds in somewhat higher latitudes, and also a belt of easterly winds circling the polar regions.



A convergence of the surface winds can be noticed in the 'intertropical convergence zone' (ITCZ) near the equator (indicated by a solid black line in the figure). At the ITCZ, moist air is warmed by the strong solar radiation near the surface; the moist and warm air rises, condensates when the pressure gets lower, and rises even further. This air moves polewards in the upper atmosphere, where it eventually sinks, establishing a 'meridional overturning circulation' in each hemisphere. The equatorward branch of this global circulation is often called the 'Hadley cell'.

High pressure regions are located over each of the subtropical gyres, where the air is circulating anticylonically around those highs in near geostrophic balance. Here, a fraction of the air in the upper atmosphere is sinking and is accordingly dry such that evaporation is high and exceeds precipitation. As a consequence, the salinity in the surface ocean is higher in the subtropics than in tropical or high-latitude regions, where precipitation exceeds evaporation. Low pressure regions can be seen in the North Pacific and Atlantic Ocean, with cyclonic surface circulation, but no such clear indication in the southern hemisphere.

The ITCZ – and with it the upwelling branch of the whole global MOC in the atmosphere – migrates seasonally towards the summer hemisphere. This migration is most pronounced in the Indian Ocean. In the northern part of the Indian Ocean, a seasonal reversal of the surface winds can even be seen. This reversal is related to the Indian monsoon, with south-westerly winds during summer extending from the Indian subcontinent to and even crossing the equator, and north-easterlies during winter. In the tropical Pacific and Atlantic Ocean, similar seasonal changes in the surface winds can be seen, but in general with smaller seasonal signals at higher latitudes.

heat is exchanged between the atmosphere and the Earth's surface. Heated up by sunlight, it warms the air above it like a hot plate. The sun's rays strike the surface of the Earth at different angles, and equal areas at different latitudes gain different amounts of heat. Thus the equatorial regions are heated up more than the poles.

Air masses flowing vertically and horizontally act as a regulatory mechanism, preventing the equatorial regions from overheating and the polar regions from cooling down to much. This is achieved by an exchange of warm air and water masses in the tropics and cooler ones at the poles, resulting in a meridional heat transport (it is worth mentioning that the ocean circulation contributes to the heat exchange between equatorial and polar region, see Figure 19). The exchange is expressed in the distinctive global wind systems which take the form of large-scale belts encircling the northern and the southern hemispheres. Meridional exchange between the wind systems driven by high and low pressure zones takes place in mid latitudes. In the tropics this movement is called Hadley Circulation: in the eye of a large tropical storms, warm, moist air rises to an altitude of over 15 kilometers and moves towards the poles. Colder air sinks down in the subtropics and flows back to the equator (trade winds). These processes determine to a large extent the regional and local weather conditions.

The stratosphere could be called the Earth's 'sun-glasses'. This is where most of the ultraviolet solar radiation, which is harmful for man and all living organisms, is filtered out. This is mainly achieved by ozone, a molecule consisting of three oxygen atoms. About 90% of the total quantity of ozone is to be found in the stratosphere. Physical and chemical processes, triggered by the absorption of solar energy, constantly create and destroy the ozone content of the stratosphere partially because of the variations in solar activity are superimposed on these processes. On the other hand decomposition processes are intensified by the presence of chemical reagents — in particular the chlorofluorocarbons (CFC) — which are derived from industrial emissions. These are the major causes of the 'ozone hole'.

2.5 The Biosphere

With the exception of the ice sheets of Antarctica and Greenland, the land on Earth is populated by a large variety of living organisms. According to conservative estimates at least eight million different species of animals and plants exist on Earth.

2.5.1 Life on Land and in the Sea

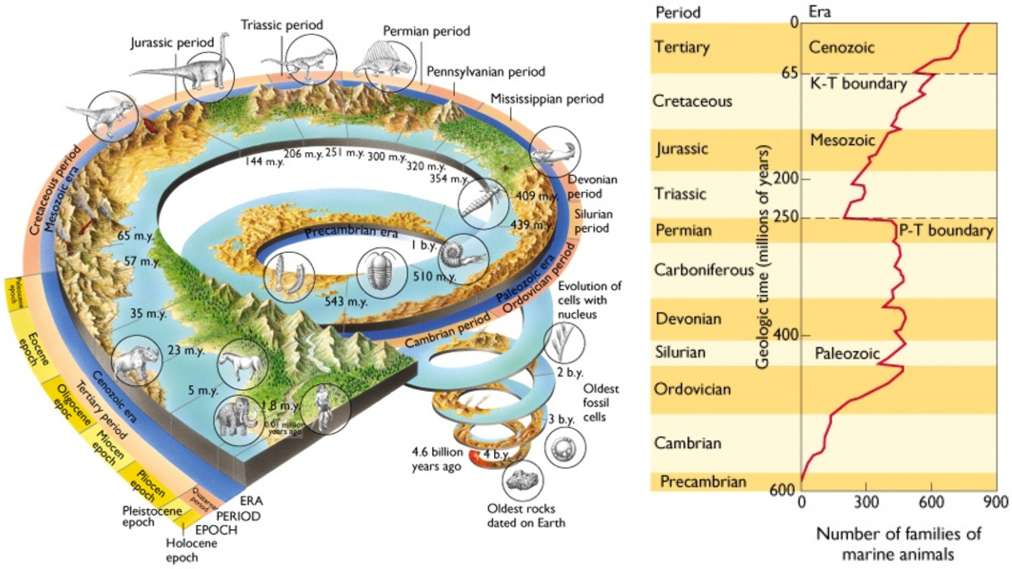


Figure 12: Development of life on Earth, shown as a spiralling timeline.

Life on Earth originated from the ocean. This is where the first microorganisms emerged, whose remains have been discovered in rocks up to four billion years old. The oldest known organisms are primitive cells without a nucleus (procaryotes). A first biosphere developed after unicellular algae began to release oxygen into the atmosphere due to photosynthetic conversion of carbon dioxide. Cells with nucleus (eucaryotes) developed much later in Earth history, about two billion years ago. During the next 400 million years evolution created an enormous multiplicity of species. Settling of life on the continents started in early Cambrian, about 600 million years ago. It was only in a long evolutionary process that the flora and fauna of today were formed. They endured climatic changes throughout the Earth's history, some of them drastic, and continually readapted.

The general increase in the number of species and individual organisms on Earth has frequently been interrupted by mass extinctions where large proportions of the diversity and biomass vanished. Such drastic events have been documented a number of times and marked transitions in the biosphere developments, e.g. the transitions from the Permian to the Triassic period and from the Triassic to the Jurassic period. A much discussed extinction is the vanishing of the dinosaurs about 65 million years ago which has been attributed to a drastic climate change following the impact of a large meteorite.

The biosphere is a consumer and producer of greenhouse gases. Carbon dioxide in the atmosphere is reduced by plants in photosynthesis. Methane is stored in permafrost soils and gas hydrates on the ocean bottom. Both gases are currently released to the atmosphere by human activities and reinforce the greenhouse effect.

