Earth's Spheres

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Hydrosphere, Biosphere and Lithosphere

Hydrosphere

A **hydrosphere** (from Greek ὕδωρ - *hydor*, "water" and σφαῖρα - *sphaira*, "sphere") in physical geography describes the combined mass of water found on, under, and over the surface of a planet.

The total mass of the Earth's hydrosphere is about 1.4×10^{18} tonnes, which is about 0.023% of the Earth's total mass. About 20×10^{12} tonnes of this is in the Earth's atmosphere (the volume of one tonne of water is approximately 1 cubic metre). Approximately 71% of the Earth's surface, an area of some 361 million square kilometres (139.5 million square miles), is covered by ocean. The average salinity of the Earth's oceans is about 35 grams of salt per kilogram of sea water (35 ‰).

Other hydrospheres

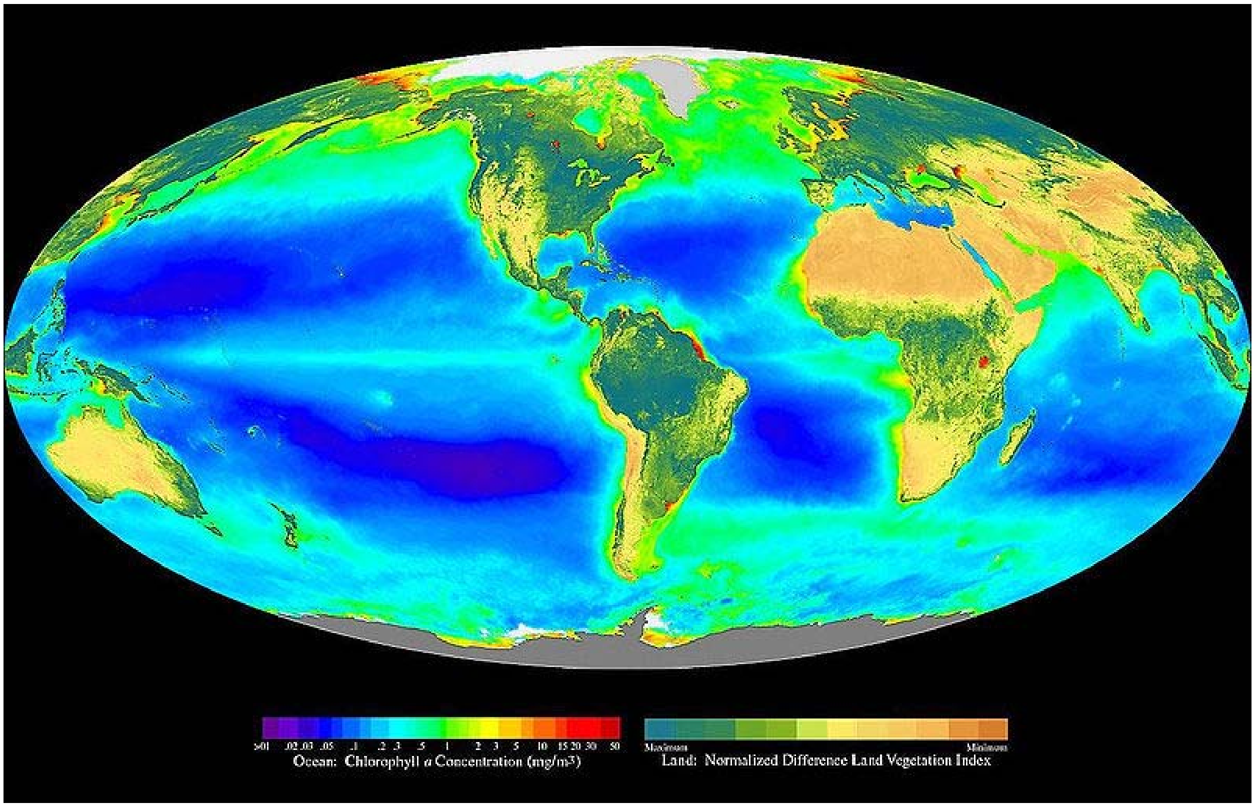
A thick hydrosphere is thought to exist around the Jovian moon Europa. The outer layer of this hydrosphere is almost entirely ice, but current models predict that there is an ocean up to 100 km in depth underneath the ice. This ocean remains in a liquid form because of tidal flexing of the moon in its orbit around Jupiter. The volume of Europa's hydrosphere is 3×10^{18} m^3, 2.3 times that of Earth.

It has been suggested that the Jovian moon Ganymede and the Saturnian moon Enceladus may also possess sub-surface oceans. However the ice covering is expected to be thicker on Jupiter's Ganymede than on Europa.

Hydrological cycle

Insolation, or energy (in the form of heat and light) from the sun, provides the energy necessary to cause evaporation from all wet surfaces including oceans, rivers, lakes, soil and the leaves of plants. Water vapor is further released as transpiration from vegetation and from humans and other animals.

Biosphere



A false-color composite of global oceanic and terrestrial photoautotroph abundance, from September 1997 to August 2000. Provided by the SeaWiFS Project, NASA/Goddard Space Flight Center and ORBIMAGE.

The **biosphere** is the global sum of all ecosystems. It can also be called the zone of life on Earth. From the broadest biophysiological point of view, the biosphere is the global ecological system integrating all living beings and their relationships, including their interaction with the elements of the lithosphere, hydrosphere and atmosphere. The biosphere is postulated to have evolved, beginning through a process of biogenesis or biopoesis, at least some 3.5 billion years ago.

Origin and use of the term

The term "biosphere" was coined by geologist Eduard Suess in 1875, which he defined as:

"The place on Earth's surface where life dwells."

While this concept has a geological origin, it is an indication of the impact of both Darwin and Maury on the earth sciences. The biosphere's ecological context comes from the 1920s, preceding the 1935 introduction of the term "ecosystem" by Sir Arthur Tansley. Vernadsky defined ecology as the science of the biosphere. It is an interdisciplinary concept for integrating astronomy, geophysics, meteorology, biogeography, evolution, geology, geochemistry, hydrology and, generally speaking, all life and earth sciences.

Gaia hypothesis

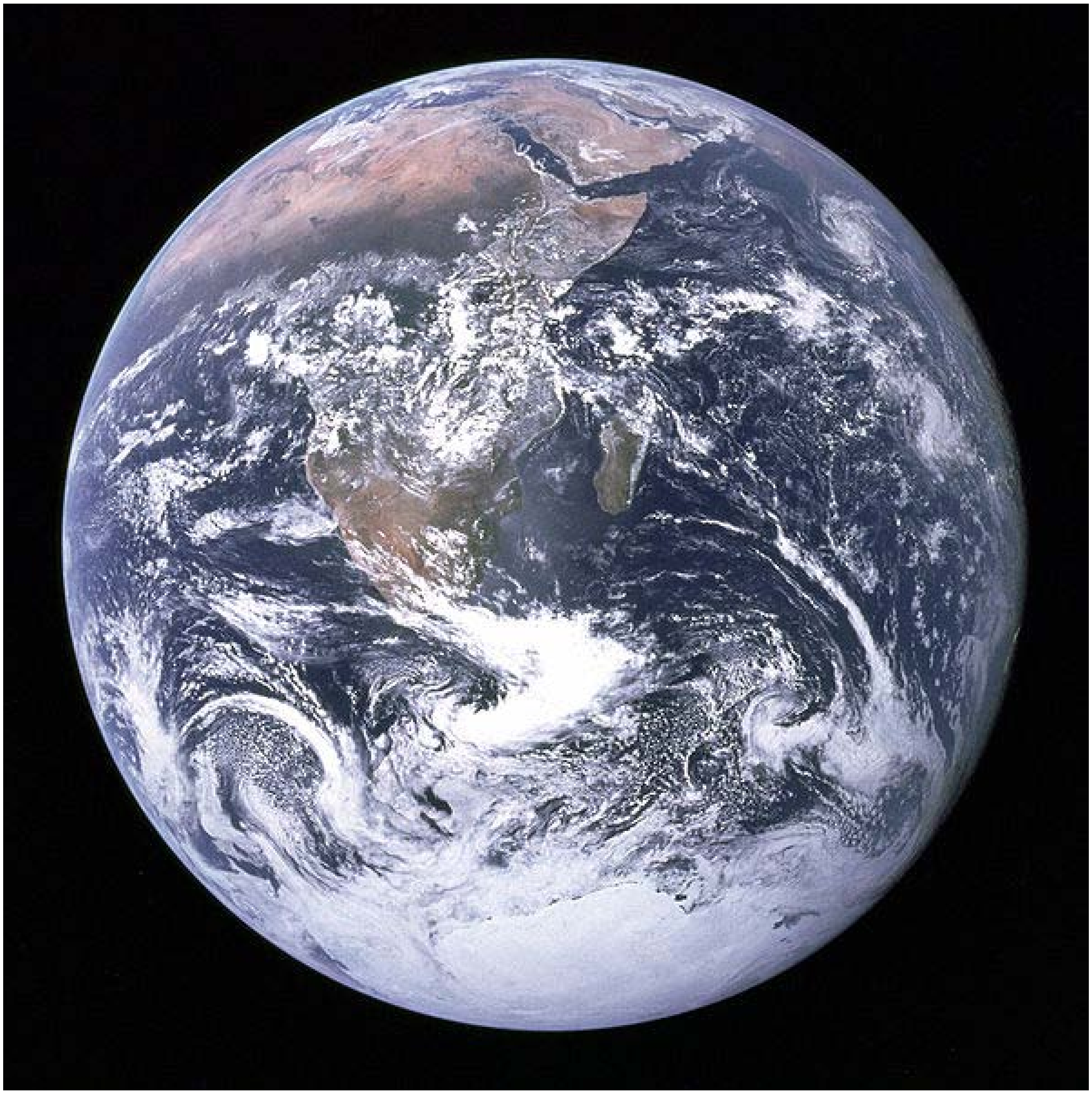
The concept that the biosphere is itself a living organism, either actually or metaphorically, is known as the Gaia hypothesis.

James Lovelock, an atmospheric scientist from the United Kingdom, proposed the Gaia hypothesis to explain how biotic and abiotic factors interact in the biosphere. This hypothesis considers Earth itself a kind of living organism. Its atmosphere, geosphere, and hydrosphere are cooperating systems that yield a biosphere full of life. In the early 1970s, Lynn Margulis, a microbiologist from the United States, added to the hypothesis, specifically noting the ties between the biosphere and other Earth systems. For example, when carbon dioxide levels increase in the atmosphere, plants grow more quickly. As their growth continues, they remove more and more carbon dioxide from the atmosphere.

Many scientists are now involved in new fields of study that examine interactions between biotic and abiotic factors in the biosphere, such as geobiology and geomicrobiology.

Ecosystems occur when communities and their physical environment work together as a system. The difference between this and a biosphere is simple, the biosphere is everything in general terms.

Extent of Earth's biosphere



Water covers 71% of the Earth's surface. Image is the Earth photographed from Apollo 17.

Every part of the planet, from the polar ice caps to the Equator, supports life of some kind. Recent advances in microbiology have demonstrated that microbes live deep beneath the Earth's terrestrial surface, and that the total mass of microbial life in so-called "uninhabitable zones" may, in biomass, exceed all animal and plant life on the surface. The actual thickness of the biosphere on earth is difficult to measure. Birds typically fly at altitudes of 650 to 1,800 meters, and fish that live deep underwater can be found down to -8,372 meters in the Puerto Rico Trench.

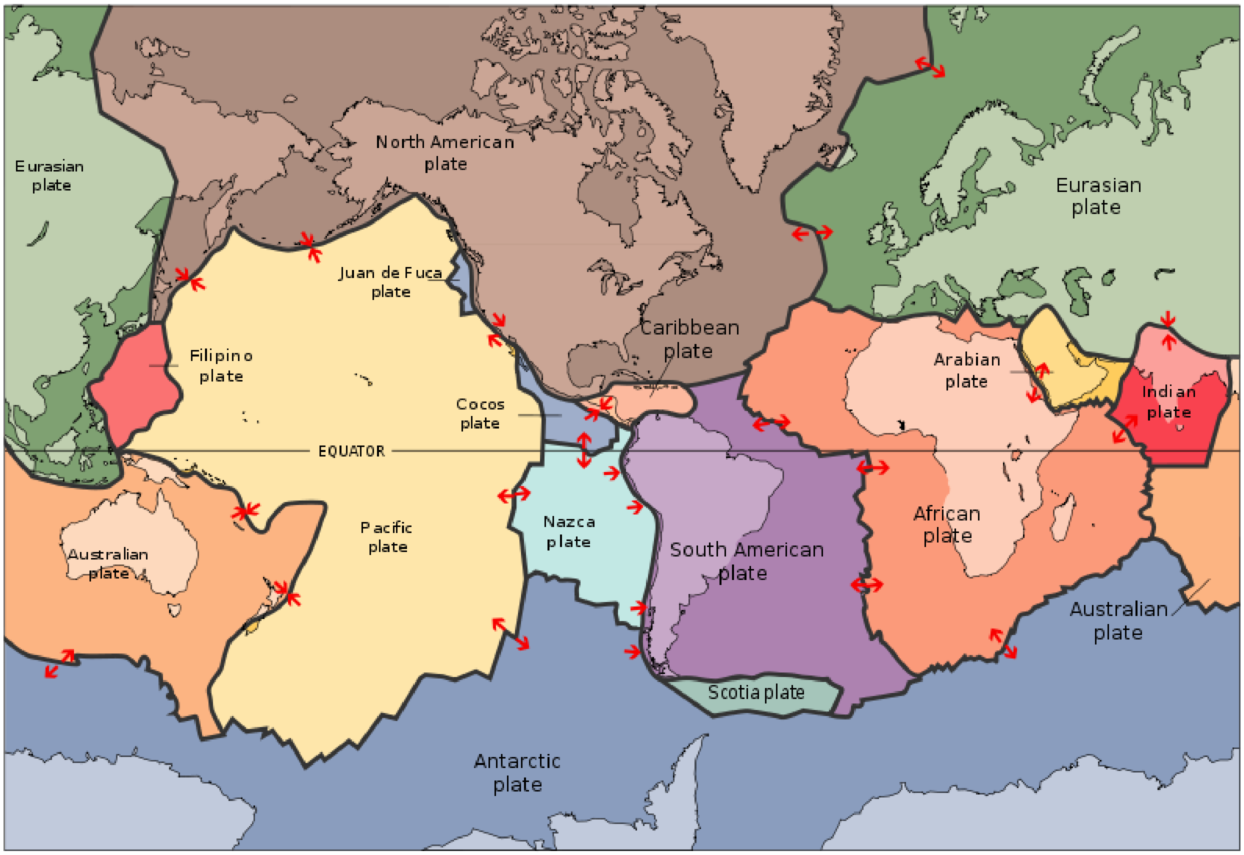
There are more extreme examples for life on the planet: Rüppell's Vulture has been found at altitudes of 11,300 meters; Bar-headed Geese migrate at altitudes of at least 8,300 meters (over

Mount Everest); Yaks live at elevations between 3,200 to 5,400 meters above sea level; mountain goats live up to 3,050 meters. Herbivorous animals at these elevations depend on lichens, grasses, and herbs.

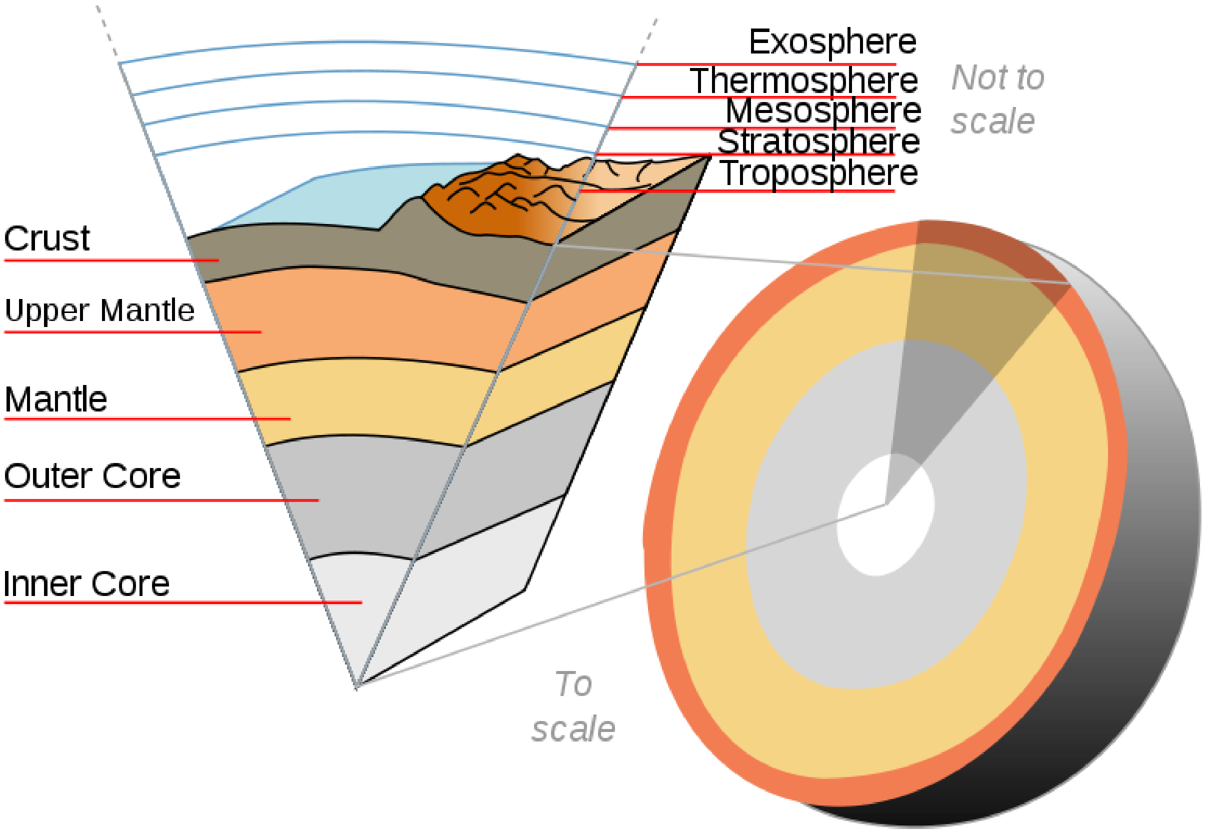
Microscopic organisms live at such extremes that, taking them into consideration puts the thickness of the biosphere much greater. Culturable microbes have been found in the Earth's upper atmosphere as high as 41 km (25 mi) (Wainwright et al., 2003, in FEMS Microbiology Letters). It is unlikely, however, that microbes are active at such altitudes, where temperatures and air pressure are extremely low and ultraviolet radiation very high. More likely these microbes were brought into the upper atmosphere by winds or possibly volcanic eruptions. Barophilic marine microbes have been found at more than 10 km (6 mi) depth in the Marianas Trench (Takamia et al., 1997, in FEMS Microbiology Letters). Microbes are not limited to the air, water or the Earth's surface. Culturable thermophilic microbes have been extracted from cores drilled more than 5 km (3 mi) into the Earth's crust in Sweden (Gold, 1992, and Szewzyk, 1994, both in PNAS), from rocks between 65-75 °C. Temperature increases with increasing depth into the Earth's crust. The speed at which the temperature increases depends on many factors, including type of crust (continental vs. oceanic), rock type, geographic location, etc. The upper known limit of microbial is 122 °C (*Methanopyrus kandleri* Strain 116), and it is likely that the limit of life in the "deep biosphere" is defined by temperature rather than absolute depth.

