The differences in groundwater levels for January 2000 and January 2014:

- Groundwater levels in west London have risen due to limited abstraction in this area, in the order of four to eight metres since 2000 which has levelled off in recent years.
- In central and east London groundwater levels have fallen in the order of 5–7 m since 2000 as a result of increased abstraction.
- Groundwater levels have fallen more than 2 m across much of south London, with falls of up to 12 m concentrated around the many large public water supply abstractions.
- In east London, where there are chalk outcrops around the River Thames from Greenwich to Woolwich, there is a risk of saline intrusion. When groundwater levels near the river are lower than the water level in the River Thames, saline river water can enter the chalk aquifer.

1.3 The carbon cycle

Carbon (C) (from the Latin *carbo* meaning coal) is one of the most chemically versatile of all the elements. Carbon forms more compounds than any other element and scientists predict that there are more than ten million different carbon compounds in existence today on Earth. Carbon is found in all life forms in addition to sedimentary rocks, diamonds, graphite, coal and petroleum (oil and natural gas).

Carbon follows a certain route on Earth, called the carbon cycle. It is the complex processes carbon undergoes as it is transformed from organic carbon (the form found in living organisms such as plants and trees) to inorganic carbon and back again. Through following the carbon cycle we can also study energy flows on Earth, because most of the chemical energy needed for life is stored in organic compounds as bonds between carbon atoms and other atoms.

Carbon atoms move through the carbon cycle in many different forms. Some important examples of carbon compounds include:

- carbon dioxide (CO_2), a gas found in the atmosphere, soils and oceans
- methane (CH_4), a gas found in the atmosphere, soils and oceans and sedimentary rocks
- calcium carbonate ($CaCO_3$), a solid compound found in calcareous rocks, oceans and in the skeletons and shells of ocean creatures
- hydrocarbons – solids, liquids or gases usually found in sedimentary rocks
- bio-molecules – complex carbon compounds produced in living things. Proteins, carbohydrates, fats and oils, and DNA are examples of bio-molecules.

Of all these forms of carbon, we study CO_2 in most detail because it is thought that this has a profound effect on climate. It is also difficult to separate a *natural* carbon cycle from one that is affected by human activity. Human activity and associated emissions of carbon dioxide (anthropogenic CO_2) fundamentally affect the carbon cycle and so affect climate.

Origins of carbon on Earth

The primary source of carbon/CO_2 is the Earth's interior. It was stored in the mantle when the Earth formed. It escapes from the mantle at constructive and destructive plate boundaries as well as hot-spot volcanoes. Much of the CO_2 released at destructive margins is derived from the metamorphism of carbonate rocks subducting with the ocean crust. Some of the carbon remains as CO_2 in the atmosphere, some is dissolved in the oceans, some carbon is held as biomass in living or dead and decaying organisms, and some is bound in carbonate rocks. Carbon is removed into long-term storage by burial of sedimentary rock layers, especially coal and black shales (these store organic carbon from undecayed biomass) and carbonate rocks like limestone (calcium carbonate).

The major stores of carbon

A gigatonne of carbon dioxide equivalent (GtC) is the unit used by the United Nations climate change panel, the Intergovernmental Panel on Climate Change (IPCC), to measure the amount of carbon in various stores. 1 Gt amounts to 10^9 tonnes (1 billion tonnes).

Transfer (flux) of carbon within the cycle is measured in gigatonnes of carbon per year (GtC/years).

The lithosphere

Key terms

Anthropogenic CO_2 – Carbon dioxide generated by human activity.

Biosphere – The total sum of all living matter.

Carbon sequestration – The capture of carbon dioxide (CO_2) from the atmosphere or capturing anthropogenic (human) CO_2 from large-scale stationary sources like power plants before it is released to the atmosphere. Once captured, the CO_2 gas (or the carbon portion of the CO_2) is put into long-term storage.

Carbon sink – A store of carbon that absorbs more carbon than it releases.

Greenhouse gas – Any gaseous compound in the atmosphere that is capable of absorbing infrared radiation, thereby trapping and holding heat in the atmosphere.

Lithosphere – The crust and the uppermost mantle; this constitutes the hard and rigid outer layer of the Earth.

Weathering – The breakdown of rocks *in situ* by a combination of weather, plants and animals.

The Earth's **lithosphere** includes the crust and the uppermost mantle; this constitutes the hard and rigid outer layer of the Earth. The uppermost part of the lithosphere, the layer that chemically reacts to the atmosphere, hydrosphere and **biosphere** through the soil forming process is called the pedosphere.

Carbon is stored in the lithosphere in both inorganic and organic forms. Inorganic deposits of carbon in the lithosphere include fossil fuels like coal, oil, and natural gas, oil shale (kerogens) and carbonate-based sedimentary deposits like limestone. Organic forms of carbon in the lithosphere include litter, organic matter and humic substances found in soils.