2.5.2 Ecosystems

The term ecosystem describes a holistic concept comprising the total of organisms in a specified spatial unit, their physical conditions and the numerous interactions between the living and non-living components of the system. An ecosystem can either be an isolated pool within an arid region or a whole ocean. It is assumed that each element in the ecosystem is linked directly or indirectly with the other elements and influences them.

The link between living and non-living components of the ecosystem is maintained by two coupled processes: the flow of energy and the exchange of nutrients. As the major source of energy, the sun is the pre-requisite for plant photosynthesis. In this process carbon dioxide, water and other biogenous elements such as nitrogen, phosphorus and sulphur are converted into protein, fats and starches via a number of intermediate stages. These substances can be called the building blocks of life. The organisms participating in photosynthesis are producers in the ecosystem.

On the other hand there are consumers — e.g. bacteria, fungi and animals — which mainly feed on the producers' organic material. This transfer of organic substance from the producer to numerous consumers, taking place in several steps, is called a food chain. As a final link of this chain, organisms break down animal and plant substances into their inorganic constituents. These serve as food for the producers. Due to the transformation of organically bound energy from one component of a food chain to another, more and more energy is gradually lost. In contrast to this loss, the nutrient budget of the ecosystem largely remains unchanged. The nutrients are only transferred between living and non-living components. These exchange processes represent constituents in bio-geochemical cycles. Prominent examples are the carbon cycle and nitrogen cycle.

Ecosystems develop in two phases. In the early stage, the growth phase, the system is characterized by a small number of species, short food chains and relative instability. In the second phase, at the end of its development, the ecosystem is more complex. It consists of a large number of species and is more stable.

Man interferes in different ways with the development of ecosystems. An important example of this is farming, where ecosystems are kept in the growth phase artificially over a long period of time. Developments are also disturbed by environmental pollution caused by man, which leads to changes in natural habitats. As a consequence, forms of vegetation disappear, changing the physical characteristics of the Earth's surface. This directly affects the radiation and moisture balances and thus the weather and climatic conditions of a region.

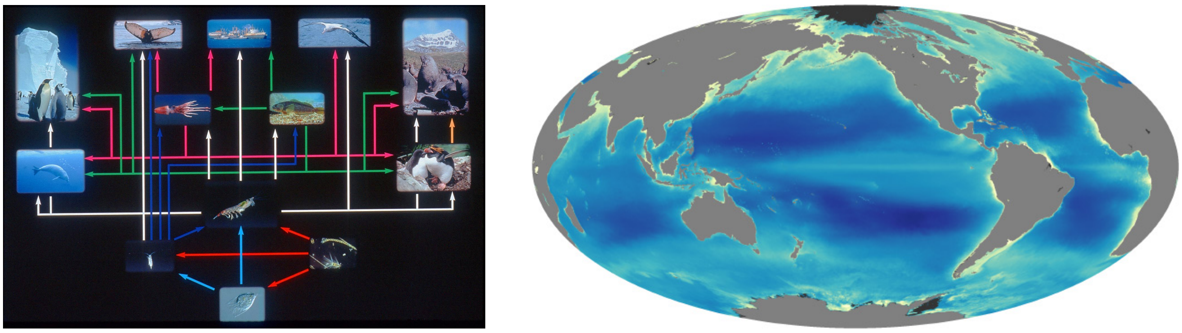


Figure 13: Left: ecosystem of the Southern Ocean. Right: an index of primary production (the chlorophyll content) of the ocean surface layer. Phytoplankton are most abundant (yellow, high chlorophyll) in high latitudes and in upwelling zones along the equator and near coastlines. They are scarce in remote oceans (dark blue), where nutrient levels are low. From `http://earthobservatory.nasa.gov/Features/Phytoplankton/page4.php`.

3 Global Cycles

Most of the exchange processes in the Earth system occur in the form of closed loops. While they constantly influence each other they obey certain natural laws. The major energy source for these processes is the sun, which enables the flow of matter through the system.

An essential characteristic of such cycles are the many feedbacks which have a decisive influence on transport rates and paths. These feedbacks are controlled by the external conditions in the components of the Earth system. As these are, in turn, modified by changes in transport rates, they are also referred to as feedback loops. There are a large number of examples of such feedback loops in the Earth system. Of those only the water cycle and the bio-geochemical cycles will be briefly discussed below.

3.1 The Water Cycle

In contrast to all other planets of the solar system Earth has water in great abundance and in all three states: gaseous, liquid and solid. By far the greatest share (97%) of the Earth's water is found in the oceans, 2% is bound as ice and the rest (1%) is accounted for by ground water, soil water, surface water, the atmosphere and the biosphere. This 3% of the total quantity consists mainly of fresh water. The fraction of water bound in ice caps depends strongly on the temperature of Earth; during the coldest stage of last ice age, the average sea level was about 120 m deeper than today, the water being bound in large ice shields. Rivers and lakes contain less that a thousandth of the total water on Earth, and the atmosphere only a very small fraction of that.

3.1.1 Basic Characteristics of the Cycle

Although the atmosphere contains only a trace amount of the total water on Earth, it acts as an important pathway for transferring water from one reservoir to another. This is because the residence time of water in the atmosphere is quite small; on average a water molecule that is evaporated stays

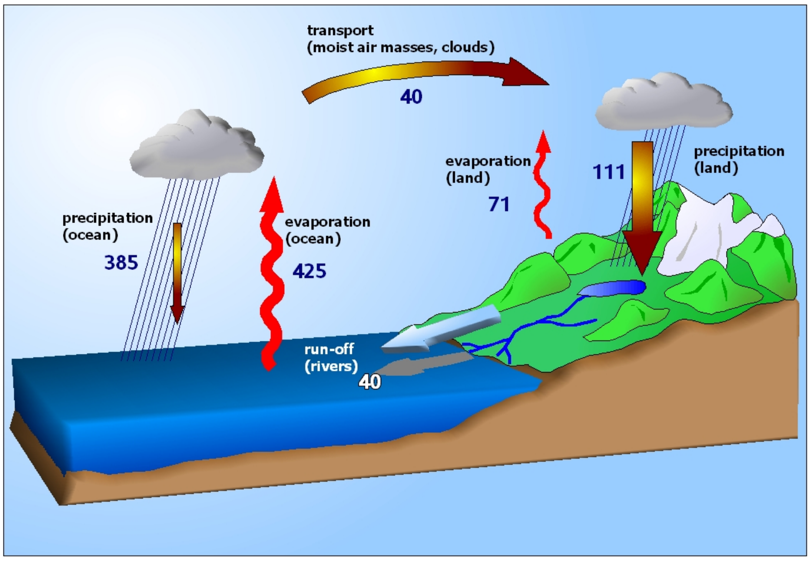


Figure 14: The water cycle of the Earth. Water participates in a global cycle as vapor, liquid or ice. It evaporates into the atmosphere, where it is transported in the gaseous state following atmospheric circulation patterns. Later it condenses and falls as rain or snow on the Earth. The numbers indicate the quantity of water transported in units of $10^9 m^3$ per year.

only about 10 days in the atmosphere before it precipitates again. Most of the water that evaporates precipitates over the ocean; only less than a third precipitates over land.

