

Chapter 8

Introduction to Earth's Atmosphere

Abstract The Earth's atmosphere is a thin envelope of gases surrounding the solid planet, the hydrosphere, and biosphere. The composition of the atmosphere consists largely of two elements, oxygen and nitrogen. The atmosphere also contains chemicals which absorb heat from the Earth's surface and radiate it in all directions including back to the surface. This results in the greenhouse effect that keeps the planet warm enough to sustain life. The greenhouse gases include water vapor, carbon dioxide, and methane. Carbon dioxide is the main greenhouse gas of concern today as it is increasing rapidly in the atmosphere largely as the result of the burning of fossil fuels. The Keeling curve shows the steady increase in carbon dioxide since 1958. Different zones of the atmosphere are defined. The effects of Arctic warming are causing changes in the Jet Stream. These changes are affecting weather patterns and weather uncertainty is increasing. The isotopes of carbon are listed and the significance of carbon-14 (^{14}C) is explained with reference to carbon dioxide from fossil fuels.

Keywords Thermosphere • Mesopause • Thermopause • Stratosphere • Ozone • Lapse rate • NOAA • Aerosols • CFCs • Methane • Keeling • Thunderstorm • Smog • Ferrel • Hadley • Polar • Exosphere • Isostatic • Rebound • PBL • Gigatonne • Westerlies • Contraction • Intertropical • Convergence

Things to Know

The following is a list of things to know from this chapter. It is intended, as it is in each chapter, to serve as a guide to points of emphasis for the student to keep in mind while reading the chapter. Before finishing with this and each chapter, the "Things to Know" should be understood and can be used for review purposes. The list may not include all of the terms and concepts required by the instructor for this topic.

Things to Know	
Thickness of the Atmosphere	Earth's Temperature
Lapse Rate	Inert Gases
Thermosphere	Chemical Composition of Earth's Atmosphere
Mesopause	Ozone Hole
Smog	Emitters of Carbon Dioxide
Stratopause	36,000 Million Metric Tons
O ₃	NOAA
Tambora	Stratosphere
D, E, and F Layers	Aerosols
"Year Without a Summer"	Tropopause
CFCs	Exosphere
CH ₄	Minus 15 Degrees Celsius
Ozone Layer	Jet Stream

8.1 Introduction

The atmosphere is the gaseous envelope which surrounds us. It is what we breathe and what provides oxygen to most animal life at the Earth's surface. The atmosphere is a relatively thin envelope compared to the mass of Planet Earth (Fig. 8.1).

Atmospheric contamination is a serious concern and may be invisible to humans as it begins to build and the concentrations of contaminants may be so gradual that it goes unnoticed. Some atmospheric contaminants may continue to build up and become visible, such as smog or the "brown haze" over cities, but the atmosphere is vitally important to the maintenance of life on Earth. There may be warning signs



Fig. 8.1 Earth's atmosphere from the International Space Station (ISS) (From NASA, Public Domain)

of atmospheric contamination, such as smog and haze that should be heeded so that things can be corrected before it becomes imminently dangerous to humans. Let's first take a look at the nature and characteristics of the atmosphere.

8.2 The Atmosphere

The atmosphere has provided for life on Earth for at least the last 3.5 billion years or so. Trilobites, ammonites, sea-scorpions, dinosaurs, mastodons, saber-toothed cats, and many other life forms that depended upon the atmosphere and hydrosphere have come and gone throughout Earth's history. These organisms are discussed in detail in Volume II of this textbook series.

8.3 Composition of the Atmosphere

The atmosphere is composed mainly of two elements; nitrogen and oxygen. These two elements comprise roughly 99.06% of the atmosphere. The other constituents of the lower atmosphere (within 25 km of Earth's surface) are listed below in Table 8.1.

All of the substances in Table 8.1 are important for one reason or another, but three stand out as influencing what is and has been occurring in the Earth's atmosphere. These three are the cause of great concern for the future of the planet. They are the greenhouse gases carbon dioxide (CO₂), methane (CH₄), and ozone (O₃). All three are greenhouse gases (GHGs) and, along with water vapor, provide the Earth with the greenhouse effect. Carbon dioxide and methane trap heat near Earth's surface and ozone filters out UV rays that cause cancer and respiratory harm to animals living at the surface of the Earth.

Table 8.1 Average composition of the atmosphere below 25 km

Chemical Components of the Atmosphere		
Component	Chemical abbreviation	Volume % (dry air)
Nitrogen	N ₂	78.08
Oxygen	O ₂	20.98
Argon ^a	Ar	0.93
Carbon dioxide	CO ₂	0.039
Neon ^a	Ne	0.0018
Helium ^a	He	0.0005
Hydrogen	H	0.00006
Krypton ^a	Kr	0.0011
Xenon ^a	Xe	0.00009
Methane	CH ₄	0.0017
Ozone ^b	O ₃	0.00006

^aInert gases

^bStrictly speaking, the concentration of ozone in the atmosphere is variable so the total % may exceed 100%

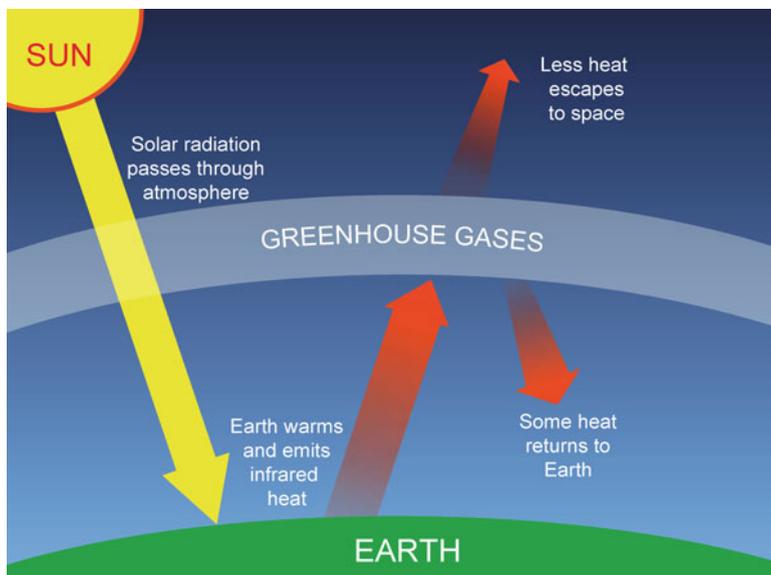


Fig. 8.2 The greenhouse effect. Greenhouse gases trap and re-emit heat energy back to Earth's surface. With the buildup of greenhouse gases in the past several decades, Earth now has the 'enhanced greenhouse effect'

The greenhouse effect is what keeps the Earth warm enough, but not too warm, to support life. This warmth is estimated to be about 33°C above what it would be without the greenhouse effect. As a result, the Earth's average global temperature is a balmy $+15^{\circ}\text{C}$, instead of a -18°C . If the Earth's surface was -18°C , no life could exist on its surface. The greenhouse effect is what has caused life as we know it to originate and evolve on Earth. It is this greenhouse effect that has been in existence since humans evolved on this planet.