Our biosphere is divided into a number of biomes, inhabited by broadly similar flora and fauna. On land, biomes are separated primarily by latitude. Terrestrial biomes lying within the Arctic and Antarctic Circles are relatively barren of plant and animal life, while most of the more populous biomes lie near the equator. Terrestrial organisms in temperate and Arctic biomes have relatively small amounts of total biomass, smaller energy budgets, and display prominent adaptations to cold, including world-spanning migrations, social adaptations, homeothermy, estivation and multiple layers of insulation.

Lithosphere



The tectonic plates of the lithosphere on Earth



Earth cutaway from core to exosphere

The **lithosphere** is the rigid outermost shell of a rocky planet. It comprises the crust and the portion of the upper mantle that behaves elastically on time scales of thousands of years or greater.

Earth's lithosphere

In the Earth, the lithosphere includes the crust and the uppermost mantle, which constitute the hard and rigid outer layer of the Earth. The lithosphere is underlain by the asthenosphere, the weaker, hotter, and deeper part of the upper mantle. The boundary between the lithosphere and the underlying asthenosphere is defined by a difference in response to stress: the lithosphere remains rigid for very long periods of geologic time in which it deforms elastically and through brittle failure, while the asthenosphere deforms viscously and accommodates strain through plastic deformation. The lithosphere is broken into tectonic plates. The uppermost part of the lithosphere that chemically reacts to the atmosphere, hydrosphere and biosphere through the soil forming process is called the pedosphere.

The concept of the lithosphere as Earth's strong outer layer was developed by Joseph Barrell, who wrote a series of papers introducing the concept. The concept was based on the presence of significant gravity anomalies over continental crust, from which he inferred that there must exist a strong upper layer (which he called the lithosphere) above a weaker layer which could flow (which he called the asthenosphere). These ideas were expanded by Daly (1940), and have been broadly accepted by geologists and geophysicists. Although these ideas about lithosphere and asthenosphere were developed long before plate tectonic theory was articulated in the 1960s, the concepts that a strong lithosphere exists and that this rests on a weak asthenosphere are essential to that theory.

The lithosphere provides a conductive lid atop the convecting mantle; as such, it affects heat transport through the Earth.

There are two types of lithosphere:

- Oceanic lithosphere, which is associated with Oceanic crust and exists in the ocean basins
- Continental lithosphere, which is associated with Continental crust

The thickness of the lithosphere is considered to be the depth to the isotherm associated with the transition between brittle and viscous behavior. The temperature at which olivine begins to deform viscously (~1000°C) is often used to set this isotherm because olivine is generally the weakest mineral in the upper mantle. Oceanic lithosphere is typically about 50–100 km thick (but beneath the mid-ocean ridges is no thicker than the crust), while continental lithosphere has a range in thickness from about 40 km to perhaps 200 km; the upper ~30 to ~50 km of typical continental lithosphere is crust. The mantle part of the lithosphere consists largely of peridotite. The crust is distinguished from the upper mantle by the change in chemical composition that takes place at the Moho discontinuity.

Oceanic lithosphere

Oceanic lithosphere consists mainly of mafic crust and ultramafic mantle (peridotite) and is denser than continental lithosphere, for which the mantle is associated with crust made of felsic rocks. Oceanic lithosphere thickens as it ages and moves away from the mid-ocean ridge. This thickening occurs by conductive cooling, which converts hot asthenosphere into lithospheric mantle, and causes the oceanic lithosphere to become increasingly thick and dense with age. The thickness of the mantle part of the oceanic lithosphere can be approximated as a thermal boundary layer that thickens as the square root of time.

$$h \sim 2\sqrt{\kappa t}$$

Here, *h* is the thickness of the oceanic mantle lithosphere, κ is the thermal diffusivity (approximately 10^{-6} m^2/s), and *t* is time.

Oceanic lithosphere is less dense than asthenosphere for a few tens of millions of years, but after this becomes increasingly denser than asthenosphere. This is because the chemically-differentiated oceanic crust is lighter than asthenosphere, but due to thermal contraction, the mantle lithosphere is more dense than the asthenosphere. The gravitational instability of mature oceanic lithosphere has the effect that at subduction zones, oceanic lithosphere invariably sinks underneath the overriding lithosphere, which can be oceanic or continental. New oceanic lithosphere is constantly being produced at mid-ocean ridges and is recycled back to the mantle at subduction zones. As a result, oceanic lithosphere is much younger than continental lithosphere: the oldest oceanic lithosphere is about 170 million years old, while parts of the continental lithosphere are billions of years old. The oldest parts of continental lithosphere underlie cratons, and the mantle lithosphere there is thicker and less dense than typical; the relatively low density of such mantle "roots of cratons" helps to stabilize these regions.

Subducted lithosphere

Geophysical studies in the early 21st Century posit that large pieces of the lithosphere have been subducted into the mantle as deep as 2900 km to near the core-mantle boundary, while others "float" in the upper mantle, while some stick down into the mantle as far as 400 km but remain "attached" to the continental plate above, similar to the extent of the "tectosphere" proposed by Jordan in 1988.

Mantle xenoliths

Geoscientists can directly study the nature of the subcontinental mantle by examining mantle xenoliths brought up in kimberlite, lamproite, and other volcanic pipes. The histories of these xenoliths have been investigated by many methods, including analyses of abundances of isotopes of osmium and rhenium. Such studies have confirmed that mantle lithospheres below some cratons have persisted for periods in excess of 3 billion years, despite the mantle flow that accompanies plate tectonics.

Chapter- 2

Atmosphere of Earth

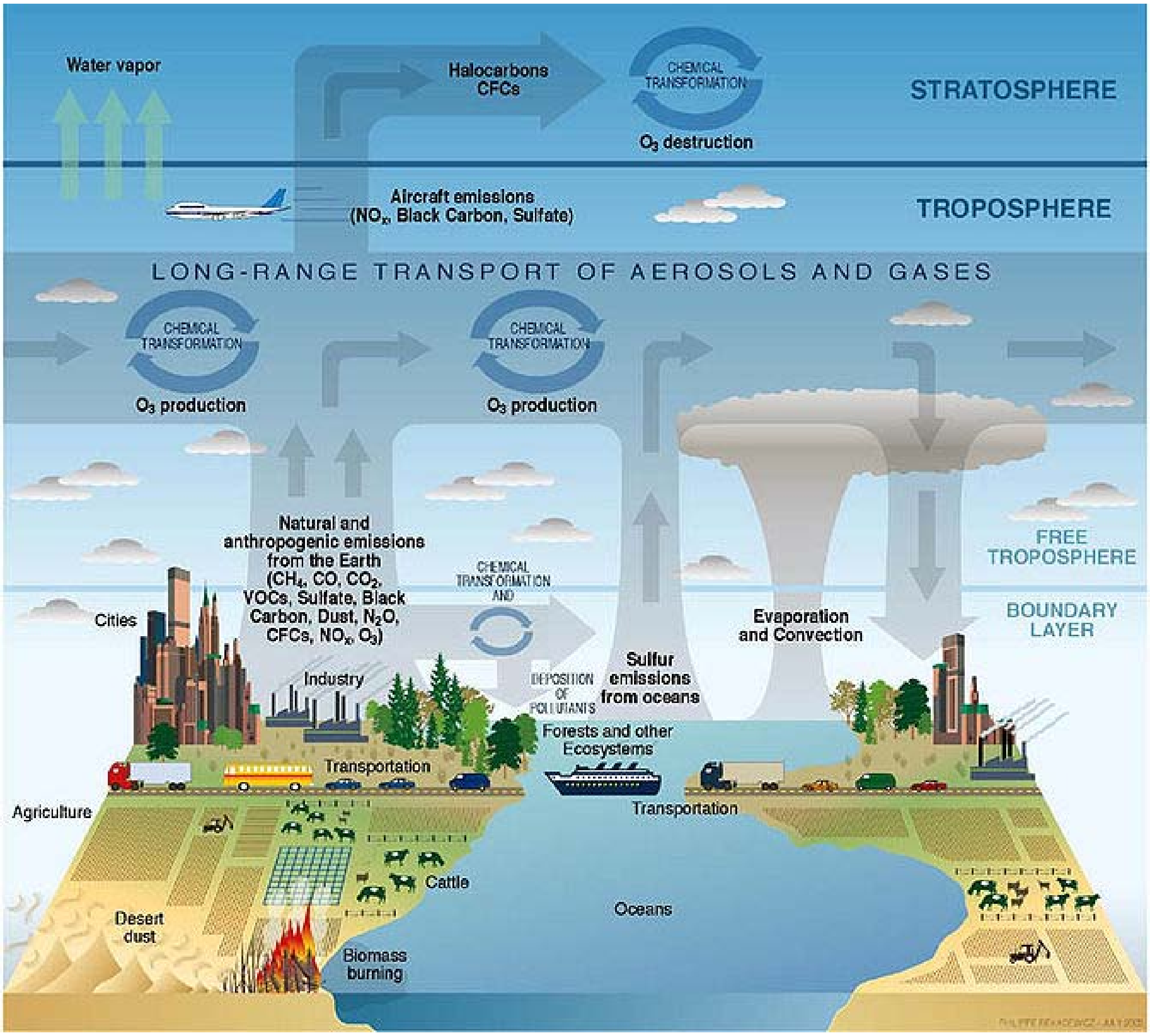
Blue light is scattered more than other wavelengths by the gases in the atmosphere, giving the Earth a blue halo when seen from space.

Limb view, of the Earth's atmosphere. Colours roughly denote the layers of the atmosphere

The **atmosphere of Earth** is a layer of gases surrounding the planet Earth that is retained by Earth's gravity. The atmosphere protects life on Earth by absorbing ultraviolet solar radiation, warming the surface through heat retention (greenhouse effect), and reducing temperature extremes between day and night. Dry air contains roughly (by volume) 78.09% nitrogen, 20.95% oxygen, 0.93% argon, 0.039% carbon dioxide, and small amounts of other gases. Air also contains a variable amount of water vapor, on average around 1%.

The atmosphere has a mass of about 5×10^{18} kg, three quarters of which is within about 11 km (6.8 mi; 36,000 ft) of the surface. The atmosphere becomes thinner and thinner with increasing altitude, with no definite boundary between the atmosphere and outer space. An altitude of 120 km (75 mi) is where atmospheric effects become noticeable during atmospheric reentry of spacecraft. The Kármán line, at 100 km (62 mi), also is often regarded as the boundary between atmosphere and outer space.

Atmospheric chemistry



Schematic of chemical and transport processes related to atmospheric composition

Atmospheric chemistry is a branch of atmospheric science in which the chemistry of the Earth's atmosphere and that of other planets is studied. It is a multidisciplinary field of research and draws on environmental chemistry, physics, meteorology, computer modeling, oceanography, geology and volcanology and other disciplines. Research is increasingly connected with other areas of study such as climatology.

The composition and chemistry of the atmosphere is of importance for several reasons, but primarily because of the interactions between the atmosphere and living organisms. The composition of the Earth's atmosphere has been changed by human activity and some of these changes are harmful to human health, crops and ecosystems. Examples of problems which have been addressed by atmospheric chemistry include acid rain, ozone depletion, photochemical smog and global warming. Atmospheric chemistry seeks to understand the causes of these problems, and by obtaining a theoretical understanding of them, allow possible solutions to be tested and the effects of changes in government policy evaluated.

Atmospheric composition

Average composition of dry atmosphere, by volume

Gas	per NASA
Nitrogen, N_2	78.084%
Oxygen, O_2	20.946%
Argon, Ar	0.934%
Minor constituents (in ppm)	
Carbon Dioxide, CO_2	383
Neon, Ne	18.18
Helium, He	5.24
Methane, CH_4	1.7
Krypton, Kr	1.14
Hydrogen, H_2	0.55
Water	
Water vapour	Highly variable; typically makes up about 1%

Notes: the concentration of CO_2 and CH_4 vary by season and location. The mean molecular mass of air is 28.97 g/mol.

History

The ancient Greeks regarded air as one of the four elements, but the first scientific studies of atmospheric composition began in the 18th century. Chemists such as Joseph Priestley, Antoine Lavoisier and Henry Cavendish made the first measurements of the composition of the atmosphere.

In the late 19th and early 20th centuries interest shifted towards trace constituents with very small concentrations. One particularly important discovery for atmospheric chemistry was the discovery of ozone by Christian Friedrich Schoenbein in 1840.

In the 20th century atmospheric science moved on from studying the composition of air to a consideration of how the concentrations of trace gases in the atmosphere have changed over time and the chemical processes which create and destroy compounds in the air. Two particularly important examples of this were the explanation of how the ozone layer is created and maintained by Sydney Chapman and Gordon Dobson, and the explanation of Photochemical smog by Arie Jan Haagen-Smit. Further studies on ozone issues led to the 1995 Nobel Prize in Chemistry award shared between Paul Crutzen, Mario Molina and Frank Sherwood Rowland.

In the 21st century the focus is now shifting again. Atmospheric chemistry is increasingly studied as one part of the Earth system. Instead of concentrating on atmospheric chemistry in isolation the focus is now on seeing it as one part of a single system with the rest of the atmosphere, biosphere and geosphere. An especially important driver for this is the links between chemistry and climate such as the effects of changing climate on the recovery of the ozone hole and vice versa but also interaction of the composition of the atmosphere with the oceans and terrestrial ecosystems.

Methodology

Observations, lab measurements and modeling are the three central elements in atmospheric chemistry. Progress in atmospheric chemistry is often driven by the interactions between these components and they form an integrated whole. For example observations may tell us that more of a chemical compound exists than previously thought possible. This will stimulate new modelling and laboratory studies which will increase our scientific understanding to a point where the observations can be explained.

Observation

Observations of atmospheric chemistry are essential to our understanding. Routine observations of chemical composition tell us about changes in atmospheric composition over time. One important example of this is the Keeling Curve - a series of measurements from 1958 to today which show a steady rise in of the concentration of carbon dioxide. Observations of atmospheric chemistry are made in observatories such as that on Mauna Loa and on mobile platforms such as aircraft (e.g. the UK's Facility for Airborne Atmospheric Measurements), ships and balloons. Observations of atmospheric composition are increasingly made by satellites with important instruments such as GOME and MOPITT giving a global picture of air pollution and chemistry. Surface observations have the advantage that they provide long term records at high time resolution but are limited in the vertical and horizontal space they provide observations from. Some surface based instruments e.g. LIDAR can provide concentration profiles of chemical compounds and aerosol but are still restricted in the horizontal region they can cover. Many observations are available on line in Atmospheric Chemistry Observational Databases.

Lab measurements

Measurements made in the laboratory are essential to our understanding of the sources and sinks of pollutants and naturally occurring compounds. Lab studies tell us which gases react with each other and how fast they react. Measurements of interest include reactions in the gas phase, on surfaces and in water. Also of high importance is photochemistry which quantifies how quickly molecules are split apart by sunlight and what the products are plus thermodynamic data such as Henry's law coefficients.

Modeling

In order to synthesise and test theoretical understanding of atmospheric chemistry, computer models (such as chemical transport models) are used. Numerical models solve the differential equations governing the concentrations of chemicals in the atmosphere. They can be very simple or very complicated. One common trade off in numerical models is between the number of chemical compounds and chemical reactions modelled versus the representation of transport and mixing in the atmosphere. For example, a box model might include hundreds or even thousands of chemical reactions but will only have a very crude representation of mixing in the atmosphere. In contrast, 3D models represent many of the physical processes of the atmosphere but due to constraints on computer resources will have far fewer chemical reactions and compounds. Models can be used to interpret observations, test understanding of chemical reactions and predict future concentrations of chemical compounds in the atmosphere. One important current trend is for atmospheric chemistry modules to become one part of earth system models in which the links between climate, atmospheric composition and the biosphere can be studied.

Some models are constructed by automatic code generators (e.g. Autochem or KPP). In this approach a set of constituents are chosen and the automatic code generator will then select the reactions involving those constituents from a set of reaction databases. Once the reactions have been chosen the ordinary differential equations (ODE) that describe their time evolution can be automatically constructed.

Structure of the atmosphere

1. Exosphere

Earth atmosphere diagram showing the exosphere and other layers. The layers are to scale. From Earth's surface to the top of the stratosphere (50km) is just under 1% of Earth's radius.