Water plays a crucial role in many global exchange processes. Carbon, nitrogen, phosphorus and oxygen are transported in the Earth system through the medium of water in liquid state. Knowledge of the magnitude and variability of the hydrological cycle is particularly important for understanding the Earth system. Even slight changes in the proportions of components in the water cycle can have considerable ecological consequences (e.g. flooding, drought and the processes of desertification). The hydrologic cycle is intimately coupled to the energy balance and the redistribution of heat, because evaporation and precipitation result in large amounts of heat being transferred.

3.1.2 Processes in the Ocean and on Land

The ocean is a practically inexhaustible source of moisture for the atmosphere. On an annual average, six times as much water vapor evaporates over the ocean as over land surfaces. This means that the precipitation rate and its regional distribution, i.e. the positions of the main areas of precipitation, depend on three main factors: large-scale atmospheric circulation, temperature distribution over the surface of the ocean, and distribution of water and land on Earth.

Water is transferred into the atmosphere by evaporation. Transport of water vapor follows atmospheric circulation patterns. During its transport, a part of the water vapor condenses. These condensation processes in turn provide energy for the atmospheric circulation. Parts of this energy are also fed into large storm systems such as tornadoes, hurricanes and typhoons.

The yearly run-off from continents to the oceans amounts to 40.000 km^3 of water, primarily derived from precipitation over land surfaces. As part of the global water cycle this water subsequently flows back into the ocean. Thus, the evaporation of water over the oceans is balanced via transport of precipitated water over the atmosphere and the land surfaces. On its way to the ocean the water carries a large amount of dissolved and undissolved substances, coupling land processes to the global ocean by feeding sediments and nutrients into the sea.

The run-off from land surfaces normally consists of surface and ground water. As there is a time lag between the subterranean and superterranean run-offs, the climatic history of a region can be deduced from the properties of its ground water (quantity, chemical and physical nature). Changes in ground water replenishment due to climatic conditions have a considerable effect on the dynamic equilibrium of the ground water flow system. For instance, they influence the position of the interface between fresh and salt water in coastal regions, on islands or in desert regions. They affect the subterranean ground water levels or spring yields and dry weather run-offs. The run-off rates of surface and ground water depend on the distribution of precipitation, surface topography, fauna and the characteristics of the underlying crustal rock formations.

The distribution of precipitation, evaporation and run-off has a direct influence on the biosphere, controlling the extension and state of land-based ecosystems. The resulting shape of the land surface and the distribution of vegetation in turn influence the hydrological cycle.

3.2 Bio-geochemical Cycles

An important issue of long-term climate variability and global changes are biological nutrient inventories and cycles: carbon, nitrogen, sulphur and phosphorus. These bio-geochemical cycles link the most important reservoirs of these elements: the hydrosphere, components of the solid Earth, the biosphere and the atmosphere. The processes which mainly drive these cycles include the constant oxidation of living and dead biomass by atmospheric oxygen. On the one hand these processes result in carbon dioxide, which may then be used in photosynthesis; on the other hand energy is released by these processes which is used for the growth and the development of living organisms. These processes cause rapid circulation of nutrients in the Earth system unless they are stored in living organisms, organic soil matter or in the decayed biomass on land or in the ocean. Bio-geochemical cycles thus comprise physical, chemical and geological processes on Earth and largely determine boundary conditions for the development of ecosystems.

Bio-geochemical cycles are also a prerequisite for the variety of species in flora and fauna and for the number of individuals within each species. In the course of evolution new species have always developed, the number of which has constantly fluctuated. However, due to man's interference these changes are occurring at an ever increasing rate. A visible sign of this human influence is the rapid decrease in the variety of species, particularly in the tropical rain forests.

3.2.1 Marine Bio-geochemistry

The role of the ocean in the climate system has already been mentioned. The point to be considered here regards the chemical properties of the World Ocean which are also extremely important for the characteristics of marine bio-geochemistry and in particular the carbon cycle. The oceans contain 90% of the free carbon on Earth and at present extract from the atmosphere about 30% of the quantity of carbon dioxide released by human activity.

The marine ecosystems are controlled by primary production, the fixation rate of nitrogen, the release of sulphuric gases and the extraction of organic material through deposition on the sea floor. The coupling between physical and chemical processes at the ocean/atmosphere interface and at the lower boundary of the oceanic mixed layer affect the supply of nutrients and the rate of photosynthesis in the top cover.

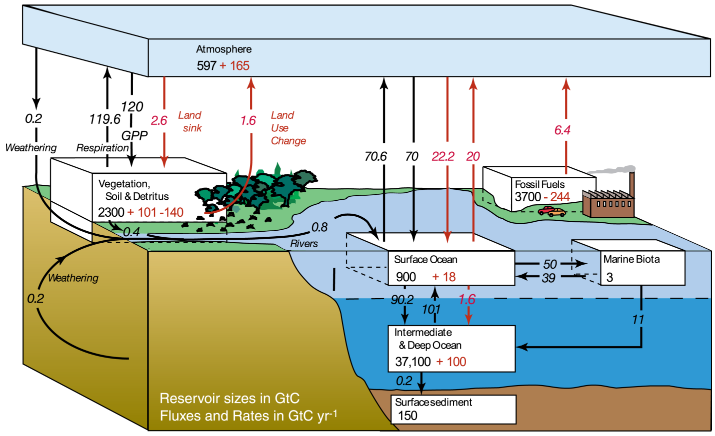


Figure 15: The global carbon cycle. The global carbon cycle for the 1990s, showing the main annual fluxes in GtC per year: pre-industrial natural fluxes in black and anthropogenic fluxes in red (modified from Sarmiento and Gruber, 2006, with changes in pool sizes from Sabine et al., 2004). The net terrestrial loss of 39 GtC is inferred from cumulative fossil fuel emissions minus atmospheric increase minus ocean storage. The loss of 140 GtC from the vegetation, soil and detritus compartment represents the cumulative emissions from land use change (Houghton, 2003), and requires a terrestrial biosphere sink of 101 GtC (in Sabine et al., given only as ranges of 140 to 80 GtC and 61 to 141 GtC, respectively; other uncertainties given in their Table 1). Net anthropogenic exchanges with the atmosphere are from Column 5 AR4 in Table 7.1. Gross fluxes generally have uncertainties of more than 20% but fractional amounts have been retained to achieve overall balance when including estimates in fractions of GtC yr1 for riverine transport, weathering, deep ocean burial, etc. GPP is annual gross (terrestrial) primary production. Atmospheric carbon content and all cumulative fluxes since 1750 are as of end 1994. From IPCC AR4WG1.