Humans have evolved on Earth under conditions that were not affected by humankind's current activities. Humans are at a unique time in Earth's history now when we can change the course of that history. We are the only species that has evolved the ability to project into the future and decide the fate of the planet and its life-sustaining features.

The illustration above (Fig. 8.2) shows how the greenhouse effect works. Solar radiation passes through the atmosphere, some is directly reflected back to space but most gets through and warms the Earth. As we've seen before, the incoming radiation is mainly ultraviolet (UV) radiation. This UV radiation heats the Earth which causes it to re-radiate heat in the form of infrared (IR) radiation. Much of this IR radiation is trapped near Earth's surface by the greenhouse gases that in turn re-radiate some of this back to the surface.

Greenhouse gases allow the Sun's radiation to pass through the atmosphere, heating the Earth's surface. Heat is re-radiated by the Earth's surface and much of it is trapped by greenhouse gases. These gases keep the Earth a pleasant average temperature

of about $+15^{\circ}\text{C}$. Of course, the temperature varies from place to place over the Earth's surface and from season to season and the $+15^{\circ}\text{C}$ is an average figure.

We will next take a look at the important greenhouse gases and the properties that make them so useful to mankind and the other species inhabiting the Earth.

8.3.1 *Carbon Dioxide*

Carbon dioxide is the gas that is most important in warming the Earth's atmosphere and its surface along with water vapor. It is so important that its role in warming the planet will be discussed separately in the following chapter.

All greenhouse gases trap heat in the lower part of the atmosphere and re-radiate it back to Earth, but carbon dioxide is special, which will become obvious in the paragraphs that follow. Water vapor does not last long in the atmosphere and falls as precipitation and condensation.

Carbon dioxide is a colorless gas and constitutes a very small percentage of the atmosphere. As will be discussed in succeeding Chap. 9, carbon dioxide is only 0.040% (400 ppmv, parts per million by volume) of the atmosphere, an infinitesimal amount. However, it is an extremely important gas because it is a major part of the carbon cycle, being used by plants in photosynthesis and by animals that consume plants, and by being a greenhouse gas that helps to warm the planet. Carbon dioxide is emitted naturally by volcanoes, hot springs, fumaroles, geysers, animals, and by the dissolution of carbonates in rocks of the Earth's crust. The recent (nineteenth, twentieth, and into the twenty-first century) increases of carbon dioxide in the atmosphere are unequivocally due to anthropogenic (i.e., man-made) causes, principally the burning of fossil fuels; and there are human fingerprints to prove that this is true.

Carbon dioxide levels fall in the spring and summer as plants consume the gas, and rise during the autumn and winter as plants go dormant, die, and decay. When plants and animals are buried and form coal, natural gas, and oil over tens and hundreds of millions of years, and are then burned at the Earth's surface to release energy, they release carbon dioxide back to the atmosphere. The illustration below, Fig. 8.3, is the well-known Keeling curve maintained by the U.S. National Oceanic and Atmospheric Administration (NOAA) at the Mauna Loa Observatory in Hawaii.

Carbon dioxide has a high affinity for heat capture and retention in the infrared and near-infrared wavelengths while being transparent to ultraviolet and visible light from the Sun. In other words, a majority of ultraviolet light from the Sun is transmitted through the atmosphere to the Earth's surface but carbon dioxide and other greenhouse gases trap heat radiation in the lower part of the atmosphere near the Earth's surface and keep it from escaping back into space. After a greenhouse gas traps a packet of infrared radiation, the gas re-radiates it partially out to space, partially to other greenhouse gas molecules in the atmosphere, or back to the Earth's surface. As carbon dioxide increases in the atmosphere, Earth's temperature also

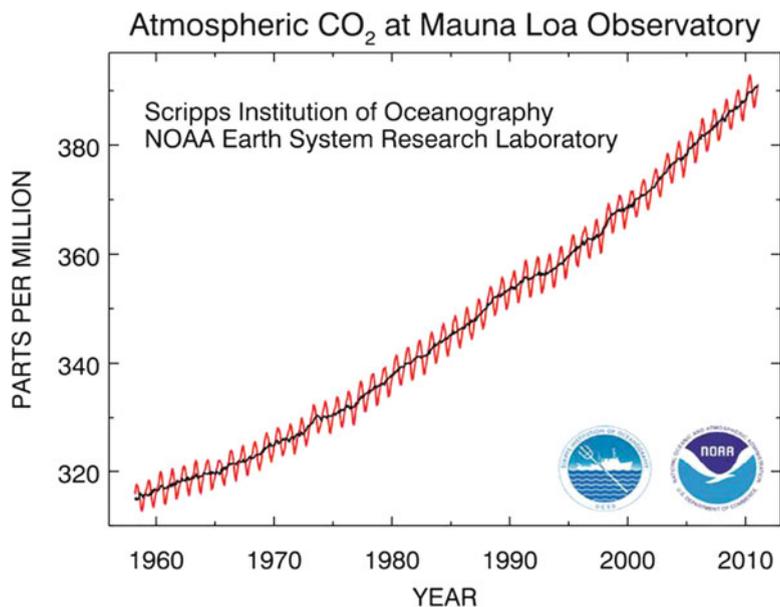


Fig. 8.3 The record of CO₂ increases in the atmosphere at Mauna Loa Observatory since 1958. This is the famous Keeling curve. The *red line* shows the seasonal variation in CO₂, lowest in the summer and highest in the winter; vegetation in middle latitudes in the Northern Hemisphere takes in CO₂ in the spring and summer and releases it in the fall and winter. The *black line* is the average annual concentration (NOAA, Public Domain)

increases. Earth's average global temperature at its surface increases because of the rise in greenhouse gas concentration in the atmosphere.