The **exosphere** is the uppermost layer of the atmosphere. In the exosphere, an upward travelling molecule moving fast enough to attain escape velocity can escape to space with a low chance of collisions; if it is moving below escape velocity it will be prevented from escaping from the celestial body by gravity. In either case, such a molecule is unlikely to collide with another molecule due to the exosphere's low density.

Earth's exosphere

The main gases within the Earth's exosphere are the lightest gases, mainly hydrogen, with some helium, carbon dioxide, and atomic oxygen near the exobase. The exosphere is the last layer before outer space. Since there is no clear boundary between outer space and the exosphere, the exosphere is sometimes considered a part of outer space.

Lower boundary

The altitude of its lower boundary, known as the *thermopause* and *exobase*, ranges from about 250 to 500 kilometres (160 to 310 mi) depending on solar activity. Its lower boundary at the edge of the thermosphere has sometimes been estimated to be 500 to 1,000 km (310 to 620 mi) above the Earth's surface. The **exobase** is also called the **critical level**, the lowest altitude of the exosphere, and is typically defined in one of two ways:

1. The height above which there are the negligible atomic collisions between the particles and
2. The height above which constituent atoms are on purely ballistic trajectories.

If we define the exobase as the height at which upward traveling molecules experience one collision on average, then at this position the mean free path of a molecule is equal to one pressure scale height. This is shown in the following. Consider a volume of air, with horizontal area *A* and height equal to the mean free path *l*, at pressure *p* and temperature *T*. For an ideal gas, the number of molecules contained in it is:

$$n = \frac{pAl}{RT}$$

where *R* is the universal gas constant. From the requirement that each molecule traveling upward undergoes on average one collision, the pressure is:

$$p = \frac{m_A n g}{A}$$

where m_A is the mean molecular mass of the gas. Solving these two equations gives:

$$l = \frac{RT}{m_A g}$$

which is the equation for the pressure scale height. As the pressure scale height is almost equal to the density scale height of the primary constituent, and since the Knudsen number is the ratio of mean free path and typical density fluctuation scale, this means that the exobase lies in the region where $\mathrm{Kn}(h_{EB}) \simeq 1$.

The fluctuation in the height of the exobase is important because this provides atmospheric drag on satellites, eventually causing them to fall from orbit if no action is taken to maintain the orbit.

Upper boundary

The upper boundary of the exosphere can be defined theoretically by the altitude about 190,000 kilometres (120,000 mi), half the distance to the Moon) at which the influence of solar radiation pressure on atomic hydrogen velocities exceeds that of the Earth’s gravitational pull. The exosphere observable from space as the geocorona is seen to extend to at least 100,000 kilometres (62,000 mi) from the surface of the Earth. The exosphere is a transitional zone between Earth’s atmosphere and interplanetary space.

2. Thermosphere

Earth atmosphere diagram showing the exosphere and other layers. The layers are to scale. From Earth's surface to the top of the stratosphere (50 kilometres (31 mi)) is just under 1% of Earth's radius.

The **thermosphere** is the biggest of all the layers of the earth's atmosphere directly above the mesosphere and directly below the exosphere. Within this layer, ultraviolet radiation causes ionization. The International Space Station has a stable orbit within the middle of the thermosphere, between 320 and 380 kilometres (200 and 240 mi). Auroras also occur in the thermosphere.

Named from the Greek θερμός (*thermos*) for heat, the thermosphere begins about 80 kilometres (50 mi) above the earth. At these high altitudes, the residual atmospheric gases sort into strata according to molecular mass. Thermospheric temperatures increase with altitude due to absorption of highly energetic solar radiation by the small amount of residual oxygen still present. Temperatures are highly dependent on solar activity, and can rise to 1,500 °C (2,730 °F). Radiation causes the atmosphere particles in this layer to become electrically charged, enabling radio waves to bounce off and be received beyond the horizon. At the exosphere, beginning at 500 to 1,000 kilometres (310 to 620 mi) above the Earth's surface, the atmosphere turns into space.

The highly diluted gas in this layer can reach 2,500 °C (4,530 °F) during the day. Even though the temperature is so high, one would not feel warm in the thermosphere, because it is so near vacuum that there is not enough contact with the few atoms of gas to transfer much heat. A normal thermometer would read significantly below 0 °C (32 °F), due to the energy lost by thermal radiation overtaking the energy acquired from the atmospheric gas by direct contact.

The dynamics of the lower thermosphere (below approximately 120 kilometres (75 mi)) are dominated by atmospheric tide, which is driven, in part, by the very significant diurnal heating. The atmospheric tide dissipates above this level since molecular concentrations do not support the coherent motion needed for fluid flow.

3. Mesosphere

The **mesosphere** (from the Greek words *mesos* = middle and *sphaira* = ball) is the layer of the Earth's atmosphere that is directly above the stratosphere and directly below the thermosphere. The mesosphere is located about 50 to 85 kilometers (30 to 50 miles) above the Earth's surface.

The stratosphere and mesosphere are referred to as the middle atmosphere. The mesopause, at an altitude of 80–90 km (50–56 mi), separates the mesosphere from the thermosphere—the second-outermost layer of the Earth's atmosphere. This is also around the same altitude as the turbopause, below which different chemical species are well mixed due to turbulent eddies. Above this level the atmosphere becomes non-uniform; the scale heights of different chemical species differ by their molecular masses.

Temperature

Within the mesosphere, temperature decreases with increasing altitude. This is due to decreasing solar heating and increasing cooling by CO_2 radiative emission. The top of the mesosphere, called the mesopause, is the coldest place on Earth. Temperatures in the upper mesosphere fall as low as −100 °C (173 K; −148 °F), varying according to latitude and season.

Dynamical features

The main dynamical features in this region are atmospheric tides, internal atmospheric gravity waves (commonly called "gravity waves") and planetary waves. Most of these tides and waves are excited in the troposphere and lower stratosphere, and propagate upward to the mesosphere. In the mesosphere, gravity-wave amplitudes can become so large that the waves become unstable and dissipate. This dissipation deposits momentum into the mesosphere and largely drives global circulation.

Noctilucent clouds are located in the mesosphere. The mesosphere is also the region of the ionosphere known as the *D layer*. The D layer is only present during the day, when some ionization occurs with nitric oxide being ionized by Lyman series-alpha hydrogen radiation. The ionization is so weak that when night falls, and the source of ionization is removed, the free electron and ion form back into a neutral molecule.

A 5 km (3.1 mi) deep sodium layer is located between 80–105 km (50–65 mi). Made of unbound, non-ionized atoms of sodium, the sodium layer radiates weakly to contribute to the airglow.

Uncertainties

The mesosphere lies above the maximum altitude for aircraft and below the minimum altitude for orbital spacecraft. It has only been accessed through the use of sounding rockets. As a result, it is the most poorly understood part of the atmosphere. The presence of red sprites and blue jets (electrical discharges or lightning within the lower mesosphere), noctilucent clouds and density shears within the poorly understood layer are of current scientific interest.

Meteors

Millions of meteors enter the atmosphere, an average of 40 tons per day. Within the mesosphere most melt or vaporize as a result of collisions with the gas particles contained there. This results in a higher concentration of iron and other refractory materials reaching the surface.

4. Stratosphere

The **stratosphere** (*stratified* and *sphaira* meaning 'ball') is the second major layer of Earth's atmosphere, just above the troposphere, and below the mesosphere. It is stratified in temperature, with warmer layers higher up and cooler layers farther down. This is in contrast to the troposphere near the Earth's surface, which is cooler higher up and warmer farther down. The border of the troposphere and stratosphere, the tropopause, is marked by where this inversion begins, which in terms of atmospheric thermodynamics is the equilibrium level. The stratosphere is situated between about 10 km (6 miles) and 50 km (31 miles) altitude above the surface at moderate latitudes, while at the poles it starts at about 8 km (5 miles) altitude.

Ozone and temperature

Within this layer, temperature increases as altitude increases; the top of the stratosphere has a temperature of about 270 K (−3°C or 29.6°F), just slightly below the freezing point of water. The stratosphere is layered in temperature because ozone (O_3) here absorbs high energy UVB and UVC energy waves from the Sun and is broken down into monoatomic oxygen (O) and diatomic oxygen (O_2). Monoatomic oxygen is found prevalent in the upper stratosphere due to the bombardment of UV light and the destruction of both ozone and diatomic oxygen. The mid stratosphere has less UV light passing through it, O and O_2 are able to combine, and is where the majority of natural ozone is produced. It is when these two forms of oxygen recombine to form ozone that they release the heat found in the stratosphere. The lower stratosphere receives very low amounts of UVC, thus monoatomic oxygen is not found here and ozone is not formed (with heat as the byproduct). This vertical stratification, with warmer layers above and cooler layers below, makes the stratosphere dynamically stable: there is no regular convection and associated turbulence in this part of the atmosphere. The top of the stratosphere is called the stratopause, above which the temperature decreases with height.

Methane (CH_4) while it is not a direct cause of ozone destruction in the stratosphere, does lead to the formation of compounds that do destroy ozone. Monoatomic oxygen (O), in the upper stratosphere, reacts with methane (CH_4) to form a hydroxyl anion (OH^-). This hydroxyl anion is then able to interact with non-soluble compounds like chlorofluorocarbons and UV light break off chlorine anions (Cl^-). These chlorine anions break off an oxygen atom from the ozone molecule, creating an oxygen molecule (O_2) and a hypochlorite molecule (ClO^-). The hypochlorite molecule then reacts with a monoatomic oxygen creating another oxygen molecule and another chlorine anion, thereby preventing the reaction of a monoatomic oxygen with O_2 to create natural ozone.

Aircraft flight

Commercial airliners typically cruise at altitudes of 9–12 km (29,000 to 39,000 ft) in temperate latitudes (in the lower reaches of the stratosphere). They do this to optimize fuel burn, mostly thanks to the low temperatures encountered near the tropopause and the low air density that reduces parasitic drag on the airframe. It also allows them to stay above any hard weather (extreme turbulence).

Because the temperature in the tropopause and lower stratosphere remains constant (or slightly increases) with increasing altitude, there is very little convective turbulence at these altitudes. Though most of the turbulence at this altitude is caused by variations in the jet stream and other local wind shears, areas of significant convective activity (thunderstorms) in the troposphere below may produce convective overshoot.

Although a few gliders have achieved great altitudes in the powerful thermals in thunderstorms, this is dangerous. Most high altitude flights by gliders use lee waves from mountain ranges and were used to set the current record of 15,447m (50,671 feet).

Circulation and mixing

The stratosphere is a region of intense interactions among radiative, dynamical, and chemical processes, in which horizontal mixing of gaseous components proceeds much more rapidly than vertical mixing.

An interesting feature of stratospheric circulation is the quasi-Biennial Oscillation (QBO) in the tropical latitudes, which is driven by gravity waves that are convectively generated in the troposphere. The QBO induces a secondary circulation that is important for the global stratospheric transport of tracers such as ozone or water vapor.

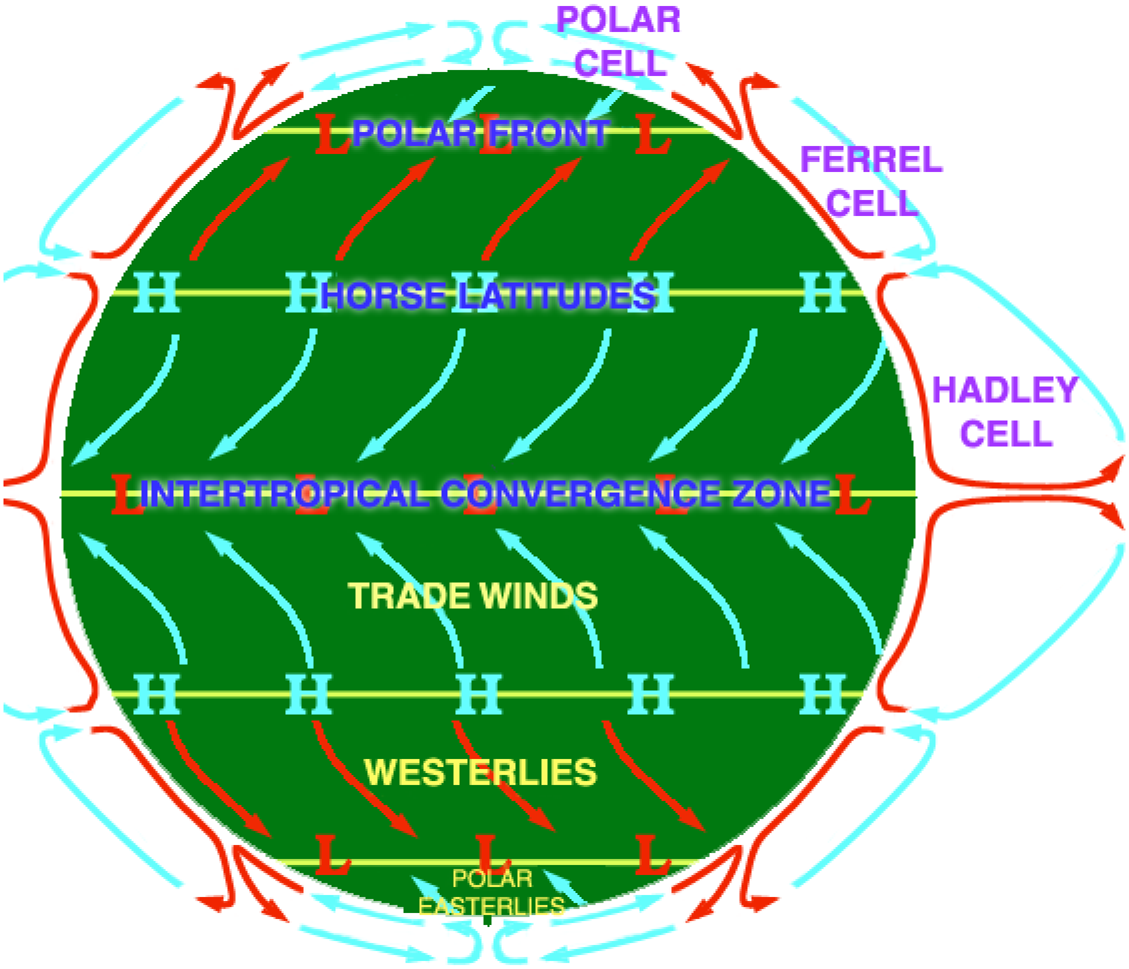
In northern hemispheric winter, sudden stratospheric warmings can often be observed which are caused by the absorption of Rossby waves in the stratosphere.

Life

Bacterial life survives in the stratosphere, making it a part of the biosphere. Also, some bird species have been reported to fly at the lower levels of the stratosphere. On November 29, 1975, a Rüppell's Vulture was reportedly ingested into a jet engine 37,900 feet above the Ivory Coast, and Bar-headed geese routinely overfly Mount Everest's summit, which is 29,028 feet.

5. Troposphere

A view of Earth's troposphere from an airplane



Atmospheric circulation shown with three large cells

The **troposphere** is the lowest portion of Earth's atmosphere. It contains approximately 75% of the atmosphere's mass and 99% of its water vapor and aerosols.

The average depth of the troposphere is approximately 17 km (11 mi) in the middle latitudes. It is deeper in the tropical regions, up to 20 km (12 mi), and shallower near the poles, at 7 km (4.3 mi) in summer, and indistinct in winter. The lowest part of the troposphere, where friction with the Earth's surface influences air flow, is the planetary boundary layer. This layer is typically a few hundred meters to 2 km (1.2 mi) deep depending on the landform and time of day. The border between the troposphere and stratosphere, called the tropopause, is a temperature inversion.

The word troposphere derives from the Greek: *tropos* for "turning" or "mixing," reflecting the fact that turbulent mixing plays an important role in the troposphere's structure and behavior. Most of the phenomena we associate with day-to-day weather occur in the troposphere.

Pressure and temperature structure

Composition

The chemical composition of the troposphere is essentially uniform, with the notable exception of water vapor. The source of water vapor is at the surface through the processes of evaporation and transpiration. Furthermore the temperature of the troposphere decreases with height, and saturation vapor pressure decreases strongly as temperature drops, so the amount of water vapor that can exist in the atmosphere decreases strongly with height. Thus the proportion of water vapor is normally greatest near the surface and decreases with height.

Pressure

The pressure of the atmosphere is maximum at sea level and decreases with higher altitude. This is because the atmosphere is very nearly in hydrostatic equilibrium, so that the pressure is equal to the weight of air above a given point. The change in pressure with height therefore can be equated to the density with this hydrostatic equation:

$$\frac{dp}{dz} = -\rho g_n = -\frac{mpg}{RT}$$

where:

- g_n stands for the standard gravity
- ρ stands for density
- z stands for height
- p stands for pressure
- R stands for the gas constant
- T stands for temperature in kelvins
- m stands for the molar mass

Since temperature in principle also depends on altitude, one needs a second equation to determine the pressure as a function of height, as discussed in the next section.*

Temperature

The temperature of the troposphere generally decreases as altitude increases. The rate at which the temperature decreases, $-dT/dz$, is called the environmental lapse rate (ELR). The ELR is nothing more the difference in temperature between the surface and the tropopause divided by the height. The reason for this temperature difference is the absorption of the sun's energy occurs at the ground which heats the lower levels of the atmosphere, and the radiation of heat occurs at the top of the atmosphere cooling the earth, this process maintaining the overall heat balance of the earth.

As parcels of air in the atmosphere rise and fall, they also undergo changes in temperature for reasons described below. The rate of change of the temperature in the parcel may be less than or more than the ELR. When a parcel of air rises, it expands, because the pressure is lower at higher altitudes. As the air parcel expands, it pushes on the air around it, doing work; but generally it does not gain heat in exchange from its environment, because its thermal conductivity is low (such a process is called adiabatic). Since the parcel does work and gains no heat, it loses energy, and so its temperature decreases. (The reverse, of course, will be true for a sinking parcel of air.)