3.2.2 Bio-geochemical Cycles in Terrestrial Ecosystems

The role played by the Earth's land-based and fresh water ecosystems is closely connected to the physical and biological processes which determine the circulation of chemical elements in the biosphere as well as the composition of the atmosphere. The equilibrium between vegetation types and their spatial distribution is a major, still unsolved issue. At the same time, the relation between this equilibrium and the occurrence of local fauna and microbial activities needs to be assessed. These factors depend on the local climate parameters (temperature, quantity of precipitation), atmospheric carbon dioxide and nitrogen exchange, the total quantity of nutrients and the special terrain conditions in a specified ecosystem. The equilibria can be permanently disturbed by human interference.

4 The Climate System

The term 'climate' is used for long-term average weather conditions, conventionally taken over 30 years. At the same time, 'climate' denotes a specific state of equilibrium in the energy balance and global energy transports. The climate system is usually defined as consisting of the atmosphere, the ocean, and sea ice and ice sheets. Conditions of the land surface are prescribed, as well as all external

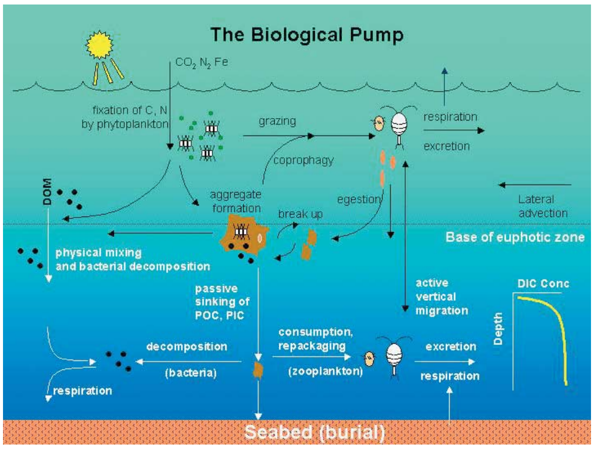


Figure 16: Processes of the marine carbon cycle in the upper layer of the ocean. Atmospheric CO2 (or N2 gas) fixed by autotrophs in the upper ocean is transported to deep waters (i.e. below the mixed layer) by various processes. Phytoplankton become senescent and sink out as aggregates, or are consumed by herbivores that produce sinking fecal pellets. Aggregates may then be decomposed by bacteria or consumed by animals. Diel vertical migration is a mechanism by which zooplankton (or nekton) feeding in the surface waters at night actively transport dissolved or particulate material to depth by metabolizing the ingested food at their daytime residence depths. Vertical migration of some phytoplankton species may bring nutrients from the nutricline into the euphotic zone. Dissolved organic carbon produced by phytoplankton or by animal excretion in surface waters can be transported downward during deep mixing events. The biological pump also includes the sinking of particulate inorganic carbon (PIC) of biological origin (calcite and aragonite - the 'carbonate pump').

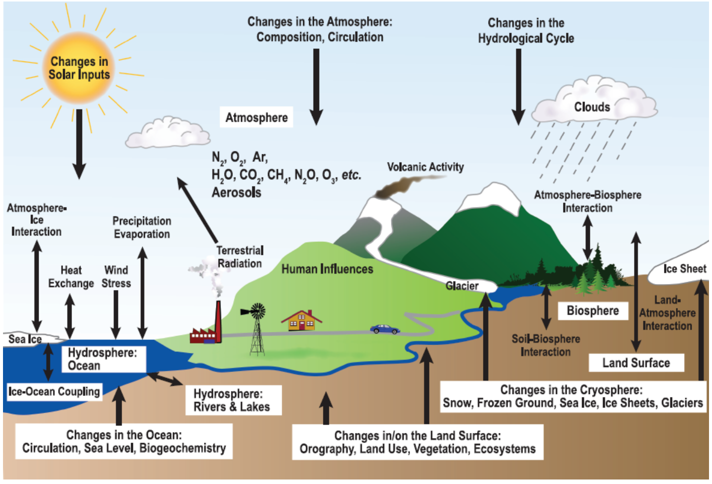


Figure 17: Schematic view of the components of the climate system, their processes and interactions. From IPCC AR4WG1.

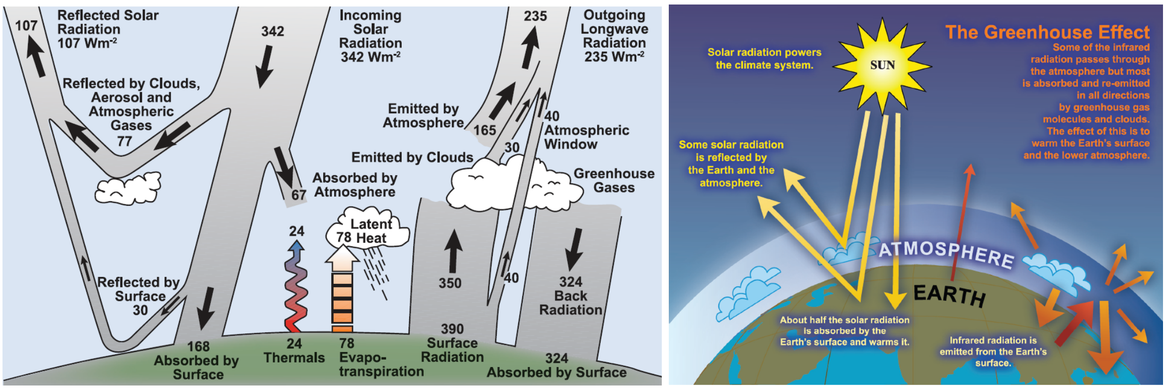


Figure 18: Right: global energy balance of the Earth and the atmosphere in the current state. Energy fluxes are given as percentage of the total incoming solar radiation. Estimate of the Earths annual and global mean energy balance. Over the long term, the amount of incoming solar radiation absorbed by the Earth and atmosphere is balanced by the Earth and atmosphere releasing the same amount of outgoing longwave radiation. About half of the incoming solar radiation is absorbed by the Earths surface. This energy is transferred to the atmosphere by warming the air in contact with the surface (thermals), by evapotranspiration and by longwave radiation that is absorbed by clouds and greenhouse gases. The atmosphere in turn radiates longwave energy back to Earth as well as out to space. From Kiehl and Trenberth (1997). Left: Illustration of the greenhouse effect. From IPCC AR4WG1.

forcing factors, as e.g. the greenhouse gas concentrations. It is a dynamic system which at most times is in a transient equilibrium. Changes in the climate system are forced through external impacts, e.g. changing carbon dioxide, volcano output, or the orbital parameters of the Earth, and through internal interactions. These influence the climate on a variety of time-scales (see also Figure 20). The solar power has increased by about 30% since its birth; the continents have changed over million of years; Earth alters its orbit with prominent periods of 100.000, 41.000, 23.000 and 19.000 years (the Milankovitch cycles); the contents of greenhouse gases has varied from years to billions of years.