Earth has an energy imbalance, as we saw in a previous chapter. There is more energy coming in from the Sun than is being radiated back out into space by the Earth and this has been measured accurately by orbiting satellites and other instruments. The amount of radiation being lost to space from the Earth is becoming less and less with time as CO₂ concentration in the atmosphere is increasing. That carbon dioxide causes global warming is a scientific fact, as it is a fundamental fact of physics that carbon dioxide absorbs infrared radiation and re-radiates it back to the Earth's surface. This fact has been demonstrated in laboratories, in the field, and by satellites many times since the nineteenth century.

Carbon dioxide has been much higher in atmospheric concentrations in the geologic past than it is today. But this does not mean that it is a good thing today; that is, that the increase in CO₂ today does no harm. Some skeptics and deniers would have us believe CO₂ is not important to today's climate and they cite the miniscule amount as a percentage of atmospheric composition, but as we've already seen, it is extremely important to recognize its influence on the warming Earth.

CO₂ has fluctuated wildly throughout geologic time, being extremely high for the first few hundred million years of the Phanerozoic Eon and most likely was

much higher during the Precambrian (older than 540 million years ago). The higher atmospheric concentrations of CO_2 in the past have been attributed to the vast intervals of time the carbon cycle needs to remove carbon from the atmosphere, thus allowing carbon dioxide to remain high for a large portion of geologic time. Plots of carbon dioxide over hundreds of millions of years show a gradual decline in concentration with time.

The high CO_2 values during early Earth history and the steadily declining values are due primarily to the speeding up of the passage of carbon atoms from their original volcanic sources into sediments as these are eroded from the continents and buried in lakes, along the course of rivers, and in the ocean basins. The continents stand higher today than perhaps at any previous time during Earth history, due largely to isostatic rebound from the most recent glaciation and retreat and the high-standing Alps, Andes, Rockies, and Himalaya Mountains and the Tibetan Plateau. These continental areas are still being uplifted by Earth processes today. To lower atmospheric CO_2 over a long period of time, one has to expose fresh rocks to provide calcium and/or to bury organic materials and these processes have taken enormous intervals of geologic time. These processes are discussed further in Volume II of this textbook series.

The greenhouse effect of CO_2 has been known since Fourier's research in 1824 and it was quantified by Arrhenius in 1896, as we saw in a preceding chapter. CO_2 absorbs and re-emits infrared (heat) radiation in the atmosphere warming the lower troposphere of the Earth and the Earth's surface. This is an undeniable fact of physics, but climate change deniers insist that this is not so; they have offered no proof of their claims.

In the more recent geologic past (revealed by several lines of evidence), as carbon dioxide has increased in the atmosphere, temperature of the lower troposphere has increased. As carbon dioxide has decreased in the atmosphere, temperature has decreased.

There is a direct correlation between carbon dioxide and temperature of the lower troposphere throughout Earth's history where such information is available and can be interpreted. There is evidence from the most recent episodes of glaciation on Earth that temperature rises before carbon dioxide, then carbon dioxide builds up in the atmosphere until it decreases again as temperature falls before the next glaciation. Climate scientists show evidence that the initial glaciation was most likely triggered by Earth's orbital cycle but the later glaciations and interglacial episodes were controlled by carbon dioxide. This relationship between glaciation and carbon dioxide is discussed further in a later chapter. It appears that carbon dioxide concentration in the atmosphere is acting as the Earth's thermostat as the carbon dioxide levels track Earth's temperature throughout a large portion of geologic time.

As geologists, climate change scientists, and paleoclimatologists refine their methods, develop new ones, and increase the accuracy of their studies, much more information and technologies are becoming available to analyze the effects of carbon dioxide and Earth's temperatures millions and millions of years in the past. And the results of all of these studies show a direct empirical relationship between car-

bon dioxide and Earth's surface temperature. The coincidence of this over millions and millions of years of Earth history is striking and is surely not an accident, although it is well known that correlation does not prove cause and effect. However, when this correlation exists between carbon dioxide increases and temperature increases are combined with all the other evidence from physics and paleoclimatology, this correlation takes on additional significance.

Carbon dioxide is not the only greenhouse gas. Water vapor is the most abundant and obvious of the greenhouse gases, but water vapor is flushed out of the atmosphere regularly by condensation and precipitation. There are other more potent greenhouse gases than water and carbon dioxide and they are discussed further in later chapters and only briefly introduced here.

Methane is a more potent greenhouse gas than either water vapor or carbon dioxide. Nitrous oxide is even more potent than methane. But it is carbon dioxide that forms the matrix which holds some water vapor and other greenhouse gases in the atmosphere. Carbon dioxide also is long-lived in the atmosphere, perhaps as long as a thousand years, and mixes throughout the troposphere, whereas water vapor precipitates out as rain, mist, sleet, hail, or snow and methane is oxidized to carbon dioxide. Because carbon dioxide is long-lasting, it becomes mixed throughout the atmosphere and is a very effective greenhouse gas. As its concentration in Earth's atmosphere is increasing at present, the temperature is also increasing and scientists are beginning to see cause and effect.

Some climate change deniers claim that more carbon dioxide is added to the atmosphere by volcanoes than by humans. This is incorrect. The anthropogenic burning of fossil fuels causes over one hundred times (130+ times) more carbon dioxide emissions annually than volcanoes.

Published estimates based on research findings of the past 30 years for present-day global emission rates of carbon dioxide from subaerial and submarine volcanoes range from about 150 million to 270 million metric tons of carbon dioxide per year, with an average of about 200 million metric tons.

These global volcanic estimates are utterly dwarfed by carbon dioxide emissions from fossil fuel burning (coal, petroleum), cement production, gas flaring and land use changes; these emissions accounted for some 36,300 million metric tons (36 gigatonnes or billion tons) of carbon dioxide in 2008, according to an international study published in December 2009. Even if one takes the highest estimate of volcanic carbon dioxide emissions at 270 million metric tons per year, human-emitted carbon dioxide levels (at 36,000 million metric tons) are more than 133.333 times higher than volcanic emissions.

Carbon dioxide may remain in the atmosphere for hundreds of years and possibly thousands of years and this longevity allows carbon dioxide to become well mixed throughout the atmosphere.

There are several facts of physics that have never been disputed in the scientific literature that relate to carbon dioxide and its role in rising Earth temperatures, and they are as follows:

- The atmospheric carbon dioxide concentration has increased steadily since the beginning of the Industrial Revolution, after being nearly constant for a couple of

thousand years. The pre-industrial carbon dioxide level is estimated at about 280 ppm. Carbon dioxide has been continuously monitored at the NOAA Mauna Loa Observatory since 1958 and has resulted in what is known as the Keeling Curve (see Fig. 8.3).