Since the heat exchanged dQ is related to the entropy change dS by dQ=T dS, the equation governing the temperature as a function of height for a thoroughly mixed atmosphere is

$$\frac{dS}{dz} = 0$$

where *S* is the entropy. The rate at which temperature decreases with height under such conditions is called the adiabatic lapse rate.

For *dry* air, which is approximately an ideal gas, we can proceed further. The adiabatic equation for an ideal gas is

$$p(z)T(z)^{-\frac{\gamma}{\gamma-1}} = constant$$

where γ is the heat capacity ratio (γ=7/5, for air). Combining with the equation for the pressure, one arrives at the dry adiabatic lapse rate,

$$\frac{dT}{dz} = -\frac{mg}{R}\frac{\gamma-1}{\gamma} = -9.8^\circ\mathrm{C/km}$$

If the air contains water vapor, then cooling of the air can cause the water to condense, and the behavior is no longer that of an ideal gas. If the air is at the saturated vapor pressure, then the rate at which temperature drops with height is called the saturated adiabatic lapse rate. More generally, the actual rate at which the temperature drops with altitude is called the environmental lapse rate. In the troposphere, the average environmental lapse rate is a drop of about 6.5 °C for every 1 km (1000 meters) increase in height.

The environmental lapse rate (the actual rate at which temperature drops with height, dT / dz) is not usually equal to the adiabatic lapse rate (or correspondingly, $dS/dz \neq 0$). If the upper air is warmer than predicted by the adiabatic lapse rate ($dS / dz > 0$), then when a parcel of air rises and expands, it will arrive at the new height at a lower temperature than its surroundings. In this case, the air parcel is denser than its surroundings, so it sinks back to its original height, and the air is stable against being lifted. If, on the contrary, the upper air is cooler than predicted by the adiabatic lapse rate, then when the air parcel rises to its new height it will have a higher temperature and a lower density than its surroundings, and will continue to accelerate upward.

Temperatures decrease at middle latitudes from an average of 15°C at sea level to about -55°C at the top of the tropopause. At the poles, the troposphere is thinner and the temperature only decreases to -45°C, while at the equator the temperature at the top of the troposphere can reach -75°C.

Tropopause

The tropopause is the boundary region between the troposphere and the stratosphere.

Measuring the temperature change with height through the troposphere and the stratosphere identifies the location of the tropopause. In the troposphere, temperature decreases with altitude. In the stratosphere, however, the temperature remains constant for a while and then increases with altitude. The region of the atmosphere where the lapse rate changes from positive (in the troposphere) to negative (in the stratosphere), is defined as the tropopause. Thus, the tropopause is an inversion layer, and there is little mixing between the two layers of the atmosphere.

Chapter- 3

Gaia Hypothesis

The study of planetary habitability is partly based upon extrapolation from knowledge of the Earth's conditions, as the Earth is the only planet currently known to harbour life.

The **Gaia hypothesis**, **Gaia theory** or **Gaia principle** is a controversial ecological hypothesis or theory proposing that the biosphere and the physical components of the Earth (atmosphere, cryosphere, hydrosphere and lithosphere) are closely integrated to form a complex interacting system that maintains the climatic and biogeochemical conditions on Earth in a preferred homeorhesis. Originally proposed by James Lovelock as the earth feedback hypothesis, it was named the Gaia Hypothesis after the Greek primordial goddess of the Earth, at the suggestion of William Golding, Nobel prizewinner in literature and friend and neighbour of Lovelock. The hypothesis is frequently described as viewing the Earth as a single organism.

History

The Gaia hypothesis was first scientifically formulated in the 1960s by the independent research scientist James Lovelock, as a consequence of his work for NASA on methods of detecting life on Mars. He initially published the *Gaia Hypothesis* in journal articles in the early 1970s followed by a popularizing 1979 book *Gaia: A new look at life on Earth*.

The theory was initially, according to Lovelock, a way to explain the fact that combinations of chemicals including oxygen and methane persist in stable concentrations in the atmosphere of the Earth. Lovelock suggested detecting such combinations in other planets' atmospheres as a relatively reliable and cheap way to detect life, which many biologists opposed at the time and since. Later, other relationships such as sea creatures producing sulfur and iodine in approximately the same quantities as required by land creatures emerged and helped bolster the theory. Rather than invent many different theories to describe each such equilibrium, Lovelock dealt with them holistically, naming this self-regulating living system after the Greek goddess Gaia, using a suggestion from the novelist William Golding, who was living in the same village as Lovelock at the time (Bowerchalke, Wiltshire, UK). The Gaia Hypothesis has since been supported by a number of scientific experiments and provided a number of useful predictions, and hence is properly referred to as the Gaia theory.

Since 1971, the noted microbiologist Dr. Lynn Margulis has been Lovelock's most important collaborator in developing Gaian concepts.

Until 1975 the hypothesis was almost totally ignored. An article in the *New Scientist* of February 15, 1975, and a popular book length version of the theory, published in 1979 as *The Quest for Gaia*, began to attract scientific and critical attention to the hypothesis. The theory was then attacked by many mainstream biologists. Championed by certain environmentalists and climate scientists, it was vociferously rejected by many others, both within scientific circles and outside them.

Lovelock's initial hypothesis

James Lovelock defined Gaia as:

> *a complex entity involving the Earth's biosphere, atmosphere, oceans, and soil; the totality constituting a feedback or cybernetic system which seeks an optimal physical and chemical environment for life on this planet.*

His initial hypothesis was that the biomass modifies the conditions on the planet to make conditions on the planet more hospitable – the Gaia Hypothesis properly defined this "hospitality" as a full homeostasis. Lovelock's initial hypothesis, accused of being teleological by his critics, was that the atmosphere is kept in homeostasis by and for the biosphere.

Lovelock suggested that life on Earth provides a cybernetic, homeostatic feedback system operated automatically and unconsciously by the biota, leading to broad stabilization of global temperature and chemical composition.

With his initial hypothesis, Lovelock claimed the existence of a global control system of surface temperature, atmosphere composition and ocean salinity. His arguments were:

- The global surface temperature of the Earth has remained constant, despite an increase in the energy provided by the Sun.
- Atmospheric composition remains constant, even though it should be unstable.
- Ocean salinity is constant.

Since life started on Earth, the energy provided by the Sun has increased by 25% to 30%; however, the surface temperature of the planet has remained remarkably constant when measured on a global scale. Furthermore, he argued, the atmospheric composition of the Earth is constant. The Earth's atmosphere currently consists of 79% nitrogen, 20.7% oxygen and 0.03% carbon dioxide. Oxygen is the second most reactive element after fluorine, and should combine with gases and minerals of the Earth's atmosphere and crust. Traces of methane (at an amount of 100,000 tonnes produced per annum) should not exist, as methane is combustible in an oxygen atmosphere. This composition should be unstable, and its stability can only have been maintained with removal or production by living organisms.

Ocean salinity has been constant at about 3.4% for a very long time. Salinity stability is important as most cells require a rather constant salinity and do not generally tolerate values above 5%. Ocean salinity constancy was a long-standing mystery, because river salts should have raised the ocean salinity much higher than observed. Recently it was suggested that salinity may also be strongly influenced by seawater circulation through hot basaltic rocks, and emerging as hot water vents on ocean spreading ridges. However, the composition of sea water is far from equilibrium, and it is difficult to explain this fact without the influence of organic processes.

The only significant natural source of atmospheric carbon dioxide (CO_2) is volcanic activity, while the only significant removal is through the precipitation of carbonate rocks. In water, CO_2 is dissolved as a "carbonic acid", which may be combined with dissolved calcium to form solid calcium carbonate (limestone). Both precipitation and solution are influenced by the bacteria and plant roots in soils, where they improve gaseous circulation, or in coral reefs, where calcium carbonate is deposited as a solid on the sea floor. Calcium carbonate can also be washed from continents to the sea where it is used by living organisms to manufacture carbonaceous tests and shells. Once dead, the living organisms' shells fall to the bottom of the oceans where they generate deposits of chalk and limestone. Part of the organisms with carbonaceous shells are the coccolithophores (algae), which also have a role in the formation of clouds. When they die, they release dimethyl sulfide gas (DMS), $(CH_3)_2S$, which is converted by atmospheric processes to sulfate particles on which water vapor condenses to make clouds.

Lovelock sees this as one of the complex processes that maintain conditions suitable for life. The volcanoes produce CO_2 in the atmosphere, CO_2 participates in rock weathering as carbonic acid, itself accelerated by temperature and soil life, the dissolved CO_2 is then used by the algae and released on the ocean floor. CO_2 excess can be compensated by an increase of coccolithophoride life, increasing the amount of CO_2 locked in the ocean floor. Coccolithophorides increase the cloud cover, hence control the surface temperature, help cool the whole planet and favor precipitations necessary for terrestrial plants. For Lovelock and other Gaia scientists like Stephan Harding, coccolithophorides are one stage in a regulatory feedback loop. Lately the atmospheric CO_2 concentration has increased and there is some evidence that concentrations of ocean algal blooms are also increasing.

Controversial concepts

Lovelock used language that caused disagreement. For instance, many evolutionary biologists such as the late science historian Stephen Jay Gould and ethologist Richard Dawkins attacked his statement in the first paragraph of his book (1979), that "the quest for Gaia is an attempt to find the largest living creature on Earth."

Lynn Margulis, a microbiologist who collaborated with Lovelock in supporting the Gaia hypothesis, argued that “Darwin's grand vision was not wrong, only incomplete. In accentuating the direct competition between individuals for resources as the primary selection mechanism, Darwin (and especially his followers) created the impression that the environment was simply a static arena.” In 1999, she wrote that the composition of the Earth's atmosphere, hydrosphere, and lithosphere are regulated around "set points" as in homeostasis, but those set points change with time.

She also wrote that there is no special tendency of biospheres to preserve their current inhabitants, and certainly not to make them comfortable. According to her, the Earth is a kind of community of trust that can exist at many discrete levels of integration. All multicellular organisms do not live or die all at once: not all cells in the body die instantaneously, nor are homeostatic "set points" constant through the life of an organism.

Critical analysis

This theory is based on the idea that the biomass self-regulates the conditions on the planet to make its physical environment (in particular temperature and chemistry of the atmosphere) on the planet more hospitable to the species that constitute its "life." The Gaia Hypothesis properly defined this "hospitality" as a full homeostasis. A model that is often used to illustrate the original Gaia Hypothesis is the so-called Daisyworld simulation.

Whether this sort of system is present on Earth is still open to debate. Some relatively simple homeostatic mechanisms are generally accepted. For example, when atmospheric carbon dioxide levels rise, the biomass of photosynthetic organisms increases and thus removes more carbon dioxide from the atmosphere, but the extent to which these mechanisms stabilize and modify the Earth's overall climate are not yet known. Less clear is the reason why such traits should evolve in a system to produce such effects. Lovelock accepts a process of systemic Darwinian evolution for such mechanisms: creatures that improve their environment for their survival do better than those that damage their environment. However, many scientists do not believe such mechanisms exist.

Criticism

After initially being largely ignored by most scientists, (from 1969 until 1977), thereafter for a period, the initial Gaia hypothesis was ridiculed by a number of scientists, such as Ford Doolittle, Dawkins and Gould. Lovelock has said that by naming his theory after a Greek goddess, championed by many non scientists, the Gaia hypothesis was derided as some kind of neo-Pagan New Age religion. Many scientists in particular also criticised the approach taken in his popular book "Gaia, a New look at Life on Earth" for being teleological; a belief that all things have a predetermined purpose. Responding to this assertion in 1990, Lovelock stated "Nowhere in our writings do we express the idea that planetary self-regulation is purposeful, or involves foresight or planning by the biota."

In 1981, W. Ford Doolittle, in the *CoEvolution Quarterly* article "Is Nature Motherly" argued that nothing in the genome of individual organisms could provide the feedback mechanisms Gaia theory proposed, and therefore the Gaia hypothesis was an unscientific theory of a maternal type without any explanatory mechanism. In Richard Dawkins' 1982 book, *The Extended Phenotype*, he argued that organisms could not act in concert as this would require foresight and planning from them. Like Doolittle he rejected the possibility that feedback loops could stabilize the system. Dawkins claimed "there was no way for evolution by natural selection to lead to altruism on a Global scale".

Stephen Jay Gould criticised Gaia as merely a metaphorical description of Earth processes. He wanted to know the actual mechanisms by which self-regulating homeostasis was regulated. Lovelock argues that no one mechanism is responsible, that the connections between the various known mechanisms may never be known, that this is accepted in other fields of biology and ecology as a matter of course, and that specific hostility is reserved for his own theory for political reasons.

Aside from clarifying his language and understanding of what is meant by a life form, Lovelock himself ascribes most of the criticism to a lack of understanding of non-linear mathematics by his critics, and a linearizing form of greedy reductionism in which all events have to be immediately ascribed to specific causes before the fact. He notes also that his theory suggests experiments in many different fields, but few of them in biology, which most of his critics are trained in. "I'm a general practitioner in a world where there's nothing but specialists... science in the last two centuries has tended to be ever-dividing" and often rivalrous, especially for funding, which Lovelock describes as overly abundant and overly focused on institutions rather than original thought. He points out that Richard Feynman not only shared this opinion (coining the term cargo cult science) but also accepted a lack of general cause and effect explanation as an inevitable phase in a theory's development, and believed that some self-regulating phenomena may not be explainable at all mathematically.

Theory

One of the criteria of the empirical definition of life is its ability to replicate and pass on their genetic information to succeeding generations. Consequently, an argument against the idea that Gaia is a "living" organism is the fact that the planet is unable to reproduce.

Lovelock, however, defines life as a self-preserving, self-similar system of feedback loops like Humberto Maturana's autopoiesis; as a self-similar system, life could be a cell as well as an organ embedded into a larger organism as well as an individual in a larger inter-dependent social context. The biggest context of interacting inter-dependent living entities is the Earth. The problematic empirical definition is getting "fuzzy on the edges": Why are highly specialized bacteria like E. coli that are unable to thrive outside their habitat considered "life", while mitochondria, which have evolved independently from the rest of the cell, are not?

Maturana and Lovelock changed this with the autopoiesis deductive definition, which to them explains the phenomenon of life better. Some aspects of the empirical definition, however, no longer apply. Reproduction becomes optional: bee swarms reproduce, while the biosphere has no need to. Lovelock himself states in the original Gaia book that even that is not true; given the possibilities, the biosphere may multiply in the future by colonizing other planets, as humankind may be the primer by which Gaia will reproduce. Humanity's exploration of space, its interest in colonizing and even terraforming other planets, lends some plausibility to the idea that Gaia might in effect be able to reproduce.

The astronomer Carl Sagan also remarked that from a cosmic viewpoint, the space probes since 1959 have the character of a planet preparing to go to seed. This might warrant interpretation as a rhetorical point, however, as it equivocates two differing meanings of "reproduction" otherwise.

Daisyworld simulations

Lovelock responded to criticisms by developing the mathematical model Daisyworld with Andrew Watson to demonstrate that feedback mechanisms could evolve from the actions or activities of self-interested organisms, rather than through classic group selection mechanisms.

Daisyworld examines the energy budget of a planet populated by two different types of plants, black daisies and white daisies. The colour of the daisies influences the albedo of the planet such that black daisies absorb light and warm the planet, while white daisies reflect light and cool the planet. Competition between the daisies (based on temperature-effects on growth rates) leads to a balance of populations that tends to favour a planetary temperature close to the optimum for daisy growth. Lovelock and Watson demonstrated the stability of Daisyworld by forcing the sun that it orbits to evolve along the main sequence, taking it from low to high solar constant. This perturbation of Daisyworld's receipt of solar radiation caused the balance of daisies to gradually shift from black to white but the planetary temperature was always regulated back to this optimum (except at the extreme ends of solar evolution). This situation is very different from the corresponding abiotic world, where temperature is unregulated and rises linearly with solar output. Later versions of Daisyworld introduced a range of grey daisies and populations of grazers and predators, and found that these further increased the stability of the homeostasis. More recently other research, modelling the real biochemical cycles of Earth, and using various "guilds" of life (eg. photosynthesisers, decomposers, herbivores and primary and secondary carnivores) has also been shown to produce Daisyworld-like regulation and stability, which helps to explain planetary biological diversity.

This enables nutrient recycling within a regulatory framework derived by natural selection amongst species, where one being's harmful waste becomes low energy food for members of another guild. This research on the Redfield ratio of Nitrogen to Phosphorus shows that local biotic processes can regulate global systems.

First Gaia conference

In 1985, the first public symposium on the Gaia Hypothesis -- Is The Earth A Living Organism? -- was held at the University of Massachusetts August 1-6. The principal sponsor was the National Audubon Society Expedition Institute. Speakers included James Lovelock, George Wald, Mary Catherine Bateson, Lewis Thomas, John Todd, Donald Michael, Christopher Bird, Thomas Berry, Michael Cohen, and William Fields. Some 500 people attended and a concert by Paul Winter concluded the program. The symposium was produced by James A. Swan and Roberta Swan.

Second Gaia conference

In 1988, to draw attention to the Gaia hypothesis, the climatologist Stephen Schneider organised a conference of the American Geophysical Union's first Chapman Conference on Gaia, held at San Diego in 1989, solely to discuss Gaia.

At the conference James Kirchner criticised the Gaia hypothesis for its imprecision. He claimed that Lovelock and Margulis had not presented one Gaia hypothesis, but four -

- CoEvolutionary Gaia — that life and the environment had evolved in a coupled way. Kirchner claimed that this was already accepted scientifically and was not new.
- Homeostatic Gaia — that life maintained the stability of the natural environment, and that this stability enabled life to continue to exist.
- Geophysical Gaia — that the Gaia theory generated interest in geophysical cycles and therefore led to interesting new research in terrestrial geophysical dynamics.
- Optimising Gaia — that Gaia shaped the planet in a way that made it an optimal environment for life as a whole. Kirchner claimed that this was not testable and therefore was not scientific.