4.1 The Energy Balance

The largest part of the solar radiation reaches the Earths surface, with about 30% being reflected back into space and the rest absorbed in clouds and air, corresponding to the average albedo of 0.3. About 70% reaches the ground and leads to a temperature increase until the established temperature drives an equal energy loss. This heat loss proceeds via three main pathways:

- *radiative heat flux:* This is the loss of heat by emission of longwave electromagnetic radiation. The largest part emitted by oceans and land is absorbed in the atmosphere, but some passes through it.
- *sensible heat flux:* This is the transfer of energy by heat conduction. It requires direct contact between a colder and a warmer medium and operates via interactions between the random movements of molecules that are the more vigorous the warmer a body is.

5: Radiation

The radiation of the sun provides the energy that drives the motion of the ocean and the atmosphere and enables life on Earth. Because the solar surface temperature is about 5900 K, the received energy is mainly in the form of short-wave visible light with wavelengths between 0.35 and 0.7 μm. In this wavelength range the atmosphere is almost transparent, i.e. only very little of this energy is absorbed in the atmosphere. One part of the solar radiation that is absorbed strongly in the atmosphere is the ultraviolet radiation below about 0.3 μm wavelength.

The radiative flux of energy from the sun decreases with the square of the distance from the sun. The average flux at the mean radius of the Earth's orbit is called the *solar constant* S and has the value $S = 1368\,\mathrm{Wm}^{-2}$. Note that the name solar constant is a bit misleading, because the actual radiative flux varies by a few percent around that value, mainly because of the slight variation of the distance between Earth and the sun over the year. S is the energy flux per unit area oriented perpendicular to the direction towards the sun. Because the sun is not always overhead, and below the horizon during the night, the average energy received per unit area at the Earth's surface is one quarter of that (one quarter is the ratio between the areas of a circle with the radius of the Earth and the surface of the Earth, assuming it is a sphere).

Some of the incoming radiation is reflected back into space. The relative amount of reflected radiation is called *albedo* and denoted by α. The albedo of clouds and of snow cover is relatively high (up to 0.9), while that of the ocean surface is relatively low with values around 0.05. On average, the albedo of the Earth is around 0.3, summarizing the the amount of cloud cover and the extent of deserts and ice shields.

Because of the albedo, the total energy from solar radiation that is available to heat the Earth is $(1-\alpha)S/4 = 239$W. This energy gain must be compensated by an equal energy loss, otherwise the Earth would continually become warmer. The only way that the Earth can loose energy into space is by thermal radiation. The thermal radiation of the Earth depends on its temperature by the Stefan-Boltzmann law (with some small correction because Earth is not a perfect black body). We can then calculate its temperature T_0 from the condition of equilibrium between the incoming and outgoing radiation: $(1-\alpha)S/4 = \sigma T_0^4$. Without atmosphere the surface temperature of the Earth would be close to this so-called radiative equilibrium temperature, which is 255 K, or $T_0 = -18°\mathrm{C}$. The actual average temperature at the surface of the Earth, however, is about 288 K, more than 33 K higher. The main reason for this is the *natural greenhouse effect* caused by the atmosphere. At the temperature of the Earth, most of the energy in the emitted thermal radiation is contained in the infrared or long-wave domain.

- *latent heat flux:* Water has a high latent heat of vaporization, i.e. it takes a lot of energy to bring water from the liquid into the gas phase. This heat is released again when water vapor forms liquid droplets e.g. in clouds. Because the heat for evaporation is mostly taken from the water when evaporation occurs, and is released in the atmosphere when it precipitates again, this amounts to a net transfer of energy into the atmosphere.

Only a small part of the heat loss is directly lost into space, the larger part heats the atmosphere, which in turn radiates into space.

In the global budget the energy input by solar radiation is balanced by the emission of terrestrial radiation at the outer rim of the atmosphere to space. The solar input, however, is not uniform on the Earth's surface as the equatorial latitudes gain more radiation then those which are more northern and more inclined with respect to the solar direction. The emission is smaller than the irradiance in low latitudes, i.e. there is a net gain of energy. Conversely, the long-wave radiation is larger than the irradiance in high latitudes, indicating a net energy loss (see Figure 19a). So, while the Earth as a whole is in radiative balance, regionally there can be an imbalance. This imbalance requires that the excess energy received at low latitudes has somehow to be transported to lower latitudes to fill the energy deficit there. Otherwise the imbalance would result in perpetual warming at the equator and cooling at the poles. The redistribution of heat is achieved by transport from low to high latitudes in the ocean and the atmosphere. They do this by the time mean circulation but also by the transient turbulent eddies, the highs and lows which can be seen weather charts and the satellite images of the

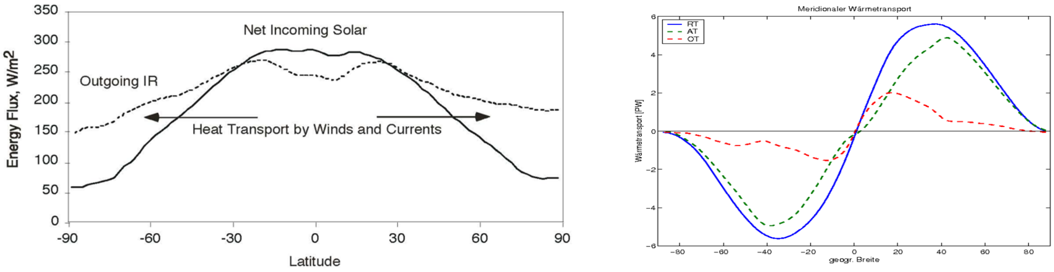


Figure 19: Right: incoming solar (solid curve) and outgoing infrared (dashed curve) energy flux as function of latitude. Left: heat transport by atmospheric (AT, green dashed) and oceanic (OT, red dashed) circulation (zonal average) and the total heat transport (RT, blue), determined from satellite radiation measurements. A typical values of the meridional heat transport is $10^{15}\mathrm{W} = 1\mathrm{PW}$.

ocean surface. There is some difference in the importance of heat transport at the different latitude belts, but overall the ocean and the atmosphere share a similar burden (see Figure 19b). The oceanic transport is driven by warmer water flowing (on average at least) predominantly poleward at the sea surface, while colder water at depth flows (on average) equatorward.

4.2 The Greenhouse Effect

If based only on the global radiation balance, the temperature of the Earth's surface results from the equilibrium between incident solar energy and thermal (infrared) radiation given off by the Earth. Small quantities of polymolecular trace gases in the lowest part of the atmosphere, the troposphere, cause part of this heat radiation to be absorbed and thus prevent it from escaping in total: part of it is radiated back as infrared and warms again the Earth's surface. The troposphere acts in the same way as glass in a greenhouse: this is why this process is called the natural greenhouse effect of the atmosphere. Without this effect the average surface temperature would not be +15°C but -18°C . The main greenhouse gases which are responsible for this effect are water vapor, carbon dioxide, methane and ozone (see the box on p. 23).