- The surplus atmospheric carbon dioxide has an isotope composition that can only come from fossil fuels. The increase in concentration is not natural; it comes from human activities. There are three isotopes of carbon in nature: carbon-12 (^{12}C), carbon-13 (^{13}C), and carbon-14 or radiocarbon (^{14}C). Studies of carbon isotope ratios prove that the bulk of the additional carbon dioxide in the atmosphere comes from the burning of fossil fuels. There is no ^{14}C being added to the atmosphere beyond that which occurs naturally. There would be additional ^{14}C added to the atmosphere from any source other than fossil fuels.
- The radiative properties of carbon dioxide have been measured in the laboratory since Fourier and Arrhenius in the nineteenth century. Carbon dioxide absorbs thermal infrared (i.e., heat) radiation and re-radiates heat back to the Earth's surface.
- Because carbon dioxide has an infrared and heat-absorbing physical property, the increase in its concentration has increased the infrared opacity of the Earth's atmosphere and blocks the outward radiation of heat. This blocking and re-radiating of heat has been measured and is being measured in laboratories since the nineteenth century and since 1978 by Earth-orbiting satellites. Less heat is escaping to outer space from the Earth's surface and more is being trapped and re-radiated to the surface.
- More net energy is now coming into the Earth's atmosphere from sunlight than is going back out to space as heat radiation. This is being accurately measured by instruments both at Earth's surface and by satellites in orbit around the Earth.
- Conservation of energy is a fundamental law of physics. When more energy comes in than goes out of a system, the system warms.
- The Earth's temperature is increasing by an amount that is consistent with predictions, based on the laws of physics and the well-known heat-absorbing properties of the excess carbon dioxide in the atmosphere.
- Measurements show that night-time temperatures are increasing faster than daytime temperatures, just as physicists and climate change scientists have predicted. The excess carbon dioxide and other greenhouse gases cause a warmer night-time atmosphere. The main source of heat at night is greenhouse gases but they do not affect the brightness of the Sun.
- Measurements show that the top of the atmosphere is getting colder, just as physicists and climate change scientists predicted, because the excess carbon dioxide in the lower atmosphere is blocking the heat from below. The troposphere is warming, the tropopause is rising, and the stratosphere is cooling.
- Heat-sensing instruments on satellites have measured a reduction in the amount of infrared radiation coming from the atmosphere, at the exact wavelengths predicted by physicists and climate change scientists. Less heat radiating from Earth to outer space means more heat is being captured by greenhouse gases.

Those that claim that carbon dioxide does not cause the Earth to warm must be prepared to refute one or more of the above facts, and so far no one has been able to do this (as of June 2012).

8.3.2 Methane (CH_4)

Methane is a greenhouse gas approximately 21 times more effective than carbon dioxide in trapping and re-radiating heat to the Earth's surface. It varies as to its effectiveness compared to carbon dioxide depending on how long it remains in the atmosphere.

Methane is a hydrocarbon gas produced both through natural sources and human activities, including the decomposition of wastes in landfills, agriculture, and especially rice cultivation, as well as ruminant digestion and manure management associated with domestic livestock. Methane is much less abundant than carbon dioxide in the atmosphere but is increasing in concentration due to its release by melting permafrost and by methane clathrates in shallow marine environments. Methane remains in the atmosphere for approximately 9–15 years and eventually is converted to carbon dioxide by oxidation.

The sudden release of methane into the atmosphere by rising temperatures is one of the main causes of concern for global warming. If permafrost continues to melt and the oceans continue to warm and the huge quantities of methane that are stored there are released to the atmosphere and converted to carbon dioxide, runaway global warming and the Venus syndrome could be fatal to most, if not all, life on the planet. The Venus syndrome is an atmosphere like that of the planet Venus whose atmosphere is largely comprised of carbon dioxide. This is a truly doomsday scenario as no life exists on Venus.

Methane is not as long-lasting in the atmosphere as is carbon dioxide, but this is little consolation as they are both greenhouse gases, methane is converted to carbon dioxide, and carbon dioxide becomes well-mixed and is long-lasting in the atmosphere.

8.3.3 Nitrous Oxide (N_2O)

Nitrous oxide (N_2O) is produced by both natural and human-related sources. Primary human-related sources of N_2O are agricultural soil management, animal manure management, sewage treatment, mobile and stationary combustion of fossil fuel, and nitric and other acid production. Nitrous oxide is also produced naturally from a wide variety of biological sources in soil and water, particularly microbial action in wet tropical forests.

Nitrous oxide is a clear, colorless gas, with a slightly sweet odor. Due to its long atmospheric lifetime (approximately 120 years) and heat trapping effects (about 310 times more powerful than carbon dioxide on a per molecule basis), N_2O is an important greenhouse gas. It is commonly known as “laughing gas.”

8.3.4 Ozone (O_3)

Ozone is an important greenhouse gas but is even more important to life on Earth as an absorber of the Sun's ultraviolet radiation. In the troposphere, ground-level or “bad” ozone is a pollutant that is a significant health risk, especially for humans with asthma

or other respiratory problems. It also damages crops, trees and other vegetation. It is a main ingredient of urban smog often seen in major metropolitan areas of the world.

The stratospheric or “good” ozone is a layer that extends upward from about 6 to 30 miles and protects life on Earth from the Sun’s harmful ultraviolet (UV) radiation. This natural shield has been gradually depleted by man-made chemicals such as chlorofluorocarbons (CFCs). A depleted ozone shield allows more UV radiation to reach the ground, leading to more cases of skin cancer, cataracts, and other health and environmental problems. The “ozone hole” over Antarctica received a great deal of publicity after its discovery in 1985. The Antarctic ozone hole was discovered by British scientists of the British Antarctic Survey.

After a series of rigorous meetings and negotiations, the Montreal Protocol on Substances that Deplete the Ozone Layer was finally agreed to on 16 September 1987 at the Headquarters of the International Civil Aviation Organization in Montreal, Canada. This is now referred to simply as the Montreal Protocol.

The ozone “hole” is really a reduction in concentrations of ozone high above the Earth in the stratosphere (Fig. 8.5). The ozone hole has steadily grown in size (up to 27 million square kilometers) and length of existence (from August through early December) over the past two decades. The size is expected to begin to be reduced and return to its pre-1980 size by 2070, according to the U. S. National Oceanic and Atmospheric Administration (NOAA). The Antarctic ozone hole had reached the size of North America by the fall of 2011.

An Arctic ozone hole has also been discovered and is thought to be due to an increasingly cold stratosphere, which results from the greenhouse effect. If more heat is trapped in the troposphere, less is available to warm the stratosphere.