Carbon in the lithosphere is distributed between these stores:

- marine sediments and sedimentary rocks contain up to 100 million GtC
- soil organic matter contains between 1,500 and 1,600 GtC
- fossil fuel deposits of coal, oil and gas contain approximately 4,100 GtC
- peat, which is dead but undecayed organic matter found in boggy areas contains approximately 250 GtC.

The hydrosphere

The ocean plays an important part in the carbon cycle. Attempts to collate measurements of the amount of carbon in the oceans have been made by the Global Ocean Data Analysis project (GLODAP) using data from research ships, commercial ships and buoys. The measurements come from deep and shallow waters from all the oceans. There is some variation in the results and figures can only be an approximation.

The oceanic stores can be divided into three:

- the surface layer (euphotic zone) where sunlight penetrates so that photosynthesis can take place contains approximately 900 GtC.
- the intermediate (twilight zone) and the deep layer of water contain approximately 37,100 GtC
- living organic matter (fish, plankton, bacteria, etc.) amount to approximately 30 GtC and dissolved organic matter 700 GtC.

This gives a total for oceanic carbon of between 37,000 GtC to 40,000 GtC.

When organisms die, their dead cells, shells and other parts sink into deep water. Decay releases carbon dioxide into this deep water. Some material sinks right to the bottom, where it forms layers of carbon-rich sediments. Over millions of years, chemical and physical processes may turn these sediments into rocks. This part of the carbon cycle can lock up carbon for millions of years. It is estimated that this sedimentary layer could store up to 100 million GtC.

The biosphere

This is defined as the total sum of all living matter. For our purposes we are going to consider the terrestrial biosphere as being separate from the oceanic biosphere. The total amount of carbon stored in the terrestrial **biosphere** has been estimated to be 3,170 GtC. The distribution of this carbon depends upon the ecosystem as shown in Figure 1.36 (page 26).

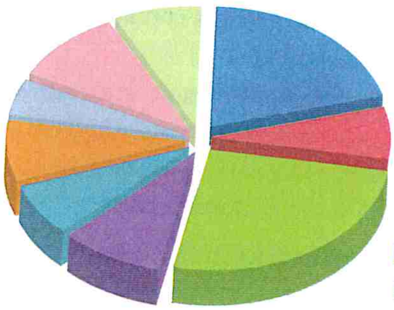

Figure 1.36 Terrestrial carbon stores by ecosystem

The main stores of carbon in the terrestrial biosphere are as follows:

- **Living vegetation:** at the global level, 19 per cent of the carbon in the Earth's biosphere is stored in plants. Unlike the oceans, much of this carbon is stored directly in the tissues of the plants. Although the exposed part of the plant is the most visible, the below-ground biomass (the root system) must also be considered. The amount of carbon in the biomass varies from between 35 and 65 per cent of the dry weight. The amount varies depending on the location and the vegetation type. It is estimated that half of the carbon in forests occurs in high-latitude forests, and a little more than one third occurs in low-latitude forests. The two largest forest reservoirs of carbon are the vast expanses in Russia, which hold roughly 25 per cent of the world's forest carbon, and the Amazon basin, which contains about 20 per cent.
- **Plant litter:** this is defined as fresh, undecomposed, and easily recognisable (by species and type) plant debris. This can be anything from leaves, cones, needles, twigs, bark, seeds/nuts, etc. The type of litter is directly affected by the type of ecosystem. Leaf tissues account for about 70 per cent of litter in forests, but woody litter tends to increase with forest age. In grasslands there is very little above ground perennial tissue so the annual fall of litter is very low.
- **Soil humus:** this originates from litter decomposition. Humus is a thick brown or black substance that remains after most of the organic litter has decomposed. It gets dispersed throughout the soil by soil organisms such as earthworms. In all forests, tropical, temperate and boreal together, approximately 31 per cent of the carbon is stored in the biomass and 69 per cent in the soil. In tropical forests, approximately 50 per cent of the carbon is stored in the biomass and 50 per cent in the soil. Altogether the world's soils hold more carbon (2,500 GtC) than the vegetation. Soil carbon can be either organic (1,550 GtC) or inorganic carbon (950 GtC). The inorganic carbon component consists of carbon itself as well as carbonate materials such as calcite, dolomite and gypsum. The amount of carbon found in living plants and animals is comparatively small relative to that found in soil (560 GtC). The soil carbon pool is approximately 3.1 times larger than the atmospheric pool of 800 GtC. Only the ocean has a larger carbon store.
- **Peat:** this is an accumulation of partially decayed vegetation or organic matter that is unique to natural areas called peatlands or mires. Peat forms in wetland conditions, where almost permanent water saturation obstructs flows of oxygen from the atmosphere into the ground. This creates low oxygen anaerobic conditions that slow down rates of plant litter decomposition. Peatlands cover over four million km² or 3 per cent of the land and freshwater surface of the planet; they occur on all continents, from the tropical to boreal and Arctic zones and from sea level to high alpine conditions. It is estimated that peat stores more than 250 GtC worldwide.
- **Animals:** these play a small role in the storage of carbon. They are, however, very important in the generation of movement of carbon through the carbon cycle.