6: *A Greenhouse Model*

Proceeding with the result from the box on p. 22 we note that the temperature $T_0 = -18°\mathrm{C}$, determined form the overall energy of the Earth, is clearly not the surface temperature of the planet. It is the 'radiation temperature' of the Earth, which is in balance with the solar input and might be associated with a fictitious atmospheric layer containing the greenhouse gases. A simple greenhouse model is the extreme case that the infrared radiation from the Earth's surface is entirely absorbed in this layer and heats it. To meet the overall balance it must radiate σT_0^4 outward to space, but at the same time this amount radiates back to the Earth (radiation is isotropic), contributing to the heating of the surface. The surface thus receives $(1-\alpha)S/4 + \sigma T_0^4$ (note that both terms have the magnitude 239W) and emits this amount by infrared radiation with a surface temperature T_s. Hence $\sigma T_s^4 = 478\mathrm{W}$, leading to $T_s = 303\mathrm{K} = 30°\mathrm{C}$. This is 15 K too hot so the model is still unrealistic but it shows the correct directions. A more realistic model must consider that not all of the energy received by the surface leaves by radiation, that the radiation from the surface is entirely absorbed in the atmosphere but that part of it escapes directly to space, and furthermore, that the atmosphere/cloud system is in fact not entirely transparent to the solar radiation (see Figure 18).

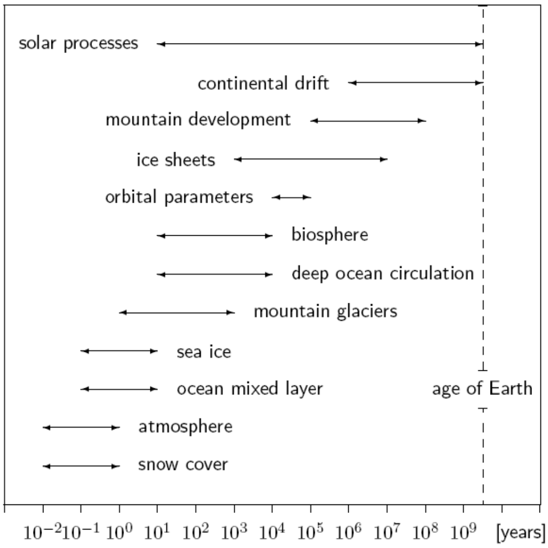


Figure 20: Times scales of natural processes and compartments of the Earth system.

5 Natural Changes

All the systems and cycles described so far are subject to changes. For a certain period we can define an average state (e.g. of climate) but going back or ahead to other time intervals we find different states. Their temporal sequence can be deduced from a number of natural ’archives’. The climatic conditions prevailing in previous eons of the Earth’s history have been recorded in ice and sediment cores, tree rings and coral deposits. Continental drift can be deduced from the rock succession of the Earth’s crust on the continents and at the bottom of the oceans. Such archives yield *proxy data* representing estimates of physical parameters. The word ’proxy’ is commonly used to describe a stand–in or substitute. In paleo-climatic reconstructions proxy variables, or short *proxies*, are measurable descriptors, which stand in for desired, but un–observable, variables such as temperature, salinity, or ice volume. The concept of proxies relies on a physical relationship between a proxy and the target variable. Therefore, each proxy is associated with a rule (a transformation algorithm), which relates it to the target variable. These algorithms have to be established through calibration, e.g. using the instrumental records.

The former state of the biosphere can be traced at many points of the Earth in fossils, witnesses of the ancient living world embedded in sediment. These ’archives’ are documentary evidence of changes which took place on our Earth without interference by man. They indicate the range of fluctuations in the past, give clues to the sequence of warm and cold cycles and can serve to test working hypotheses about vital processes in the Earth system. Finally they form the basis for models with which such changes can be simulated.

5.1 Time and Space Scales in the Earth System

When considering natural changes it is advisable to observe the vital processes within their characteristic time scales. It should be emphasized again at this point that changes which take place within a certain specified period can have an effect on processes taking place on a completely different time

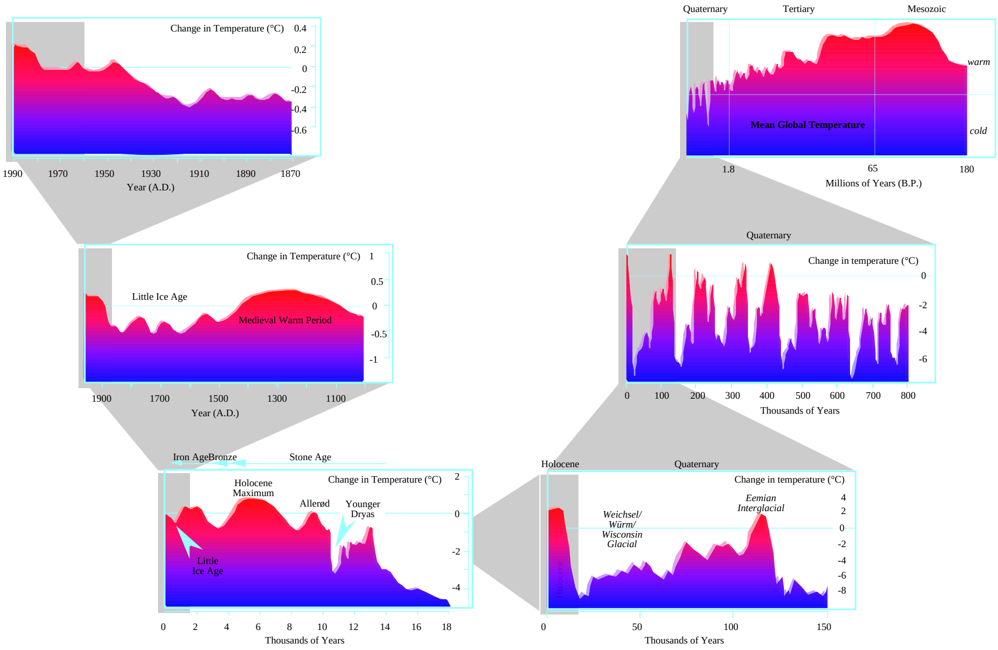


Figure 21: Variations of climate indicators from instrumental records and proxies. Direct measurements of temperature date back to about 1750. Proxies data are mainly from the oxygen isotope ratio $\delta^{18}O$ which relates to the ocean surface temperature and the volume of ice sheets.

scale. This can be seen, for example, in the great natural catastrophes, which usually take place within a very short period of time but whose effects are also visible in long-term changes of the Earth system.

One example for such an event is the supposed impact of a large meteorite towards the end of the Cretaceous period (about 65 million years ago). It is believed that the ejected masses from this impact were flung up into the stratosphere and thus led to a change in the global radiation balance. The world-wide temperature decrease which followed could explain the extinction of many species of animals and plants, including dinosaurs.

5.2 Billions of Years - Development of Life - Continental Drift

The Earth as we know it is the result of 4,5 billion years of continued development. Signs of the sequence of events can be detected in geological structures of the Earth's crust and in the internal structure of the mantle. Based on measurements of the gravitational and magnetic fields and by examining rock samples from the crust and upper mantle the sequence of geological events can be deduced.