8.3.5 Chlorofluorocarbons (CFCs)

Chlorofluorocarbons are substances that are completely anthropogenic. They do not occur as a result of natural causes or processes.

The non-reactivity of CFCs, so desirable to industry, allows them to drift for years in the atmosphere until they eventually reach the stratosphere. High in the stratosphere, intense UV solar radiation severs chlorines away from the CFCs, and it is these unattached chlorines that are able to catalytically convert ozone molecules into oxygen molecules. It is these catalytic reactions that were leading to the destruction of the ozone layer in the stratosphere prior to the acceptance of the Montreal Protocol in 1987.

8.3.6 Other Trace Gases

Other trace gases in the atmosphere include the noble gases, inert or unreactive gases, of which the most abundant is argon. Other noble gases include neon, helium, krypton and xenon. Hydrogen is also present in trace quantities in the atmosphere,

but because it is so light, over time much of it has escaped to space from Earth's gravitation. Water vapor is also a trace gas, is not well mixed in the atmosphere, and is flushed out of the atmosphere by precipitation.

8.3.7 Aerosols

Aerosols are liquids and solids which are dispersed in the atmosphere and consist of soot, dust, sea salt crystals, spores, bacteria, viruses, and many other types of materials which float around in the air.

Aerosol concentration in the atmosphere varies widely but is thought to average about one part per billion (ppb). Despite this small fraction, aerosols play an important role in climate change. Volcanic dust after violent explosive eruptions may produce aerosols (volcanic ash, sulfur, and dust) which block a percentage of the Sun's radiation from impacting Earth. This has caused cooling of the surface of the planet for as long as 1–2 years. Liquids as aerosols cause more dispersion of the Sun's radiation and solid aerosols block the Sun's rays.

The year 1816 is referred to as “the year without a summer” due to a series of volcanic eruptions, the last of which was the explosive eruption of Mount Tambora in Indonesia in 1815, the largest known eruption in over 1,600 years and possibly the largest eruption in the history of humankind. A solar minimum may also have contributed to the coldness during the summer months. It snowed in the northeastern part of the U.S. in New York, Connecticut, and most of New England in June. Nearly a foot of snow fell in Quebec City, Canada in early June. Crops were lost and there was an additional loss of most summer-growing plants. There was regional malnutrition, starvation, and an increased death rate.

Aerosols also scatter incoming solar radiation resulting in slight cooling as this scattering occurs in all directions, some of which impacts the Earth's surface.

8.4 Lapse Rate

Lapse rate is the rate of decline of temperature with altitude in the atmosphere, thus

$$\lambda = dT / dz$$

Where λ is the lapse rate of temperature divided by units of altitude, T = temperature and z = altitude. Although the actual atmospheric lapse rate varies, under normal atmospheric conditions the average atmospheric lapse rate results in a temperature decrease of 3.5°F (1.94°C) per 1,000 ft (304 m) of altitude, or height above the Earth's surface. The actual lapse rate varies from place to place and from time to time over the Earth and it may be reversed in the case of an air inversion, where the temperature increases with altitude. The lapse rate may be expressed as a wet and a dry lapse rate and using either the metric or English system.

8.5 Vertical Structure of the Atmosphere

The Earth is a layered planet. The atmosphere is layered, there are layers in the Earth's crust, and there are layers below the crust until one arrives at the center of the Earth.

The atmosphere may be thought of as a column of air (Fig. 8.5). It consists of (from bottom to top) the troposphere, stratosphere, mesosphere, thermosphere, exosphere, and magnetosphere (not shown in Figs. 8.5 or 8.6). Each layer has its own set of characteristics and is described below. Each layer grades into the adjacent layer.

The troposphere is the layer where most clouds and weather occur. There are some clouds that form in the stratosphere but their effect on weather is minimal.

The troposphere and stratosphere are separated by the tropopause. The stratosphere and mesosphere are separated by the stratopause. The mesosphere and thermosphere are separated by the mesopause.

The tropopause is the area of the atmosphere where the temperature stops cooling and starts warming. It is a temperature gradient, as are the other layers of the atmosphere, and one layer grades into the other. The tropopause varies in height depending on its latitude as can be seen in Fig. 8.4.

The mesopause is the coldest place on Earth with temperatures as low as -100°C (-146°F or 173 K). The altitude of the mesopause for many years was assumed to be at around 85 km, but observations to higher altitudes and modeling studies in the last few years (since the year 2000) have shown that in fact the mesopause consists of two temperature minima; one at about 85 km and a stronger minimum at about 100 km in elevation above Earth's surface (Fig. 8.5).

The ozone layer is in the lower part of the stratosphere (Fig. 8.6) and filters out enough ultraviolet radiation from Sunlight to protect animal and plant life living at Earth's surface.

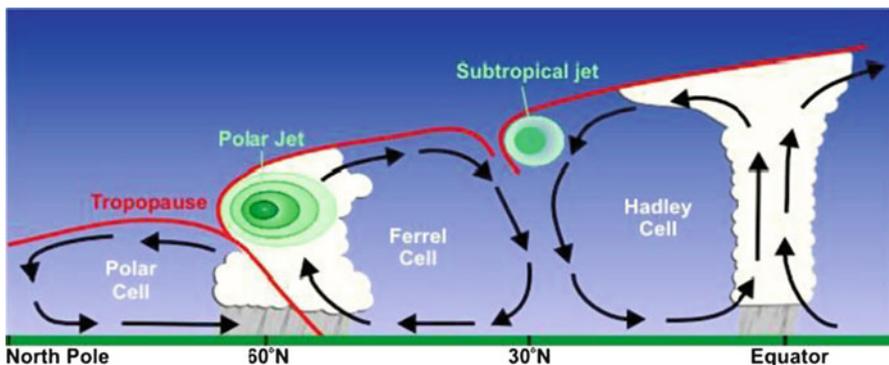


Fig. 8.4 The tropopause varies in elevation within the atmosphere being higher at the Equator and lower at the poles (NOAA, Public Domain)