Of Homeostatic Gaia, Kirchner recognised two alternatives. "Weak Gaia" asserted that life tends to make the environment stable for the flourishing of all life. "Strong Gaia" according to Kirchner, asserted that life tends to make the environment stable, *to enable* the flourishing of all life. Strong Gaia, Kirchner claimed, was untestable and therefore not scientific.

Referring to the Daisyworld Simulations, Kirchner responded that these results were predictable because of the intention of the programmers — Lovelock and Watson, who selected examples that produced the responses they desired.

Lawrence E. Joseph in his book *Gaia: The Growth of an Idea* argued that Kirchner's attack was principally against Lovelock's integrity as a scientist. Lovelock did not attack Kirchner's views for ten years, until his autobiography "Homage to Gaia", where he calls Kirchner's position *sophistry*. Lovelock and other Gaia-supporting scientists, however, did attempt to disprove the claim that the theory is not scientific because it is impossible to test it by controlled experiment. For example, against the charge that Gaia was teleological Lovelock and Andrew Watson offered the Daisyworld model (and its modifications, above) as evidence against most of these criticisms.

Lovelock was careful to present a version of the Gaia Hypothesis that had no claim that Gaia intentionally or consciously maintained the complex balance in her environment that life needed to survive. It would appear that the claim that Gaia acts "intentionally" was a metaphoric statement in his popular initial book and was not meant to be taken literally. This new statement of the Gaia hypothesis was more acceptable to the scientific community.

The accusations of teleologism were largely dropped after this conference.

Range of views

Some have found James Kirchner's suggested spectrum, proposed at the First Gaia Chapman Conference, useful in suggesting that the original Gaia hypothesis could be split into a spectrum of hypotheses, ranging from the undeniable (Weak Gaia) to the radical (Strong Gaia).

Weak Gaia

At one end of this spectrum is the undeniable statement that the organisms on the Earth have altered its composition. A stronger position is that the Earth's biosphere effectively acts as if it is a self-organizing system, which works in such a way as to keep its systems in some kind of "meta-equilibrium" that is broadly conducive to life. The history of evolution, ecology and climate show that the exact characteristics of this equilibrium intermittently have undergone rapid changes, which are believed to have caused extinctions and felled civilizations.

Weak Gaian hypotheses suggest that Gaia is co-evolutive. Co-evolution in this context has been thus defined: "Biota influence their abiotic environment, and that environment in turn influences the biota by Darwinian process." Lovelock (1995) gave evidence of this in his second book, showing the evolution from the world of the early thermo-acido-philic and methanogenic bacteria towards the oxygen enriched atmosphere today that supports more complex life.

The weakest form of the theory has been called "influential Gaia". It states that biota minimally influence certain aspects of the abiotic world, e.g. temperature and atmosphere.

The weak versions are more acceptable from an orthodox science perspective, as they assume non-homeostasis. They state the evolution of life and its environment may affect each other. An example is how the activity of photosynthetic bacteria during Precambrian times have completely modified the Earth atmosphere to turn it aerobic, and as such supporting evolution of life (in particular eukaryotic life). However, these theories do not claim the atmosphere modification has been done in coordination and through homeostasis. Also such critical theories have yet to explain how conditions on Earth have not been changed by the kinds of run-away positive feedbacks that have affected Mars and Venus.

Biologists and earth scientists usually view the factors that stabilize the characteristics of a period as an undirected emergent property or entelechy of the system; as each individual species pursues its own self-interest, for example, their combined actions tend to have counterbalancing effects on environmental change. Opponents of this view sometimes reference examples of lives' actions that have resulted in dramatic change rather than stable equilibrium, such as the conversion of the Earth's atmosphere from a reducing environment to an oxygen-rich one. However, proponents argue these atmospheric changes improved the environment's suitability for life.

Some go a step further and hypothesize that all lifeforms are part of one single living planetary being called *Gaia*. In this view, the atmosphere, the seas and the terrestrial crust would be results of interventions carried out by Gaia through the coevolving diversity of living organisms. While it is arguable that the Earth as a unit does not match the generally accepted biological criteria for life itself (*Gaia* has not yet reproduced, for instance; it still might *spread* to other planets through human space colonization and terraforming), many scientists would be comfortable characterizing the earth as a single "system".

Strong Gaia

A version called "Optimizing Gaia" asserts that biota manipulate their physical environment for the purpose of creating biologically favorable, or even optimal, conditions for themselves. "The Earth's atmosphere is more than merely anomalous; it appears to be a contrivance specifically constituted for a set of purposes". Further, "... it is unlikely that chance alone accounts for the fact that temperature, pH and the presence of compounds of nutrient elements have been, for immense periods, just those optimal for surface life. Rather, ... energy is expended by the biota to actively maintain these optima".

Another strong hypothesis is the one called "Omega Gaia". Teilhard de Chardin claimed that the Earth is evolving through stages of cosmogenesis, affecting the geosphere, biogenesis of the biosphere, and noogenesis of the noosphere, culminating in the *Omega Point*. Another form of the strong Gaia hypothesis is proposed by Guy Murchie who extends the quality of a holistic lifeform to galaxies. "After all, we are made of star dust. Life is inherent in nature." Murchie describes geologic phenomena such as sand dunes, glaciers, fires, etc. as living organisms, as well as the life of metals and crystals. "The question is not whether there is life outside our planet, but whether it is possible to have "nonlife".

There are speculative versions of the Gaia hypothesis, including versions that hold that the Earth is conscious or part of some universe-wide evolution such as expressed in the Selfish Biocosm hypothesis strain of a larger speculative Gaia philosophy. These extreme forms of the Gaia hypothesis, that the entire Earth is a single unified organism that is *consciously* manipulating the climate to make conditions more conducive to life, are metaphysical or mystical views for which no evidence exists, and that cannot be tested scientifically. The political branch of Gaia theory is the Gaia Movement, a collection of different organisations operating in different countries, but all sharing a concern for how humans might live more sustainably within the "living system".

Recent developments

Gaia Theory has developed considerably and in recent years both Lovelock's and Margulis's understanding of Gaia have gained some increased support as a potentially viable, testable scientific hypothesis or theory.. Margulis dedicated the last of eight chapters in her book, *The Symbiotic Planet*, to Gaia. She resented the widespread personification of Gaia and stressed that Gaia is "not an organism", but "an emergent property of interaction among organisms". She defined Gaia as "the series of interacting ecosystems that compose a single huge ecosystem at the Earth's surface. Period." Yet still she argues, "the surface of the planet behaves as a physiological system in certain limited ways". Margulis seems to agree with Lovelock in that, in what comes to these physiological processes, the Earth's surface is "best regarded as alive". The book's most memorable "slogan" was actually quipped by a student of Margulis': "Gaia is just symbiosis as seen from space". This neatly connects Gaia theory to Margulis' own theory of endosymbiosis.

Third Gaia conference

By the time of the 2nd Chapman Conference on the Gaia Hypothesis, held at Valencia, Spain, on 23 June 2000, the situation had developed significantly in accordance with the developing science of Bio-geophysiology. Rather than a discussion of the Gaian teleological views, or "types" of Gaia Theory, the focus was upon the specific mechanisms by which basic short term homeostasis was maintained within a framework of significant evolutionary long term structural change.

The major questions were:

1. "How has the global biogeochemical/climate system called Gaia changed in time? What is its history? Can Gaia maintain stability of the system at one time scale but still undergo vectorial change at longer time scales? How can the geologic record be used to examine these questions?"
2. "What is the structure of Gaia? Are the feedbacks sufficiently strong to influence the evolution of climate? Are there parts of the system determined pragmatically by whatever disciplinary study is being undertaken at any given time or are there a set of parts that should be taken as most true for understanding Gaia as containing evolving organisms over time? What are the feedbacks among these different parts of the Gaian system, and what does the near closure of matter mean for the structure of Gaia as a global ecosystem and for the productivity of life?"
3. "How do models of Gaian processes and phenomena relate to reality and how do they help address and understand Gaia? How do results from Daisyworld transfer to the real world? What

> are the main candidates for "daisies"? Does it matter for Gaia theory whether we find daisies or not? How should we be searching for daisies, and should we intensify the search? How can Gaian mechanisms be investigated using process models or global models of the climate system that include the biota and allow for chemical cycling?"

In 1997, Tyler Volk argued that a Gaian system is almost inevitably produced as a result of an evolution towards far-from-equilibrium homeostatic states that maximise entropy production, and Kleidon (2004) agreed stating: "...homeostatic behavior can emerge from a state of MEP associated with the planetary albedo"; "...the resulting behavior of a biotic Earth at a state of MEP may well lead to near-homeostatic behavior of the Earth system on long time scales, as stated by the Gaia hypothesis." Staley (2002) has similarly proposed "...an alternative form of Gaia theory based on more traditional Darwinian principles... In [this] new approach, environmental regulation is a consequence of population dynamics, not Darwinian selection. The role of selection is to favor organisms that are best adapted to prevailing environmental conditions. However, the environment is not a static backdrop for evolution, but is heavily influenced by the presence of living organisms. The resulting co-evolving dynamical process eventually leads to the convergence of equilibrium and optimal conditions."

Fourth Gaia conference

A third international conference on the Gaia Theory, sponsored by the Northern Virginia Regional Park Authority and others, was held in October 2006 at the Arlington, VA campus of George Mason University. Lynn Margulis, Distinguished University Professor in the Department of Geosciences, University of Massachusetts-Amherst, and long-time advocate of the Gaia Theory, was a keynote speaker. Among many other speakers: Tyler Volk, Co-director of the Program in Earth and Environmental Science at New York University; Dr. Donald Aitken, Principal of Donald Aitken Associates; Dr. Thomas Lovejoy, President of the Heinz Center for Science, Economics and the Environment; Robert Correll, Senior Fellow, Atmospheric Policy Program, American Meteorological Society and noted environmental ethicist, J. Baird Callicott. James Lovelock, the theory’s progenitor, prepared a video specifically for the event.

This conference approached Gaia Theory as both science and metaphor as a means of understanding how we might begin addressing 21st century issues such as climate change and ongoing environmental destruction.

Gaia hypothesis in ecology

After much criticism, a modified Gaia hypothesis is now considered within ecological science basically consistent with the planet Earth being the ultimate object of ecological study. Ecologists generally consider the biosphere as an ecosystem and the Gaia hypothesis, though a simplification of that original proposed, to be consistent with a modern vision of global ecology, relaying the concepts of biosphere and biodiversity. The Gaia hypothesis has been called geophysiology or Earth System Science, which takes into account the interactions between biota, the oceans, the geosphere, and the atmosphere. To promote research and discussion in these fields an organisation, "Gaia Society for Research and Education in Earth System Science" was started.

An example of the change in acceptability of Gaia theories is the Amsterdam declaration of the scientific communities of four international global change research programmes — the International Geosphere-Biosphere Programme (IGBP), the International Human Dimensions Programme on Global Environmental Change (IHDP), the World Climate Research Programme (WCRP) and the international biodiversity programme DIVERSITAS — recognise that, in addition to the threat of significant climate change, there is growing concern over the ever-increasing human modification of other aspects of the global environment and the consequent implications for human well-being.

The programmes have stated the following:

"Research carried out over the past decade under the auspices of the four programmes to address these concerns has shown that:

1. The Earth System behaves as a single, self-regulating system with physical, chemical, biological, and human components. The interactions and feedbacks between the component parts are complex and exhibit multi-scale temporal and spatial variability. The understanding of the natural dynamics of the Earth System has advanced greatly in recent years and provides a sound basis for evaluating the effects and consequences of human-driven change.
2. Human activities are significantly influencing Earth's environment in many ways in addition to greenhouse gas emissions and climate change. Anthropogenic changes to Earth's land surface, oceans, coasts and atmosphere and to biological diversity, the water cycle and biogeochemical cycles are clearly identifiable beyond natural variability. They are equal to some of the great forces of nature in their extent and impact. Many are accelerating. Global change is real and is happening now.
3. Global change cannot be understood in terms of a simple cause-effect paradigm. Human-driven changes cause multiple effects that cascade through the Earth System in complex ways. These effects interact with each other and with local- and regional-scale changes in multidimensional patterns that are difficult to understand and even more difficult to predict.
4. Earth System dynamics are characterised by critical thresholds and abrupt changes. Human activities could inadvertently trigger such changes with severe consequences for Earth's environment and inhabitants. The Earth System has operated in different states over the last half million years, with abrupt transitions (a decade or less) sometimes occurring between them. Human activities have the potential to switch the Earth System to alternative modes of operation that may prove irreversible and less hospitable to humans and other life. The probability of a human-driven abrupt change in Earth's environment has yet to be quantified but is not negligible.
5. In terms of some key environmental parameters, the Earth System has moved well outside the range of the natural variability exhibited over the last half million years at least. The nature of changes now occurring simultaneously in the Earth System, their magnitudes and rates of change are unprecedented. The Earth is currently operating in a no-analogue state."

Sir Crispin Tickell in the 46th Annual Bennett Lecture for the 50th Anniversary of Geology at the University of Leicester in his recent talk "Earth Systems Science: Are We Pushing Gaia Too Hard?" stated "as a theory, Gaia is now winning."

He continued "The same goes for the earth systems science, which is now the concern of the Geological Society of London (with which the Gaia Society recently merged). Whatever the label, earth systems science, or Gaia, has now become a major subject of inquiry and research, and no longer has to justify itself."

These findings would seem to be fully in accord with the Gaia theory. Despite this endorsement, the late W. D. Hamilton, one of the founders of modern Darwinism, whilst conceding the empirical basis of the planetary homeostatic processes on which Gaia is based, states that it is a theory still awaiting its Copernicus. The homeostatic nature of the global system has been recognized as a consequence of the 2nd law of thermodynamics. In their comprehensive book on the thermodynamics of life, Eric D. Schneider and Dorion Sagan argue that Gaia belongs to a class of complex thermodynamic systems, not just living ones, that are naturally purposeful; and that life optimizes rather than maximizes entropy production.

The Revenge of Gaia

In James Lovelock's 2006 book, *The Revenge of Gaia*, he argues that the lack of respect humans have had for Gaia, through the damage done to rainforests and the reduction in planetary biodiversity, is testing Gaia's capacity to minimize the effects of the addition of greenhouse gases in the atmosphere. This eliminates the planet's negative feedbacks and increases the likelihood of homeostatic positive feedback potential associated with runaway global warming. Similarly the warming of the oceans is extending the oceanic thermocline layer of tropical oceans into the Arctic and Antarctic waters, preventing the rise of oceanic nutrients into the surface waters and eliminating the algal blooms of phytoplankton on which oceanic foodchains depend. As phytoplankton and forests are the main ways in which Gaia draws down greenhouse gases, particularly carbon dioxide, taking it out of the atmosphere, the elimination of this environmental buffering will see, according to Lovelock, most of the earth becoming uninhabitable for humans and other life-forms by the middle of this century, with a massive extension of tropical deserts.

Given these conditions, Lovelock expects human civilization will be hard pressed to survive. He expects the change to be similar to the Paleocene-Eocene Thermal Maximum when atmospheric concentration of CO_2 was 450 ppm. At that point the Arctic Ocean was 23 °C and had crocodiles in it, with the rest of the world mostly scrub and desert. He says of sustainable development and renewable energy that it came "200 years too late" and that more effort should go into adaptation, including more use of nuclear fission as a viable energy source in the future (unclear reference - clarification needed). He likens the Kyoto Protocol to the Munich conferences that failed to prevent World War II, including the likelihood that the disaster will cause people to come together in common cause. "We have been through no less than seven of these events as humans...comparable in extent to the change" likely to be wrought by global warming.

He claims that Gaia's self-regulation will likely prevent any extraordinary runaway effects that wipe out life itself, but that humans will survive and be "culled and, I hope, refined."

According to James Lovelock, by 2040, the world population of more than six billion will have been culled by floods, drought and famine. Indeed "[t]he people of Southern Europe, as well as South-East Asia, will be fighting their way into countries such as Canada, Australia and Britain".

"By 2040, parts of the Sahara desert will have moved into middle Europe. We are talking about Paris - as far north as Berlin. In Britain we will escape because of our oceanic position."

"If you take the Intergovernmental Panel on Climate Change predictions, then by 2040 every summer in Europe will be as hot as it was in 2003 - between 110F and 120F. It is not the death of people that is the main problem, it is the fact that the plants can't grow — there will be almost no food grown in Europe."

"We are about to take an evolutionary step and my hope is that the species will emerge stronger. It would be hubris to think humans as they now are God's chosen race."

Chapter- 4

Pedosphere and Cryosphere

Pedosphere

The **pedosphere** (from the Greek πέδον [pedon] soil, earth + σφαίρα [sfaíra] sphere) is the outermost layer of the Earth that is composed of soil and subject to soil formation processes. It exists at the interface of the lithosphere, atmosphere, hydrosphere and biosphere.

The pedosphere acts as the mediator of chemical and biogeochemical flux into and out of these respective systems and is made up of gaseous, mineralic, fluid and biologic components. The pedosphere lies within the Critical Zone, a broader interface that includes vegetation, pedosphere, groundwater aquifer systems, regolith and finally ends at some depth in the bedrock where the biosphere and hydrosphere cease to make significant changes to the chemistry at depth. As part of the larger global system, any particular environment in which soil forms is influenced solely by its geographic position on the globe as climatic, geologic, biologic and anthropogenic changes occur with changes in longitude and latitude.