With the development of photosynthesizing algae three billion years ago the atmosphere, which until then had mainly consisted of carbon dioxide and nitrogen, became increasingly oxygenic. Free oxygen only increased slowly since the soil and water of early Earth were still full of reducing constituents (with low oxygen content). The land surface was a deadly environment for any form of life. The ozone layer in the higher atmosphere, which protects against harmful UV radiation, only formed very gradually. Through an increase in oxygen and a decrease in carbon dioxide the atmosphere developed in such a way that its greenhouse potential brought about a temperate climate. This was the

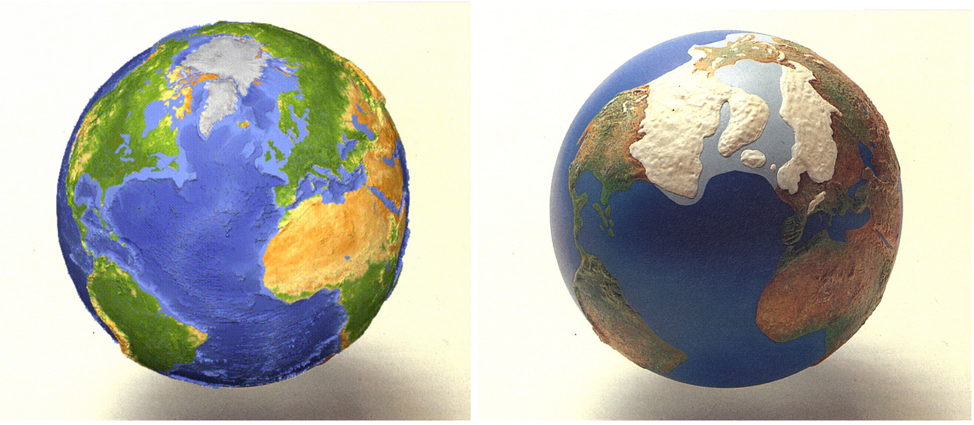


Figure 22: Northern hemisphere ice sheet cover today (left) and during the Last Glacial Maximum (right).

prerequisite for development of life as we know it today.

5.3 Millions of Years - Ice Ages

The climatic history of the Earth reveals a large number of fluctuations which involved drastic changes in the conditions of life on our planet. The most significant climatic fluctuations of the last million years can be deduced from the sediments of the ocean floor. Cold and warm cycles alternated in irregular cycles lasting about 100.000 years. During the cold cycles parts of North America, Europe and Siberia were covered with large ice caps. The sea ice cover of the Antarctic Ocean extended far north and the sea level was about 120 m lower than it is today.

The sequence of warm and cold cycles is determined by changes in the Earth's orbit round the sun due to the attraction of the Earth by the giant planets Jupiter and Saturn. There are various parameters of the Earth's orbit which fluctuate over fixed periods. The prevailing period of change from cold to warm cycles of 100.000 years is due to a change in the Earth's orbit from a more elliptical to a more circular shape. Other periods last about 41.000 and about 20.000 years. The Serbian mathematician MILANKOVITCH was the first to recognize the connection between variations in the orbit, resulting fluctuations in the distribution of solar radiation on the Earth, and the climatic cycles between cold and warm periods. This led to the first mathematical theory of climatic fluctuations on Earth, the Milankovitch theory of glacial cycles.

Though the Milankovitch forcing functions are solid and general excepted in the scientific community, there is a number questions concerning their climatic impact. First, the effect of the orbital variations on the net radiation received by the Earth appears small, e.g. the annual mean deviation from the 100.000 years cycle of the ellipticity is less than 0.3% and the other effects only lead to a redistribution of radiated energy on Earth. There must be clear positive feedbacks to induce change as seen during the ice ages. The ice-albedo feedback is made responsible: variations of solar flux in northerly latitudes might lead to more snow, a process which amplifies due to the feedback on albedo. Second, there is question why the ice age fluctuation have only occurred in the last million or so years — the Milankovitch forcing has been active ever before. The answer is very likely found in the specific pattern of the continents. For example, only 5 millions before our time the Isthmus of Panama had closed, and 25 millions ago, Antarctica had been completely separated and Drake Passage came

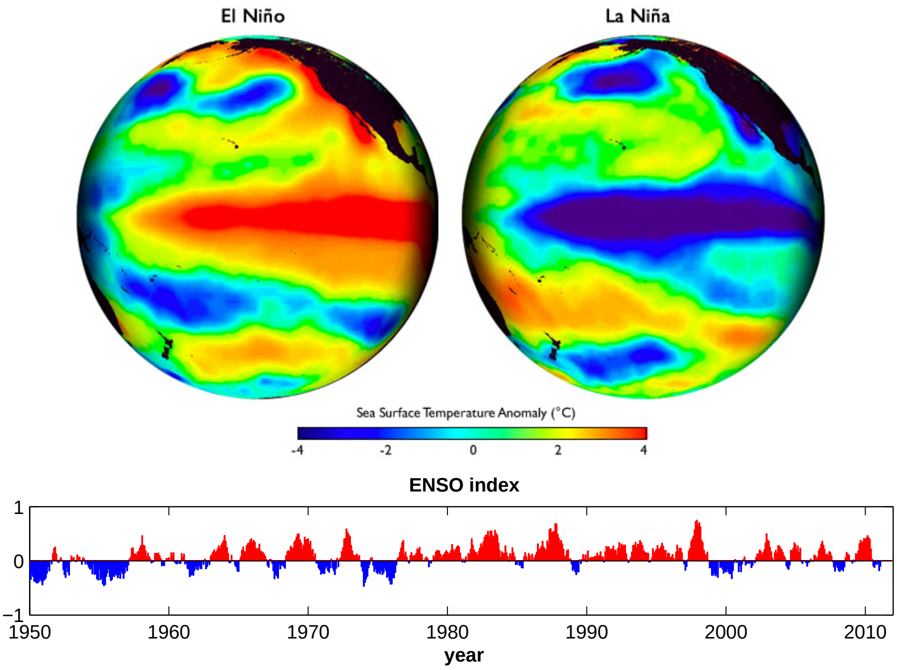


Figure 23: The maps show the anomalies of the sea surface temperature during El Nino and La Nina episodes. The colors indicate areas that are warmer or cooler than the long-term average. From Steve Albers, NOAA.

into existence. The climate changed due to these events: equatorial currents were now confined into ocean basins, and the deep ocean became cold by watermass formation around Antarctica. Going further back in time, Pangaea was situated in tropical region (at times before 225 millions of years): there was no northern continent to capture snow and create ice masses.

5.4 The last 10.000 Years - Setting the Stage of our Present Climate

During the last 10.000 years the climate and ecological structures which we know today were established as a result of numerous natural evolutions. The remains of the continental ice caps from the last ice age disappeared 6.500 years ago - with the exception of Greenland and Antarctica. The decline in glaciation did not, however, take place evenly. Sometimes there was a return to ice-age conditions within only a few hundred years. Recent research has led to the conclusion that these short-term climatic fluctuations are caused by a reduction in the oceanic heat transport in the Atlantic. This might be caused by an increased input of fresh water into the North Atlantic which resulted from a sudden deflection of melt water from the North American ice cap.