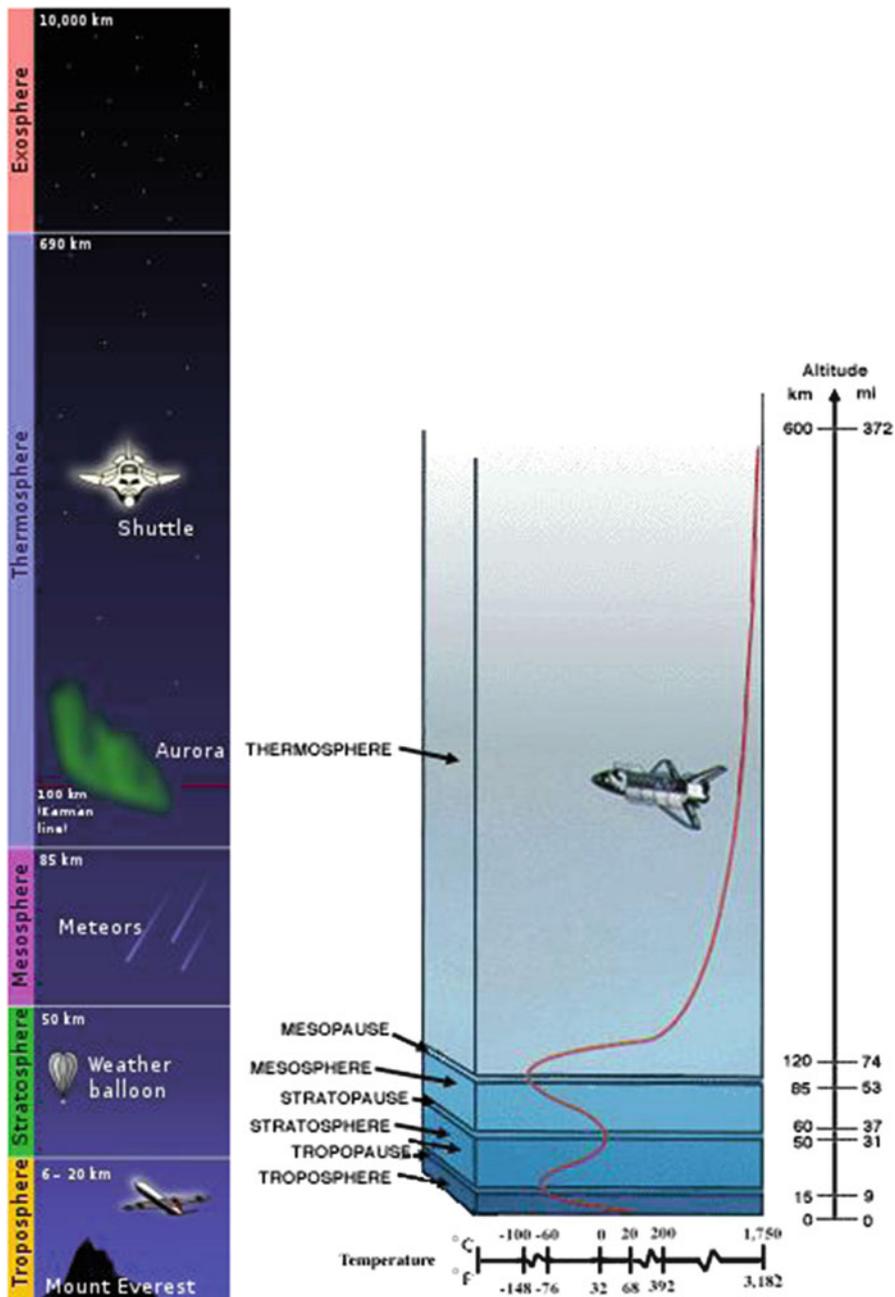


Fig. 8.5 Vertical slice through the Earth's atmosphere, not to scale, showing the five main layers and the tropopause, stratopause, and mesopause (From NASA, Public Domain)

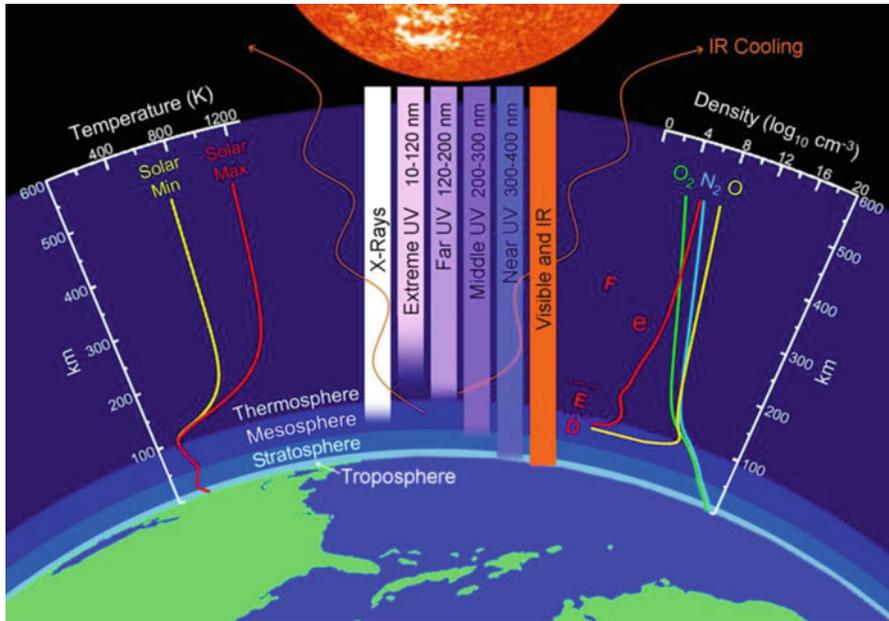


Fig. 8.6 Layers of Earth's upper atmosphere showing the penetrations of X-rays, UV rays, visible and IR radiation, temperature and density variations in the different layers (Credit: John Emmert/NRL, NASA, Public Domain)

The tropopause has been rising in altitude for the past several decades due to global warming. As the troposphere warms and the air expands, the tropopause rises.

The atmosphere's lowest or bottom layer, the layer in contact with the Earth, is the troposphere. The troposphere is the layer where weather occurs and it extends from the Earth's surface to about 20 km in height.

The troposphere has a temperature gradient, warmer at its base and cooler at its top. The base of the troposphere is getting warmer and this warmer air is increasing vertically. The temperature gradient from top to bottom in the troposphere is lessening. Greenhouse gases are keeping the troposphere warm at the base. The Sun's rays impact the Earth's surface and warm it. This in turn, along with heat radiation from greenhouse gases, further warms the lower atmosphere.

Above the troposphere is the stratosphere. The stratosphere extends above the troposphere for about 30 km, to a height of around 50 km. Jet planes fly in the stratosphere and temperature increases near the top because it's warmed by the Sun. The ozone layer is contained within the lower part of the stratosphere and absorbs harmful ultraviolet rays from the Sun. Ultraviolet (UV) rays are known to cause skin cancer and have other undesirable impacts on humans and other species.