The pedosphere lies below the vegetative cover of the biosphere and above the hydrosphere and lithosphere. The soil forming process (pedogenesis) can begin without the aid of biology but is significantly quickened in the presence of biologic reactions. Soil formation begins with the chemical and/or physical breakdown of minerals to form the initial material that overlies the bedrock substrate. Biology quickens this by secreting acidic compounds (dominantly fulvic acids) that help break rock apart. Particular biologic pioneers are lichen, mosses and seed bearing plants but many other inorganic reactions take place that diversify the chemical makeup of the early soil layer. Once weathering and decomposition products accumulate, a coherent soil body allows the migration of fluids both vertically and laterally through the soil profile causing ion exchange between solid, fluid and gaseous phases. As time progresses, the bulk geochemistry of the soil layer will deviate away from the initial composition of the bedrock and will evolve to a chemistry that reflects the type of reactions that take place in the soil.

Lithosphere

The primary conditions for soil development are controlled by the chemical composition of the rock that the soil will eventually be forming on. Rock types that form the base of the soil profile are often either sedimentary (carbonate or siliceous), igneous or metaigneous (metamorphosed igneous rocks) or volcanic and metavolcanic rocks. The rock type and the processes that lead to its exposure at the surface are controlled by the regional geologic setting of the specific area under study, which revolve around the underlying theory of plate tectonics, subsequent deformation, uplift, subsidence and deposition.

Metaigneous and metavolcanic rocks form the largest component of cratons and are high in silica. Igneous and volcanic rocks are also high in silica but with non-metamorphosed rock, weathering becomes faster and the mobilization of ions is more widespread. Rocks high in silica produce silicic acid as a weathering product. There are few rock types that lead to localized enrichment of some of the biologically limiting elements like phosphorus (P) and nitrogen (N). Phosphatic shale ($<15\%$ P_2O_5) and phosphorite ($>15\%$ P_2O_5) form in anoxic deep water basins that preserve organic material. Greenstone (metabasalt), phyllite and schist release up to 30-50% of the nitrogen pool. Thick successions of carbonate rocks are often deposited on craton margins during sea level rise. The widespread dissolution of carbonate and evaporate minerals leads to elevated levels of Mg^{2+}, HCO_3^-, Sr^{2+}, Na^+, Cl^- and SO_4^{2-} ions in aqueous solution.

Weathering

Weathering is the breaking down of Earth's rocks, soils and minerals through direct contact with the planet's atmosphere. Weathering occurs *in situ*, or "with no movement", and thus should not be confused with erosion, which involves the movement of rocks and minerals by agents such as water, ice, wind, and gravity.

In addition, weathering is the effect of atmospheric exposure to man-made structures and materials.

Two important classifications of weathering processes exist — physical and chemical weathering. **Mechanical** or **physical weathering** involves the breakdown of rocks and soils through direct contact with atmospheric conditions, such as heat, water, ice and pressure. The second classification, **chemical weathering**, involves the direct effect of atmospheric chemicals or biologically produced chemicals (also known as **biological weathering**) in the breakdown of rocks, soils and minerals.

The materials left over after the rock breaks down combined with organic material creates soil. The mineral content of the soil is determined by the parent material, thus a soil derived from a single rock type can often be deficient in one or more minerals for good fertility, while a soil weathered from a mix of rock types (as in glacial, aeolian or alluvial sediments) often makes more fertile soil.

Physical weathering

Physical weathering is the class of processes that causes the disintegration of rocks without chemical change. The primary process in physical weathering is abrasion (the process by which clasts and other particles are reduced in size). However, chemical and physical weathering often go hand in hand. For example, cracks exploited by physical weathering will increase the surface area exposed to chemical action. Furthermore, the chemical action at minerals in cracks can aid the disintegration process.

Thermal stress

Thermal stress weathering (sometimes called insolation weathering) results from expansion or contraction of rock, caused by temperature changes. Thermal stress weathering comprises two main types, thermal shock and thermal fatigue. Thermal stress weathering is an important mechanism in deserts, where there is a large diurnal temperature range, hot in the day and cold at night. The repeated heating and cooling exerts stress on the outer layers of rocks, which can cause their outer layers to peel off in thin sheets. Although temperature changes are the principal driver, moisture can enhance thermal expansion in rock. Forest fires and range fires are also known to cause significant weathering of rocks and boulders exposed along the ground surface. Intense, localized heat can rapidly expand a boulder, causing its surface to exfoliate or spall.

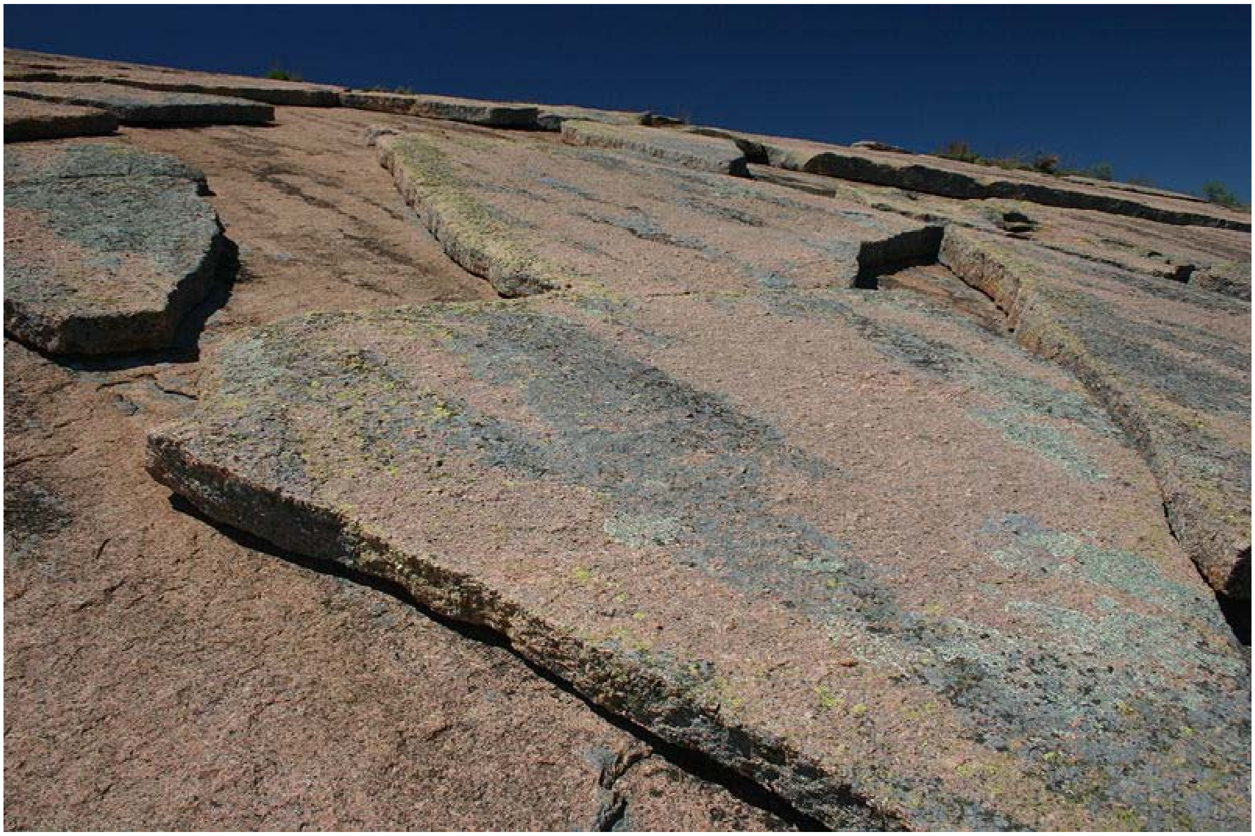
Frost weathering

A rock in Abisko, Sweden fractured along existing joints possibly by frost weathering or thermal stress

Frost weathering or *cryofracturing* is the collective name for several processes where ice is present. This processes include frost shattering, frost-wedging and freeze-thaw weathering. This type of weathering is common in mountain areas where the temperature is around the freezing point of water. Certain frost-susceptible soils expand or heave upon freezing as a result of water migrating via capillary action to grow ice lenses near the freezing front. This same phenomena occurs within pore spaces of rocks. The ice accumulations grow larger as they attract liquid water from the surrounding pores. The ice crystal growth weakens the rocks which, in time, break up. It is caused by the expansion of ice when water freezes, so putting considerable stress on the walls of containment.

Freeze induced weathering action occurs mainly in environments where there is a lot of moisture, and temperatures frequently fluctuate above and below freezing point—that is, mainly alpine and periglacial areas. An example of rocks susceptible to frost action is chalk, which has many pore spaces for the growth of ice crystals. This process can be seen in Dartmoor where it results in the formation of tors. When water that has entered the joints freezes, the ice formed strains the walls of the joints and causes the joints to deepen and widen. When the ice thaws, water can flow further into the rock. Repeated freeze-thaw cycles weaken the rocks which, over time, break up along the joints into angular pieces. The angular rock fragments gather at the foot of the slope to form a talus slope (or scree slope). The splitting of rocks along the joints into blocks is called block disintegration. The blocks of rocks that are detached are of various shapes depending on rock structure.

Pressure release



Pressure release could have caused the exfoliated granite sheets shown in the picture

In pressure release, also known as unloading, overlying materials (not necessarily rocks) are removed (by erosion, or other processes), which causes underlying rocks to expand and fracture parallel to the surface. Often the overlying material is heavy, and the underlying rocks experience high pressure under them, for example, a moving glacier. Pressure release may also cause exfoliation to occur.

Intrusive igneous rocks (e.g. granite) are formed deep beneath the Earth's surface. They are under tremendous pressure because of the overlying rock material. When erosion removes the overlying rock material, these intrusive rocks are exposed and the pressure on them is released. The outer parts of the rocks then tend to expand. The expansion sets up stresses which cause fractures parallel to the rock surface to form. Over time, sheets of rock break away from the exposed rocks along the fractures. Pressure release is also known as "exfoliation" or "sheeting"; these processes result in batholiths and granite domes, an example of which is Dartmoor.

Hydraulic action

Hydraulic action occurs when water (generally from powerful waves) rushes rapidly into cracks in the rock face, thus trapping a layer of air at the bottom of the crack, compressing it and weakening the rock. When the wave retreats, the trapped air is suddenly released with explosive force. This explosive release of highly pressurized air blows fragments off of the rock face and threeby widens the crack.

Salt-crystal growth

Salt crystallization, otherwise known as haloclasty, causes disintegration of rocks when saline solutions seep into cracks and joints in the rocks and evaporate, leaving salt crystals behind. These salt crystals expand as they are heated up, exerting pressure on the confining rock.

Salt crystallization may also take place when solutions decompose rocks (for example, limestone and chalk) to form salt solutions of sodium sulfate or sodium carbonate, of which the moisture evaporates to form their respective salt crystals.

The salts which have proved most effective in disintegrating rocks are sodium sulfate, magnesium sulfate, and calcium chloride. Some of these salts can expand up to three times or even more.

It is normally associated with arid climates where strong heating causes strong evaporation and therefore salt crystallization. It is also common along coasts. An example of salt weathering can be seen in the honeycombed stones in sea wall. Honeycomb is a type of tafoni, a class of cavernous rock weathering structures, which likely develop in large part by chemical and physical salt weathering processes.

Biological Weathering

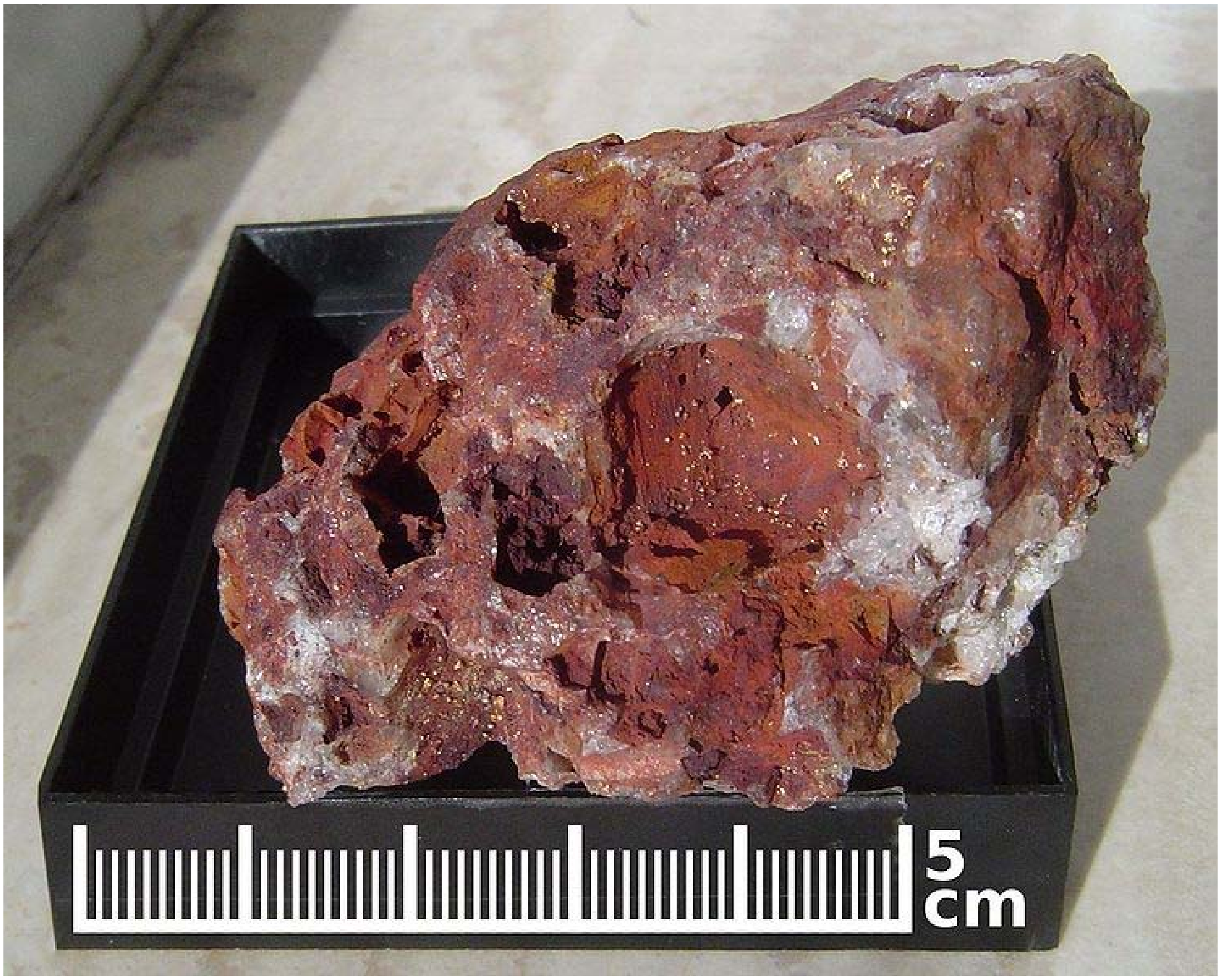
Living organisms may contribute to mechanical weathering (as well as chemical weathering). Lichens and mosses grow on essentially bare rock surfaces and create a more humid chemical microenvironment. The attachment of these organisms to the rock surface enhances physical as well as chemical breakdown of the surface microlayer of the rock. On a larger scale seedlings sprouting in a crevice and plant roots exert physical pressure as well as providing a pathway for water and chemical infiltration. Burrowing animals and insects disturb the soil layer adjacent to the bedrock surface thus further increasing water and acid infiltration and exposure to oxidation processes.

Chemical weathering

Comparison of unweathered (left) and weathered (right) limestone

Chemical weathering changes the composition of rocks, often transforming them when water interacts with minerals to create various chemical reactions. Chemical weathering is a gradual and ongoing process as the mineralogy of the rock adjusts to the near surface environment. New or *secondary minerals* develop from the original minerals of the rock. In this the processes of oxidation and hydrolysis are most important.

Dissolution



A pyrite cube has dissolved away from host rock, leaving gold behind

Rainfall is acidic because atmospheric carbon dioxide dissolves in the rainwater producing weak carbonic acid. In unpolluted environments, the rainfall pH is around 5.6. Acid rain occurs when gases such as sulphur dioxide and nitrogen oxides are present in the atmosphere. These oxides react in the rain water to produce stronger acids and can lower the pH to 4.5 or even 3.0. Sulfur dioxide, SO_2, comes from volcanic eruptions or from fossil fuels, can become sulfuric acid within rainwater, which can cause solution weathering to the rocks on which it falls.

Some minerals, due to their natural solubility (e.g. evaporites), oxidation potential (iron-rich minerals, such as pyrite), or instability relative to surficial conditions will weather through dissolution naturally, even without acidic water.

One of the most well-known solution weathering processes is carbonation, the process in which atmospheric carbon dioxide leads to solution weathering. Carbonation occurs on rocks which contain calcium carbonate, such as limestone and chalk. This takes place when rain combines with carbon dioxide or an organic acid to form a weak carbonic acid which reacts with calcium carbonate (the limestone) and forms calcium bicarbonate. This process speeds up with a decrease in temperature, not because low temperatures generally drive reactions faster, but because colder water holds more dissolved carbon dioxide gas. Carbonation is therefore a large feature of glacial weathering.

The reactions as follows:

$CO_2 + H_2O \Rightarrow H_2CO_3$

carbon dioxide + water => carbonic acid

$H_2CO_3 + CaCO_3 \Rightarrow Ca(HCO_3)_2$

carbonic acid + calcium carbonate => calcium bicarbonate

Carbonation on the surface of well-jointed limestone produces a dissected limestone pavement which is most effective along the joints, widening and deepening them.

Hydration

Olivine weathering to iddingsite within a mantle xenolith

Mineral hydration is a form of chemical weathering that involves the rigid attachment of H+ and OH- ions to the atoms and molecules of a mineral.

When rock minerals take up water, the increased volume creates physical stresses within the rock. For example iron oxides are converted to iron hydroxides and the hydration of anhydrite forms gypsum.