The atmosphere

Carbon has been in the atmosphere from early in the Earth's history. Atmospheric carbon dioxide levels have reached very high values in the deep past, possibly topping over 7,000 ppm (parts per million) in the Cambrian period around 500 million years ago. Its lowest concentration has probably been over the last 2 million years during the Quaternary glaciation when it sank to about 180 ppm.

Today, carbon dioxide is a trace gas in the Earth's atmosphere. Estimates of the overall amount of carbon stored in the atmosphere vary from 720 GtC to 800 GtC. It makes up about 0.04 per cent (400 ppm) of the atmosphere; this low concentration belies its importance to the planet and all life on it. Due to human activities, the present concentration of

CO_2 in the Earth's atmosphere is higher than it has been for at least 800,000 years, and, in all likelihood, the highest in the past 20 million years. Despite its relatively small concentration, CO_2 is a potent **greenhouse gas** and plays a vital role in regulating the Earth's surface temperature. The recent phenomenon of global warming has been attributed primarily to increasing industrial CO_2 emissions into Earth's atmosphere.

Atmospheric carbon has been measured at the Mauna Loa Observatory (MLO) on Hawaii since 1958. The undisturbed air, remote location and minimal influences of vegetation and human activity at MLO are ideal for monitoring atmospheric constituents. The observatory is part of the American National Oceanic and Atmospheric Administration (NOAA). The measurements show that the global annual mean concentration of CO_2 in the atmosphere has increased markedly since the Industrial Revolution, from 280 ppm to 317.7 ppm in March 1958 to 400.3 ppm as of February 2015. This increase is largely attributed to human derived (anthropogenic) sources, particularly the burning of fossil fuels and deforestation.

Figure 1.37 The NOAA atmospheric observatory station, Mauna Loa, Hawaii

A graph of this change has been named after the scientist who first started this research; it is called the Keeling Curve.

Keeling was one of the first scientists to gather evidence that linked fossil fuel emissions to rising levels of carbon dioxide. Keeling's research has been backed up by other readings from around the world; for example, the CO_2 trapped in ice cores from Antarctica and Greenland can be used to give a 'proxy' measure of the CO_2 in the atmosphere at the time that snow was laid down.

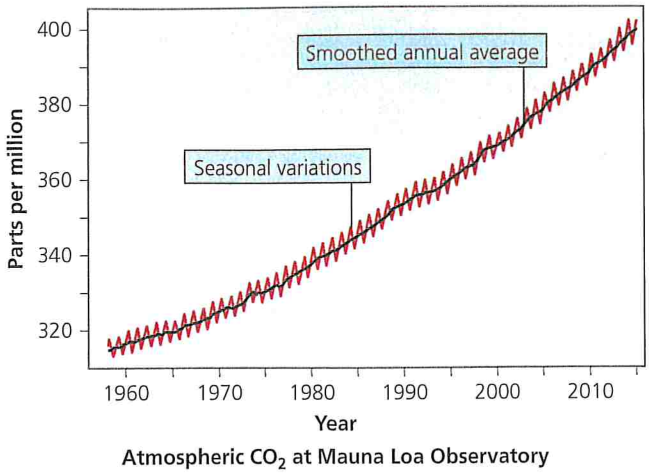

Figure 1.38 The Keeling curve of the changing concentration of atmospheric CO_2

Source: NOAA

The daily average at Mauna Loa first exceeded 400 ppm on 10 May 2013. It is currently rising at a rate of approximately 2 ppm/year and accelerating.

Movement of carbon

Carbon moves from one store to another in a continuous cycle (see Figure 1.39, page 28)

This cycle consists of several carbon stores as described above. The processes by which the carbon moves between these stores are known as transfers or fluxes. If more carbon enters a store than leaves it, that store is considered a **net carbon sink**. If more carbon leaves a store than enters it, that store is considered a **net carbon source**.

The geological component

The geological component of the carbon cycle is where it interacts with the rock cycle in the processes of **weathering**, burial, subduction and volcanic eruptions.

In the atmosphere, carbon dioxide is removed from the atmosphere by dissolving in water and forming carbonic acid:

$$CO_2 + H_2O \rightarrow H_2CO_3 \text{ (carbonic acid)}$$

As this weakly acidic water reaches the surface as rain, it reacts with minerals at the Earth's surface, slowly dissolving them into their component ions through the process of chemical weathering. These component ions are carried in surface waters like streams and rivers, eventually to the ocean, where