Chemical composition in the stratosphere changes dramatically due to the ozone layer, but is otherwise rather consistent throughout. Ozone molecules are being destroyed at the South Pole causing the layer to become so thin that scientists call it a "hole."

The ozone layer is thinning due to destruction by atoms of chlorine and bromine. The main source of these chemicals is transportation through the atmosphere of freons and halons, totally anthropogenic and emitted from Earth's surface by humans. These substances are commonly referred to as ozone-depleting substances (ODSs). As emissions of these substances increase, the ozone depletion increases.

Above the stratosphere is the mesosphere, which extends from about 50 km to about 85 km within which temperatures decrease upward again. The coldest parts of the atmosphere occur in the mesosphere and may reach -100°C .

Above the mesosphere lies the thermosphere, which is a thick layer and extends to about 690 km. In the thermosphere the air is thin and is very sensitive to solar activity. As one goes up in the thermosphere, temperatures increase. Astronauts in the International Space Station orbit the Earth in this layer and the Space Shuttle flies into this layer. The thermosphere may heat to $1,500^{\circ}\text{C}$ due to incoming solar radiation.

Recently (July 2011), the thermosphere has undergone a contraction which is causing some concern among atmospheric and climate change scientists. The thermosphere, which blocks harmful ultraviolet rays, expands and contracts regularly due to the Sun's activities. Since 2007, the Sun has been in a period of solar activity known as a solar minimum and sunspots have been a rarity. The contraction happened during the deep solar minimum of 2008–2009, a fact which comes as little surprise to researchers. The thermosphere always cools and contracts when solar activity is low. In this case, however, the magnitude of the collapse was two to three times greater than low solar activity could explain, and scientists have so far been unable to explain it completely.

Figure 8.6 shows the penetration of various types of radiation passing through various atmospheric layers and those absorbed by the Earth's atmosphere, as well as variations in density and temperature in the atmosphere.

8.6 Atmospheric Circulation

Wind is defined simply as moving air. Wind on the Earth is caused by different atmospheric pressure or by air being moved by convection. Convection moves air vertically and in a circular motion, up and down, as opposed to laterally from Equator to pole.

The lower part of the atmosphere is sometimes referred to as the planetary boundary layer (PBL) where it is influenced by its contact with the Earth's surface (Fig. 8.7). It is in this layer that most turbulence occurs and vertical mixing is greatest. Above the PBL, the wind is approximately parallel to the isobars of a weather or barometric map and the winds are said to be geostrophic. Within the PBL the wind is affected by surface drag and flows across the isobars.

In Fig. 8.8, typical development of a thunderstorm is shown. Cumulous clouds develop from convection as hot moist air rises from the Earth's surface to higher and higher elevations. As the cumulus clouds grow larger, there is air circulation within them and the moist air eventually chills and precipitates as rainfall in a thunderstorm. Three stages in the development of a thunderstorm are shown in Fig. 8.8; (1) a towering cumulus stage, (2) a mature stage, and (3) the dissipating stage.

Depiction of various surfaces and PBL processes

--- Top of the planetary boundary layer

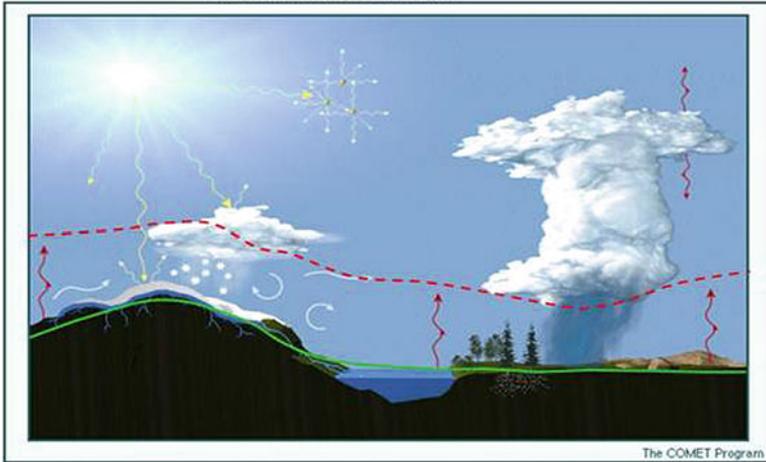


Fig. 8.7 The vertical movement of air within the lower part of the atmosphere. Depiction of where the planetary boundary layer (PBL) lies on a sunny day (red dashed line represents the top of the PBL; arrows represent direction of air movement) (NOAA, Public Domain)

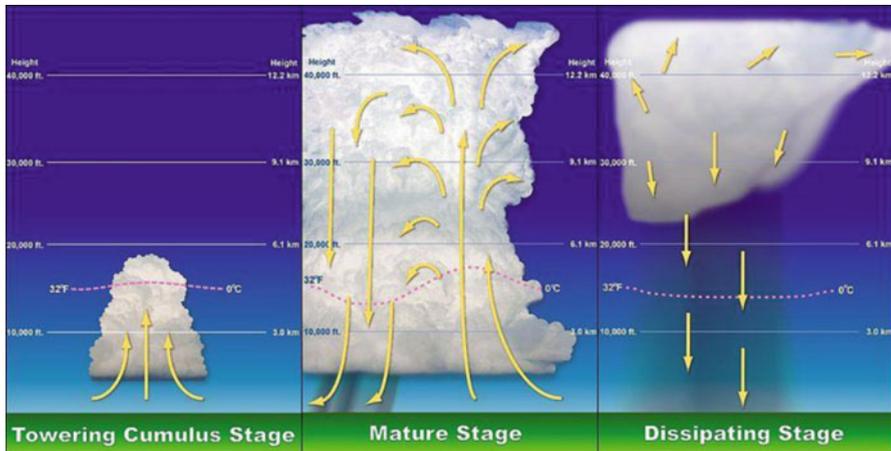
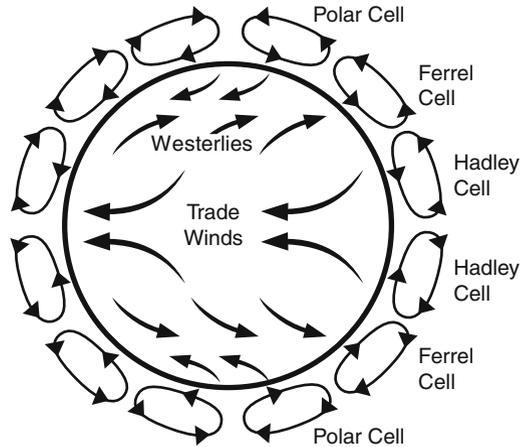


Fig. 8.8 The formation and dissipation of a thunderstorm (From NOAA, Public Domain)

Air moves from high pressure areas to areas of low pressure. Barometric pressure is the weight of a column of air, or atmospheric pressure. On weather maps, high and low pressure areas are marked “H” and “L” respectively and contour lines connecting points of equal barometric pressure (isobars) are drawn. If these isobars are close together, wind is stronger; further apart, the wind is not as strong.