A freshly broken rock shows differential chemical weathering (probably mostly oxidation) progressing inward. This piece of sandstone was found in glacial drift near Angelica, New York

Hydrolysis on silicates and carbonates

Hydrolysis is a chemical weathering process affecting silicate and carbonate minerals. In such reactions, pure water ionizes slightly and reacts with silicate minerals. An example reaction:

$Mg_2SiO_4 + 4H^+ + 4OH^- \rightleftharpoons 2Mg^{2+} + 4OH^- + H_4SiO_4$

olivine (forsterite) + four ionized water molecules ⇌ ions in solution + silicic acid in solution

This reaction results in complete dissolution of the original mineral, assuming enough water is available to drive the reaction. However, the above reaction is to a degree deceptive because pure water rarely acts as a H^+ donor. Carbon dioxide, though, dissolves readily in water forming a weak acid and H^+ donor.

$Mg_2SiO_4 + 4CO_2 + 4H_2O \rightleftharpoons 2Mg^{2+} + 4HCO_3^- + H_4SiO_4$

olivine (forsterite) + carbon dioxide + water ⇌ Magnesium and bicarbonate ions in solution + silicic acid in solution

This hydrolysis reaction is much more common. Carbonic acid is consumed by silicate weathering, resulting in more alkaline solutions because of the bicarbonate. This is an important reaction in controlling the amount of CO_2 in the atmosphere and can affect climate.

Aluminosilicates when subjected to the hydrolysis reaction produce a secondary mineral rather than simply releasing cations.

$2KAlSi_3O_8 + 2H_2CO_3 + 9H_2O \rightleftharpoons Al_2Si_2O_5(OH)_4 + 4H_4SiO_4 + 2K^+ + 2HCO_3^-$

Orthoclase (aluminosilicate feldspar) + carbonic acid + water ⇌ Kaolinite (a clay mineral) + silicic acid in solution + potassium and bicarbonate ions in solution

Oxidation

Oxidized pyrite cubes

Within the weathering environment chemical oxidation of a variety of metals occurs. The most commonly observed is the oxidation of Fe^{2+} (iron) and combination with oxygen and water to form Fe^{3+} hydroxides and oxides such as goethite, limonite, and hematite. This gives the affected rocks a reddish-brown coloration on the surface which crumbles easily and weakens the rock. This process is better known as 'rusting'. Many other metallic ores and minerals oxidize and hydrate to produce colored deposits, such as chalcopyrites or $CuFeS_2$ oxidizing to copper hydroxide and iron oxides.

Biological

A number of plants and animals may create chemical weathering through release of acidic compounds, i.e. moss on roofs is classed as weathering.

Biological weathering of lava by lichen, La Palma

The most common form of biological weathering is the release of chelating compounds, i.e. acids, by plants so as to break down aluminium and iron containing compounds in the soils beneath them. Decaying remains of dead plants in soil may form organic acids which, when dissolved in water, cause chemical weathering. Extreme release of chelating compounds can easily affect surrounding rocks and soils, and may lead to podsolisation of soils.

Building weathering

Buildings made of any stone, brick or concrete are susceptible to the same weathering agents as any exposed rock surface. Also statues, monuments and ornamental stonework can be badly damaged by natural weathering processes. This is accelerated in areas severely affected by acid rain.

Biosphere

Inputs from the biosphere may begin with lichen and other microorganisms that secrete oxalic acid. These microorganisms, associated with the lichen community or independently inhabiting rocks, include a number of blue-green algae, green algae, various fungi, and numerous bacteria. Lichen has long been viewed as the pioneers of soil development as the following statement suggests:

“The initial conversion of rock into soil is carried on by the pioneer lichens and their successors, the mosses, in which the hair-like rhizoids assume the role of roots in breaking down the surface into fine dust”

However, lichens are not necessarily the only pioneering organisms nor the earliest form of soil formation as it has been documented that seed-bearing plants may occupy an area and colonize quicker than lichen. Also, eolian sedimentation can produce high rates of sediment accumulation. Nonetheless, lichen can certainly withstand harsher conditions than most vascular plants and although they have slower colonization rates, do form the dominant group in alpine regions.

Acids released from plant roots include acetic and citric acids. During the decay of organic matter Phenolic acids are released from plant matter and humic and fulvic acids are released by soil microbes. These organic acids speed up chemical weathering by combining with some of the weathering products in a process known as chelation. In the soil profile, the organic acids are often concentrated at the top while carbonic acid plays a larger role towards the bottom or below in the aquifer.

As the soil column develops further into thicker accumulations, larger animals come to inhabit the soil and continue to alter the chemical evolution of their respective niche. Earthworms aerate the soil and convert large amounts of organic matter into rich humus, improving soil fertility. Small burrowing mammals store food, grow young and may hibernate in the pedosphere altering the course of soil evolution. Large mammalian herbivores above ground transport nutrients in form of nitrogen-rich waste and phosphorus-rich antlers while predators leave phosphorus-rich piles of bones on the soil surface, leading the localized enrichment of the soil below.

Redox conditions in wetland soils

Nutrient cycling in lakes and freshwater wetlands depends heavily on redox conditions. Under a few millimeters of water heterotrophic bacteria metabolize and consume oxygen. They therefore deplete the soil of oxygen and create the need for anaerobic respiration. Some anaerobic microbial processes include denitrification, sulfate reduction and methanogenesis and are responsible for the release of N_2 (nitrogen), H_2S (hydrogen sulfide) and CH_4 (methane). Other anaerobic microbial processes are linked to changes in the oxidation state of iron and manganese. As a result of anaerobic decomposition, the soil stores large amounts of organic carbon because decomposition is incomplete.

The redox potential describes which way chemical reactions will proceed in oxygen deficient soils and controls the nutrient cycling in flooded systems. Redox potential, or reduction potential, is used to express the likelihood of an environment to receive electrons and therefore become reduced. For example, if a system already has plenty of electrons (anoxic, organic-rich shale) it is reduced and will likely donate electrons to a part of the system that has a low concentration of electrons, or an oxidized environment, to equilibrate to the chemical gradient. The oxidized environment has high redox potential, whereas the reduced environment has a low redox potential.

The redox potential is controlled by the oxidation state of the chemical species, pH and the amount of oxygen (O_2) there is in the system. The oxidizing environment accepts electrons because of the presence of O_2, which acts as electron acceptors:

$O_2 + 4e^- + 4H^+ \rightarrow H_2O$

This equation will tend to move to the right in acidic conditions which causes higher redox potentials to be found at lower pH levels. Bacteria, heterotrophic organisms, consume oxygen while decomposing organic material which depletes the soils of oxygen, thus increasing the redox potential. In low redox conditions the deposition of ferrous iron (Fe^{2+}) will increase with decreasing decomposition rates, thus preserving organic remains and depositing humus. At high redox potential, the oxidized form of iron, ferric iron (Fe^{3+}), will be deposited commonly as hematite. By using analytical geochemical tools such as x-ray fluorescence (XRF) or inductively coupled mass spectroscopy (ICP-MS) the two forms of Fe (Fe^{2+} and Fe^{3+}) can be measured in ancient rocks therefore determining the redox potential for ancient soils.

Such a study was done on Permian through Triassic rocks (300-200 million years old) in Japan and British Colombia. The geologists found hematite throughout the early and middle Permian but began to find the reduced form of iron in pyrite within the ancient soils near the end of the Permian and into the Triassic. This suggests that conditions became less oxygen rich, even anoxic, during the late Permian which eventually lead to the greatest extinction in earth’s history, the P-T extinction.

Decomposition in anoxic or reduced soils is also carried out by sulfur-reducing bacteria which, instead of O_2 use SO_4^{2-} as an electron acceptor and produce hydrogen sulfide (H_2S) and carbon dioxide in the process:

$$2H^+ + SO_4^{2-} + 2(CH_2O) \rightarrow 2CO_2 + H_2S + 2H_2O$$

The H_2S gas percolates upwards and reacts with Fe^{2+} and precipitates pyrite, acting as a trap for the toxic H_2S gas. However, H_2S is still a large fraction of emissions from wetland soils. In most freshwater wetlands there is little sulfate (SO_4^{2-}) so methanogenesis becomes the dominant form of decomposition by methanogenic bacteria only when sulfate is depleted. Acetate, a compound that is a byproduct of fermenting cellulose is split by methanogenic bacteria to produce methane (CH_4) and carbon dioxide (CO_2), which are released to the atmosphere. Methane is also released during the reduction of CO_2 by the same bacteria.

Atmosphere

In the pedosphere it is safe to assume that gases are in equilibrium with the atmosphere. Because plant roots and soil microbes release CO_2 to the soil, the concentration of bicarbonate(HCO_3) in soil waters is much greater than that in equilibrium with the atmosphere, the high concentration of CO_2 and the occurrence of metals in soil solutions results in lower pH levels in the soil. Gases that escape from the pedosphere to the atmosphere include the gaseous byproducts of carbonate dissolution, decomposition, redox reactions and microbial photosynthesis. The main inputs from the atmosphere are aeolian sedimentation, rainfall and gas diffusion. Eolian sedimentation includes anything that can be entrained by wind or that stays suspended, seemingly indefinitely, in air and includes a wide variety of aerosol particles, biological particles like pollen and dust to pure quartz sand. Nitrogen is the most abundant constituent in rain, as water vapor utilizes aerosol particles to nucleate rain droplets.

Soil in Forests

Soil is well developed in the forest as suggested by the thick humus layers, rich diversity of large trees and animals that live there. In forests, precipitation exceeds evapotranspiration which results in an excess of water that percolates downward through the soil layers. Slow rates of decomposition leads to large amounts of fulvic acid, greatly enhancing chemical weathering. The downward percolation, in conjunction with chemical weathering leaches magnesium (Mg), iron (Fe), and aluminum (Al) from the soil and transports them downward, a process known as podzolization. This process leads to marked contrasts in the appearance and chemistry of the soil layers.

Soil in the Tropics

Tropical forests (rainforests) receive more insolation and rainfall over longer growing seasons than any other environment on earth. With these elevated temperatures, insolation and rainfall, biomass is extremely productive leading to carbon production as much as $800gCm^{2-}yr^{-}$. Higher temperatures and larger amounts of water contribute to higher rates of chemical weathering. Increased rates of decomposition cause smaller amounts of fulvic acid to percolate and leach metals from the zone of active weathering. Thus, in stark contrast to soil in forests, tropical forests have little to no podzolization and therefore do not have marked visual and chemical contrasts with the soil layers. Instead, the mobile metals Mg, Fe and Al are precipitated as oxide minerals giving the soil a rusty red color.

Soil in Grasslands and Deserts

Precipitation in grasslands is equal to or less than evapotranspiration and causes soil development to operate in relative drought. Leaching and migration of weathering products is therefore decreased. Large amounts of evaporation causes buildup of calcium (Ca) and other large cations flocculate clay minerals and fulvic acids in the upper soil profile. Impermeable clay limits downward percolation of water and fulvic acids, reducing chemical weathering and podzolization. The depth to the maximum concentration of clay increases in areas of increased precipitation and leaching. When leaching is decreased, the Ca precipitates as calcite ($CaCO_3$) in the lower soil levels, a layer known as caliche.

Deserts behave similarly to grasslands but operate in constant drought as precipitation is less than evapotranspiration. Chemical weathering proceeds more slowly than in grasslands and beneath the caliche layer may be a layer of gypsum and halite. To study soils in deserts, pedologists have used the concept of chronosequences to relate timing and development of the soil layers. It has been shown that P is leached very quickly from the system and therefore decreases with increasing age. Furthermore, carbon buildup in th soils is decrease due to slower decomposition rates. As a result, the rates of carbon circulation in the biogeochemical cycle is decreased.

Cryosphere

The **cryosphere**, derived from the Ancient Greek word "κρύος" (*cryos* meaning "cold", "frost" or "ice"), is the term which collectively describes the portions of the Earth’s surface where water is in solid form, including sea ice, lake ice, river ice, snow cover, glaciers, ice caps and ice sheets, and frozen ground (which includes permafrost). Thus there is a wide overlap with the hydrosphere. The cryosphere is an integral part of the global climate system with important linkages and feedbacks generated through its influence on surface energy and moisture fluxes, clouds, precipitation, hydrology, atmospheric and oceanic circulation. Through these feedback processes, the cryosphere plays a significant role in global climate and in climate model response to global change.

Overview of the Cryosphere and its larger components, from the UN Environment Programme Global Outlook for Ice and Snow.

Structure

Frozen water is found on the Earth’s surface primarily as snow cover, freshwater ice in lakes and rivers, sea ice, glaciers, ice sheets, and frozen ground and permafrost (permanently-frozen ground). The residence time of water in each of these cryospheric sub-systems varies widely. Snow cover and freshwater ice are essentially seasonal, and most sea ice, except for ice in the central Arctic, lasts only a few years if it is not seasonal. A given water particle in glaciers, ice sheets, or ground ice, however, may remain frozen for 10-100,000 years or longer, and deep ice in parts of East Antarctica may have an age approaching 1 million years.

Most of the world’s ice volume is in Antarctica, principally in the East Antarctic Ice Sheet. In terms of areal extent, however, Northern Hemisphere winter snow and ice extent comprise the largest area, amounting to an average 23% of hemispheric surface area in January. The large areal extent and the important climatic roles of snow and ice, related to their unique physical properties, indicate that the ability to observe and model snow and ice-cover extent, thickness, and physical properties (radiative and thermal properties) is of particular significance for climate research.

There are several fundamental physical properties of snow and ice that modulate energy exchanges between the surface and the atmosphere. The most important properties are the surface reflectance (albedo), the ability to transfer heat (thermal diffusivity), and the ability to change state (latent heat). These physical properties, together with surface roughness, emissivity, and dielectric characteristics, have important implications for observing snow and ice from space. For example, surface roughness is often the dominant factor determining the strength of radar backscatter. Physical properties such as crystal structure, density, length, and liquid-water content are important factors affecting the transfers of heat and water and the scattering of microwave energy.

The surface reflectance of incoming solar radiation is important for the surface energy balance (SEB). It is the ratio of reflected to incident solar radiation, commonly referred to as albedo. Climatologists are primarily interested in albedo integrated over the shortwave portion of the electromagnetic spectrum (~0.3 to 3.5 nm), which coincides with the main solar energy input. Typically, albedo values for non-melting snow-covered surfaces are high (~80-90%) except in the case of forests. The higher albedos for snow and ice cause rapid shifts in surface reflectivity in autumn and spring in high latitudes, but the overall climatic significance of this increase is spatially and temporally modulated by cloud cover. (Planetary albedo is determined principally by cloud cover, and by the small amount of total solar radiation received in high latitudes during winter months.) Summer and autumn are times of high-average cloudiness over the Arctic Ocean so the albedo feedback associated with the large seasonal changes in sea-ice extent is greatly reduced. Groisman *et al.* (1994a) observed that snow cover exhibited the greatest influence on the Earth radiative balance in the spring (April to May) period when incoming solar radiation was greatest over snow-covered areas.

The thermal properties of cryospheric elements also have important climatic consequences. Snow and ice have much lower thermal diffusivities than air. Thermal diffusivity is a measure of the speed at which temperature waves can penetrate a substance. Snow and ice are many orders of magnitude less efficient at diffusing heat than air. Snow cover insulates the ground surface, and sea ice insulates the underlying ocean, decoupling the surface-atmosphere interface with respect to both heat and moisture fluxes. The flux of moisture from a water surface is eliminated by even a thin skin of ice, whereas the flux of heat through thin ice continues to be substantial until it attains a thickness in excess of 30 to 40 cm. However, even a small amount of snow on top of the ice will dramatically reduce the heat flux and slow down the rate of ice growth. The insulating effect of snow also has major implications for the hydrological cycle. In non-permafrost regions, the insulating effect of snow is such that only near-surface ground freezes and deep-water drainage is uninterrupted.

While snow and ice act to insulate the surface from large energy losses in winter, they also act to retard warming in the spring and summer because of the large amount of energy required to melt ice (the latent heat of fusion, 3.34×10^5 J/kg at 0°C). However, the strong static stability of the atmosphere over areas of extensive snow or ice tends to confine the immediate cooling effect to a relatively shallow layer, so that associated atmospheric anomalies are usually short-lived and local to regional in scale. In some areas of the world such as Eurasia, however, the cooling associated with a heavy snowpack and moist spring soils is known to play a role in modulating the summer monsoon circulation. Gutzler and Preston (1997) recently presented evidence for a similar snow-summer circulation feedback over the southwestern United States.

The role of snow cover in modulating the monsoon is just one example of a short-term cryosphere-climate feedback involving the land surface and the atmosphere. From Figure 1 it can be seen that there are numerous cryosphere-climate feedbacks in the global climate system. These operate over a wide range of spatial and temporal scales from local seasonal cooling of air temperatures to hemispheric-scale variations in ice sheets over time-scales of thousands of years. The feedback mechanisms involved are often complex and incompletely understood. For example, Curry *et al.* (1995) showed that the so-called “simple” sea ice-albedo feedback involved complex interactions with lead fraction, melt ponds, ice thickness, snow cover, and sea-ice extent.

Snow

Snow cover has the second-largest areal extent of any component of the cryosphere, with a mean maximum areal extent of approximately 47 million km². Most of the Earth's snow-covered area (SCA) is located in the Northern Hemisphere, and temporal variability is dominated by the seasonal cycle; Northern Hemisphere snow-cover extent ranges from 46.5 million km² in January to 3.8 million km² in August. North American winter SCA has exhibited an increasing trend over much of this century (Brown and Goodison 1996; Hughes *et al.* 1996) largely in response to an increase in precipitation. However, the available satellite data show that the hemispheric winter snow cover has exhibited little interannual variability over the 1972-1996 period, with a coefficient of variation (COV=s.d./mean) for January Northern Hemisphere snow cover of < 0.04. According to Groisman *et al.* (1994a) Northern Hemisphere spring snow cover should exhibit a decreasing trend to explain an observed increase in Northern Hemisphere spring air temperatures this century. Preliminary estimates of SCA from historical and reconstructed in situ snow-cover data suggest this is the case for Eurasia, but not for North America, where spring snow cover has remained close to current levels over most of this century. Because of the close relationship observed between hemispheric air temperature and snow-cover extent over the period of satellite data (IPCC 1996), there is considerable interest in monitoring Northern Hemisphere snow-cover extent for detecting and monitoring climate change.