There were warm periods - climatic optima - about 6.000 years ago and in the middle ages between 1000 and 1220. Average temperatures then were about 2 to 3 degrees above today's values. Between 1550 and 1850 there was a cold period - the so-called little ice age - shown in a sporadic sequence of cold winters and a general shift of the climate zones by about 500 km to the south.

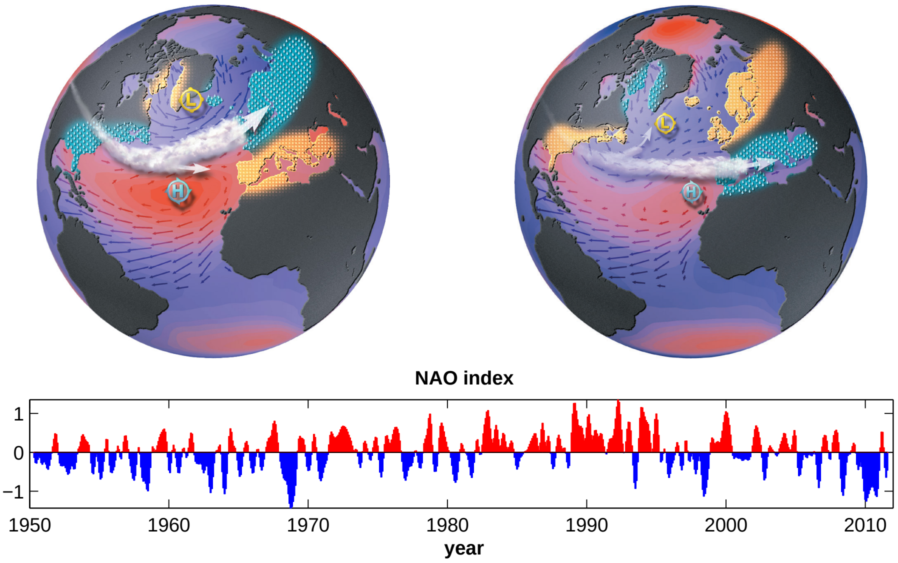


Figure 24: The two states of the North Atlantic Oscillation NAO. During a positive NAO (left), pressures in the Azores high are especially high and pressures in the Icelandic low are lower than normal. This increased pressure difference causes westerly winds to intensify between 50 and 60N. Storms are more frequent, northern Europe gets warmer and wetter weather as the winds blow off the ocean, while the Mediterranean is unusually dry. North-east America is generally wet, while Labrador and Greenland are cold and dry. During a negative NAO (right), the Azores high and the Icelandic low are much weaker. Pressure differences are therefore smaller and both systems are located to the south. Weaker westerly winds bring less moisture in the air to northern Europe, and less heat. Because these winds are further south, Mediterranean weather is wetter and winter in North-east America is warmer and drier than normal. From `http://www.ldeo.columbia.edu/res/pi/NAO/`.

5.5 Years and Decades — ENSO — NAO

The El Nino events represent the largest short-term fluctuation known today in the oceanic climate. They take place in a time range of up to one decade. El Nino events were particularly significant in 1986/87, 1991/92 and 1997/98. The name El Nino - the (Christ-) child - is derived from a Peruvian coastal current which periodically leads to a warming of the ocean at Christmas time. In El Nino years this warming takes on drastic proportions (up to 12 degrees along the coast), displacing the cold Humboldt Current. This has a devastating ecological and economical effect on the coastal states. The fishing industry, which accounts for up to one fifth of world production in these normally cold, nutrient-rich regions, collapses almost completely in El Nino years. On the other hand the occurrence of tropical mussels increases enormously. Many different variables such as surface temperatures in air and water, surface pressure and wind, water level and precipitation reveal a pattern of correlation with global dimensions during El Nino years. The cool periods between El Nino event a called La Nina. El Nino is part of a larger variability phenomenon, the Southern Oscillation (SO) which is a fluctuation of the pressure system over the southern hemisphere, with inverse centers lying over Indonesia and Chile. To emphasize the large-scale character of this climate fluctuation, El Nino is generally called ENSO (El Nino - Southern Oscillation).

As a final example of decadal climate variability we mention the North Atlantic Oscillation (NAO), representing variations of the pressure field over the North Atlantic with time scale from months to decades. The Icelandic low and the Azores high pressure centers act in phase to generate a concomitant strengthening and weakening of the prevailing westerlies, with significant influences on the Eurasian climate. NAO is connected to another system of large-scale pressure differences, the Arctic Oscillation (AO). The interest in all of these oscillations lies of course in the potential predictability.

6 Anthropogenically induced changes

Earth's energy balance was described in Section 4.1 as leveled out. The current state, however, is unbalanced: there is a net flux of energy into the Earth system of roughly $1\mathrm{Wm}^{-2}$: Earth is warming up, and according to observations (see Figure 25) the global mean temperature has increased at a rate of 0.8°C per 100 years since 1850. It is nowadays generally accepted that the origin of the *global warming* lies in the increase of greenhouse gases, above all carbon dioxide, due to fossil fuel burning and land use, leading to an anthropogenically induced greenhouse effect on top of the natural one.

Significant trends, mostly attributed human influences, have been observed in many state parameters of the Earth system. The global sea level is rising; not only the surface temperature of the Earth is rising but also ocean interior is warming; the ice area in the Arctic is diminishing; Greenland and maybe Antarctica are in a net melting state. These issues are described and regularly assessed by the IPCC. But not only climate variables are under strong observation, the biosphere is changing as well in consequence of human interference, as mentioned above. Mankind has thus definitely become unintentionally an active member in the Earth system.

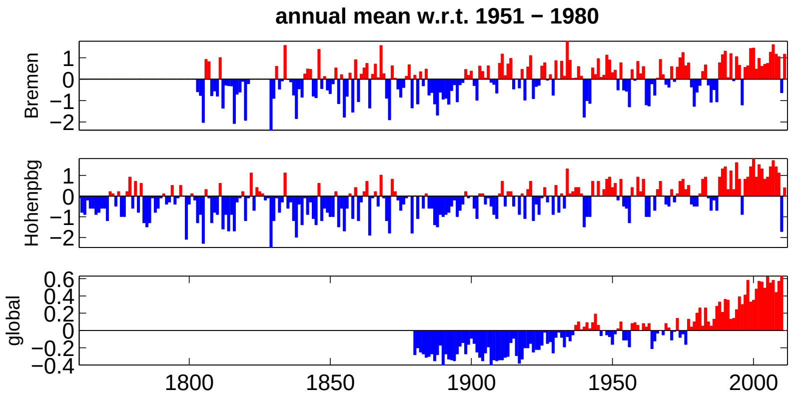


Figure 25: Development of the surface temperature in °C in Bremen, Hohenpeißenberg, and globally, according to observations. Shown are deviations from the time interval 1951 to 1980. Data: Bremen W. Olbers (from 1803 – 1821) and H.-J. Heinemann (from 1829); Hohenpeißenberg (from 1761); global GISS (from 1880): `http://data.giss.nasa.gov/gistemp/`.