Global warming has caused the troposphere to warm and a warming troposphere, where the majority of weather occurs, means more moisture and more energy for

Fig. 8.9 Global circulation of Earth's atmosphere displaying Hadley cell, Ferrell cell and Polar cell (Redrawn by John Cook from NASA, Public Domain)



storms to develop. The atmosphere in 2012 holds about 4% more moisture than it did before the middle of the last century. Warmer air holds more moisture than colder air and this moisture has to fall somewhere. Therefore there is more uncertainty in the weather patterns that develop; more storms in some areas, more wind shear and more tornadoes, more droughts in some areas, more heat waves, etc.

Global warming is also affecting the Jet Stream, a river of air which flows aloft and meanders like a river on land. It circles the Earth in the northern latitudes. As the Arctic region warms and there is less sea ice formed, more heat energy is released to the atmosphere in the Arctic.

The Jet Stream separates the cold air of the Arctic north of the Jet Stream from warm air south of the Jet Stream. As the Arctic warms and there is less temperature difference on both sides of the Jet Stream, the air movement slows and its meanders become larger. There are larger loops in its course. A large southern loop causes cold air to move south; a larger northern loop causes warm air to move north.

The Sun heats the ground or ocean surface most intensely in tropical areas. The heated air rises, and as it rises, it cools; and as it cools it loses its moisture as rain or snow, depending on the temperature. This belt of converging air masses, called the doldrums due to low air and water circulation sometimes causing sailing ships to struggle to escape the region, includes some of the rainiest areas on Earth. The cooled, now drier air is forced by continuously rising air to move out of the way, and so it moves towards the temperate latitudes. Air moves by convection from tropical to temperate to Polar Regions. Air also moves laterally by differences in pressure.

Such air from the tropics meets air moving down from the poles at about 30°N and °S, called the horse latitudes, where it settles. Here the sinking air compresses, warms, and absorbs moisture from the surface. This is why the major desert belts of Earth lie in the horse latitudes. This warm, dry air is displaced by more sinking air and so some of it returns back to the Equatorial zone, and some returns to the poles. Such cycling air between low and mid-latitudes defines a Hadley Cell (see Fig. 8.9).

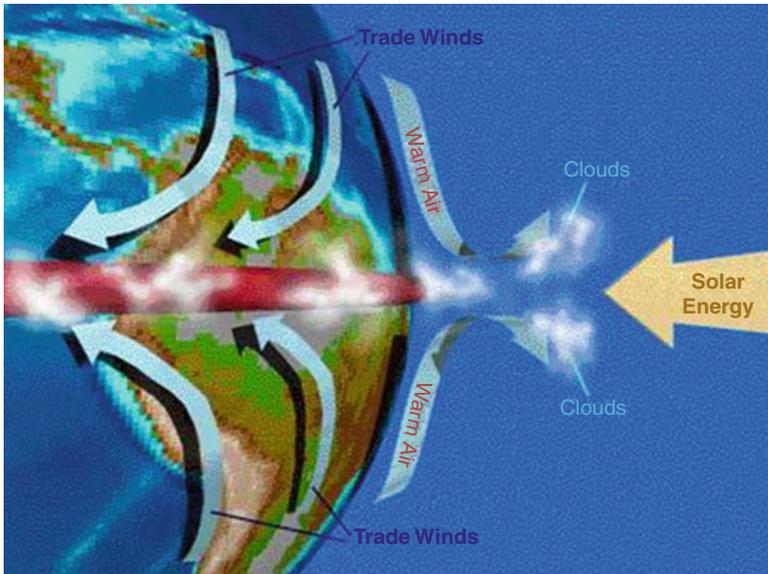


Fig. 8.10 Solar energy causing the circulation of the atmosphere (NASA, Public Domain)

A similar cell forms between the horse latitudes and the stormy polar fronts at 60°N and 60°S , where warm temperate air moving toward the poles meets very cold air rolling down from the poles. The lighter warm air is forced to rise over the denser cold air, which chills it and forces precipitation. From this polar front, air returns both toward the Equator and toward the poles. Air immediately over the pole sinks. While it is not warm, it is extremely dry (only centimeters of snow every year). From the poles, air within the polar cap streams back towards the polar front.

Thus, six belt-like Hadley Cells circulate air from pole to pole and establish patterns of climate over the planet. The cells are also characterized by specific patterns of wind flow, a function of the Coriolis force generated by the spin of the Earth. In the temperate zone between the horse latitudes and the polar front, the prevailing westerlies dominate air circulation. In the tropics, the easterly trade winds dominate. Winds around the poles are also easterly. Winds are named from the directions from which they come; therefore, easterlies come from the east, westerlies from the west.

The Ferrel Cell is a secondary circulation feature dependent for its existence upon the Hadley cell and the Polar cell. The Ferrel Cell behaves as an atmospheric “ball bearing” between the Hadley cell and the Polar cell, and comes about as a result of the eddy circulations (the high and low pressure areas) of the mid-latitudes. For this reason it is sometimes known as the “zone of mixing.” At its southern extent (in the Northern Hemisphere), it overrides the Hadley cell, and at its northern extent, it overrides the Polar cell. Just as the Trade Winds (Figs. 8.9 and 8.10) are to be found below the Hadley cell, the Westerlies



Fig. 8.11 Dunes of Maspalomas in Gran Canaria, one of the Canary Islands (Public Domain)

can be found beneath the Ferrel cell. Thus, strong high pressure areas which divert the prevailing westerlies, such as a Siberian high (which could be considered an extension of the Arctic high), could be said to override the Ferrel cell, making it discontinuous.

One result of wind activity is that it carries small particles; especially in areas where the land surface consists of loose materials. Moving air is able to pick up loose particles, such as sand and dust, and transport them until there is a loss of wind velocity. It then deposits these particles, sometimes in various sand deposits known as sand dunes (Fig. 8.11). Deposits of finer materials like dust are left on the windward side of obstructions or simply scattered across the landscape.

Additional Readings

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