Snow cover is an extremely important storage component in the water balance, especially seasonal snowpacks in mountainous areas of the world. Though limited in extent, seasonal snowpacks in the Earth's mountain ranges account for the major source of the runoff for stream flow and groundwater recharge over wide areas of the midlatitudes. For example, over 85% of the annual runoff from the Colorado River basin originates as snowmelt. Snowmelt runoff from the Earth's mountains fills the rivers and recharges the aquifers that over a billion people depend on for their water resources. Further, over 40% of the world's protected areas are in mountains, attesting to their value both as unique ecosystems needing protection and as recreation areas for humans. Climate warming is expected to result in major changes to the partitioning of snow and rainfall, and to the timing of snowmelt, which will have important implications for water use and management. These changes also involve potentially important decadal and longer time-scale feedbacks to the climate system through temporal and spatial changes in soil moisture and runoff to the oceans.(Walsh 1995). Freshwater fluxes from the snow cover into the marine environment may be important, as the total flux is probably of the same magnitude as desalinated ridging and rubble areas of sea ice. In addition, there is an associated pulse of precipitated pollutants which accumulate over the Arctic winter in snowfall and are released into the ocean upon ablation of the sea-ice.

Sea ice

Sea ice covers much of the polar oceans and forms by freezing of sea water. Satellite data since the early 1970s reveal considerable seasonal, regional, and interannual variability in the sea-ice covers of both hemispheres. Seasonally, sea-ice extent in the Southern Hemisphere varies by a factor of 5, from a minimum of 3-4 million km² in February to a maximum of 17-20 million km² in September. The seasonal variation is much less in the Northern Hemisphere where the confined nature and high latitudes of the Arctic Ocean result in a much larger perennial ice cover, and the surrounding land limits the equatorward extent of wintertime ice. Thus, the seasonal variability in Northern Hemisphere ice extent varies by only a factor of 2, from a minimum of 7-9 million km² in September to a maximum of 14-16 million km² in March.

The ice cover exhibits much greater regional-scale interannual variability than it does hemispherical. For instance, in the region of the Seas of Okhotsk and Japan, maximum ice extent decreased from 1.3 million km² in 1983 to 0.85 million km² in 1984, a decrease of 35%, before rebounding the following year to 1.2 million km². The regional fluctuations in both hemispheres are such that for any several-year period of the satellite record some regions exhibit decreasing ice coverage while others exhibit increasing ice cover. The overall trend indicated in the passive microwave record from 1978 through mid-1995 shows that the extent of Arctic sea ice is decreasing 2.7% per decade. Subsequent work with the satellite passive-microwave data indicates that from late October 1978 through the end of 1996 the extent of Arctic sea ice decreased by 2.9% per decade while the extent of Antarctic sea ice increased by 1.3% per decade.

Lake ice and river ice

Ice forms on rivers and lakes in response to seasonal cooling. The sizes of the ice bodies involved are too small to exert other than localized climatic effects. However, the freeze-up/break-up processes respond to large-scale and local weather factors, such that considerable interannual variability exists in the dates of appearance and disappearance of the ice. Long series of lake-ice observations can serve as a proxy climate record, and the monitoring of freeze-up and break-up trends may provide a convenient integrated and seasonally specific index of climatic perturbations. Information on river-ice conditions is less useful as a climatic proxy because ice formation is strongly dependent on river-flow regime, which is affected by precipitation, snow melt, and watershed runoff as well as being subject to human interference that directly modifies channel flow, or that indirectly affects the runoff via land-use practices.

Lake freeze-up depends on the heat storage in the lake and therefore on its depth, the rate and temperature of any inflow, and water-air energy fluxes. Information on lake depth is often unavailable, although some indication of the depth of shallow lakes in the Arctic can be obtained from airborne radar imagery during late winter (Sellman *et al.* 1975) and spaceborne optical imagery during summer (Duguay and Lafleur 1997). The timing of breakup is modified by snow depth on the ice as well as by ice thickness and freshwater inflow.

Frozen ground and permafrost

Frozen ground (permafrost and seasonally frozen ground) occupies approximately 54 million km² of the exposed land areas of the Northern Hemisphere (Zhang et al., 2003) and therefore has the largest areal extent of any component of the cryosphere. Permafrost (perennially frozen ground) may occur where mean annual air temperatures (MAAT) are less than -1 or -2°C and is generally continuous where MAAT are less than -7°C. In addition, its extent and thickness are affected by ground moisture content, vegetation cover, winter snow depth, and aspect. The global extent of permafrost is still not completely known, but it underlies approximately 20% of Northern Hemisphere land areas. Thicknesses exceed 600 m along the Arctic coast of northeastern Siberia and Alaska, but, toward the margins, permafrost becomes thinner and horizontally discontinuous. The marginal zones will be more immediately subject to any melting caused by a warming trend. Most of the presently existing permafrost formed during previous colder conditions and is therefore relic. However, permafrost may form under present-day polar climates where glaciers retreat or land emergence exposes unfrozen ground. Washburn (1973) concluded that most continuous permafrost is in balance with the present climate at its upper surface, but changes at the base depend on the present climate and geothermal heat flow; in contrast, most discontinuous permafrost is probably unstable or "in such delicate equilibrium that the slightest climatic or surface change will have drastic disequilibrium effects".

Under warming conditions, the increasing depth of the summer active layer has significant impacts on the hydrologic and geomorphic regimes. Thawing and retreat of permafrost have been reported in the upper Mackenzie Valley and along the southern margin of its occurrence in Manitoba, but such observations are not readily quantified and generalized. Based on average latitudinal gradients of air temperature, an average northward displacement of the southern permafrost boundary by 50-to-150 km could be expected, under equilibrium conditions, for a 1°C warming.

Only a fraction of the permafrost zone consists of actual ground ice. The remainder (dry permafrost) is simply soil or rock at subfreezing temperatures. The ice volume is generally greatest in the uppermost permafrost layers and mainly comprises pore and segregated ice in Earth material. Measurements of bore-hole temperatures in permafrost can be used as indicators of net changes in temperature regime. Gold and Lachenbruch (1973) infer a 2-4°C warming over 75 to 100 years at Cape Thompson, Alaska, where the upper 25% of the 400-m thick permafrost is unstable with respect to an equilibrium profile of temperature with depth (for the present mean annual surface temperature of -5°C). Maritime influences may have biased this estimate, however. At Prudhoe Bay similar data imply a 1.8°C warming over the last 100 years (Lachenbruch *et al.* 1982). Further complications may be introduced by changes in snow-cover depths and the natural or artificial disturbance of the surface vegetation.

The potential rates of permafrost thawing have been established by Osterkamp (1984) to be two centuries or less for 25-meter-thick permafrost in the discontinuous zone of interior Alaska, assuming warming from -0.4 to 0°C in 3–4 years, followed by a further 2.6°C rise. Although the response of permafrost (depth) to temperature change is typically a very slow process (Osterkamp 1984; Koster 1993), there is ample evidence for the fact that the active layer thickness quickly responds to a temperature change (Kane *et al.* 1991). Whether, under a warming or cooling scenario, global climate change will have a significant effect on the duration of frost-free periods in both regions with seasonally- and perennially-frozen ground.

Glaciers and ice sheets

Ice sheets and glaciers are flowing ice masses that rest on solid land. They are controlled by snow accumulation, surface and basal melt, calving into surrounding oceans or lakes and internal dynamics. The latter results from gravity-driven creep flow ("glacial flow") within the ice body and sliding on the underlying land, which leads to thinning and horizontal spreading. Any imbalance of this dynamic equilibrium between mass gain, loss and transport due to flow results in either growing or shrinking ice bodies.

Ice sheets are the greatest potential source of global freshwater, holding approximately 77% of the global total. This corresponds to 80 m of world sea-level equivalent, with Antarctica accounting for 90% of this. Greenland accounts for most of the remaining 10%, with other ice bodies and glaciers accounting for less than 0.5%. Because of their size in relation to annual rates of snow accumulation and melt, the residence time of water in ice sheets can extend to 100,000 or 1 million years. Consequently, any climatic perturbations produce slow responses, occurring over glacial and interglacial periods. Valley glaciers respond rapidly to climatic fluctuations with typical response times of 10–50 years. However, the response of individual glaciers may be asynchronous to the same climatic forcing because of differences in glacier length, elevation, slope, and speed of motion. Oerlemans (1994) provided evidence of coherent global glacier retreat which could be explained by a linear warming trend of 0.66°C per 100 years.

While glacier variations are likely to have minimal effects upon global climate, their recession may have contributed one third to one half of the observed 20th Century rise in sea level (Meier 1984; IPCC 1996). Furthermore, it is extremely likely that such extensive glacier recession as is currently observed in the Western Cordillera of North America, where runoff from glacierized basins is used for irrigation and hydropower, involves significant hydrological and ecosystem impacts. Effective water-resource planning and impact mitigation in such areas depends upon developing a sophisticated knowledge of the status of glacier ice and the mechanisms that cause it to change. Furthermore, a clear understanding of the mechanisms at work is crucial to interpreting the global-change signals that are contained in the time series of glacier mass balance records.

Combined glacier mass balance estimates of the large ice sheets carry an uncertainty of about 20%. Studies based on estimated snowfall and mass output tend to indicate that the ice sheets are near balance or taking some water out of the oceans. Marinebased studies suggest sea-level rise from the Antarctic or rapid ice-shelf basal melting. Some authors (Paterson 1993; Alley 1997) have suggested that the difference between the observed rate of sea-level rise (roughly 2 mm/y) and the explained rate of sea-level rise from melting of mountain glaciers, thermal expansion of the ocean, etc. (roughly 1 mm/y or less) is similar to the modeled imbalance in the Antarctic (roughly 1 mm/y of sea-level rise; Huybrechts 1990), suggesting a contribution of sea-level rise from the Antarctic.

Relationships between global climate and changes in ice extent are complex. The mass balance of land-based glaciers and ice sheets is determined by the accumulation of snow, mostly in winter, and warm-season ablation due primarily to net radiation and turbulent heat fluxes to melting ice and snow from warm-air advection, (Munro 1990). However, most of Antarctica never experiences surface melting. Where ice masses terminate in the ocean, iceberg calving is the major contributor to mass loss. In this situation, the ice margin may extend out into deep water as a floating ice shelf, such as that in the Ross Sea. Despite the possibility that global warming could result in losses to the Greenland ice sheet being offset by gains to the Antarctic ice sheet, there is major concern about the possibility of a West Antarctic Ice Sheet collapse. The West Antarctic Ice Sheet is grounded on bedrock below sea level, and its collapse has the potential of raising the world sea level 6–7 m over a few hundred years.

Most of the discharge of the West Antarctic Ice Sheet is via the five major ice streams (faster flowing ice) entering the Ross Ice Shelf, the Rutford Ice Stream entering Ronne-Filchner shelf of the Weddell Sea, and the Thwaites Glacier and Pine Island Glacier entering the Amundsen Ice Shelf. Opinions differ as to the present mass balance of these systems (Bentley 1983, 1985), principally because of the limited data. The West Antarctic Ice Sheet is stable so long as the Ross Ice Shelf is constrained by drag along its lateral boundaries and pinned by local grounding.

Chapter- 5

Geosphere, Anthroposphere and Asthenosphere

Geosphere

The term **geosphere** is often used to refer to the densest parts of Earth, which consist mostly of rock and regolith.

In Aristotelian physics, the term was applied to four spherical *natural places*, concentrically nested around the center of the Earth, as described in the lectures *Physica* and *Meteorologica*. They were believed to explain the motions of the four *terrestrial elements: Earth*, *Water*, *Air* and *Fire*.

In modern texts, geosphere refers to the solid parts of the Earth and is used along with atmosphere, hydrosphere, and biosphere to describe the systems of the Earth. In that context, sometimes the term "lithosphere" is used instead of geosphere. However, the lithosphere only refers to the uppermost layers of the solid Earth (oceanic and continental crustal rocks and uppermost mantle).

Since space exploration began, it has been observed that the extent of the ionosphere or plasmasphere is highly variable, and often much larger than previously appreciated, at times extending to the boundaries of the Earth's magnetosphere or geomagnetosphere. This highly variable outer boundary of *geogenic* matter has been referred to as the "geopause", to suggest the relative scarcity of such matter beyond it, where the solar wind dominates.

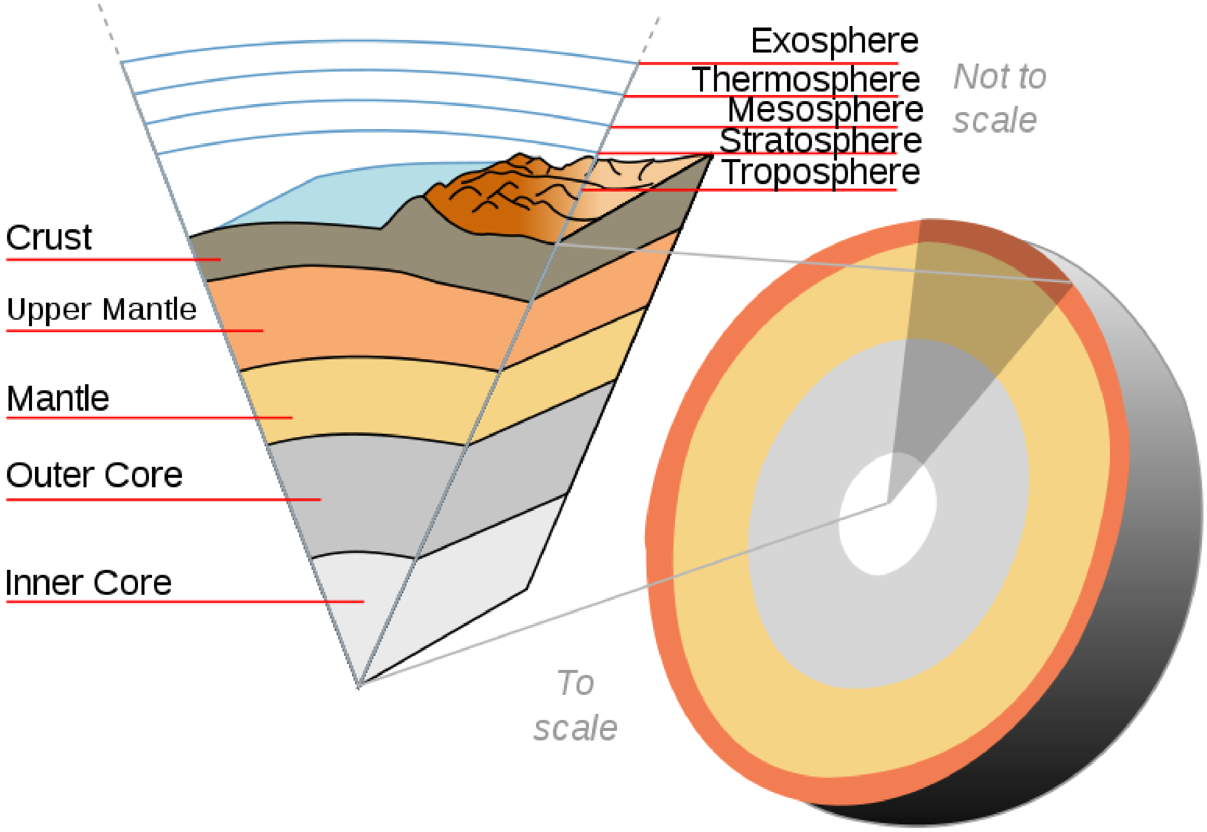
Anthroposphere

The **anthroposphere** (sometimes also referred as *technosphere*) is that part of the environment that is made or modified by humans for use in human activities and human habitats. It is one of the Earth's spheres.

As human technology becomes more evolved, so do the impacts of human activities on the environment.

Examples: deforestation for housing, land setup, etc.

Asthenosphere



Earth cutaway from core to exosphere

The **asthenosphere** (from Greek *asthenēs 'weak'* + sphere) is the highly viscous mechanically weak ductilely-deforming region of the upper mantle of the Earth. It lies below the lithosphere, at depths between 100 and 200 km (~ 62 and 124 miles) below the surface, but perhaps extending as deep as 700 km (~ 435 miles).

Characteristics

The **asthenosphere** is a portion of the upper mantle just below the lithosphere that is involved in plate tectonic movements and isostatic adjustments. In spite of its heat, pressures keep it plastic, and it has a relatively low density. Seismic waves pass relatively slowly through the asthenosphere, compared to the overlying lithospheric mantle, thus it has been called the *low-velocity zone* (LVZ), although the two are not exactly the same. The lower boundary of the LVZ lies at a depth of 180–220 km, whereas the base of the asthenosphere lies at a depth of about 700 km. This was the observation that originally alerted seismologists to its presence and gave some information about its physical properties, as the speed of seismic waves decreases with decreasing rigidity.

Under the thin oceanic plates the asthenosphere is usually much closer to the seafloor surface, and at mid-ocean ridges it rises to within a few kilometers of the ocean floor.

The upper part of the asthenosphere is believed to be the zone upon which the great rigid and brittle lithospheric plates of the Earth's crust move about. Due to the temperature and pressure conditions in the asthenosphere, rock becomes ductile, moving at rates of deformation measured in cm/yr over lineal distances eventually measuring thousands of kilometers. In this way, it flows like a convection current, radiating heat outward from the Earth's interior. Above the asthenosphere, at the same rate of deformation, rock behaves elastically and, being brittle, can break, causing faults. The rigid lithosphere is thought to "float" or move about on the slowly flowing asthenosphere, creating the movement of crustal plates.

Historical

Although its presence was suspected as early as 1926, the worldwide occurrence of the asthenosphere was confirmed by analyses of earthquake waves from the Great Chilean Earthquake of May 22, 1960.