Earth's Modern Atmosphere

3

Key Learning Concepts for Chapter 3

The following learning concepts help guide the student's reading and comprehension efforts. The operative word is in italics. These are included in each chapter of *Geosystems.* The student is told: "after reading the chapter you should be able to":

• ***Draw*** a diagram showing three profiles of atmospheric structure based on three criteria for analysis—composition, temperature, and function.

• ***List*** and ***describe*** the components of the modern atmosphere, giving their relative percentage contributions by volume.

• ***Describe*** conditions within the stratosphere; specifically, ***review*** the function and status of the ozonosphere, or ozone layer.

• ***Distinguish*** between natural and anthropogenic pollutants in the lower atmosphere.

• ***Construct*** a simple diagram illustrating the pollution from photochemical reactions in motor vehicle exhaust, and ***describe*** the sources and effects of industrial smog.

Overview

We examine the modern atmosphere using the criteria of composition, temperature, and function. Our look at the atmosphere also includes the spatial impacts of both natural and human-produced air pollution. We all interact with the atmosphere with each breath we take, the energy we consume, the travelling we do, and the products we buy. Human activities cause stratospheric ozone losses and the blight of acid deposition on ecosystems. These matters are essential to physical geography, for they are influencing the atmospheric composition of the future.

Earth's atmosphere is a unique reservoir of gases, the product of billions of years of development. This chapter examines its structure, function, and composition, starting from outer space and descending through the various layers and regions of the atmosphere to the surface of Earth. A consideration of our modern atmosphere must also include the spatial aspects of human-induced problems that affect it, such as air pollution, the stratospheric ozone predicament, and the blight of acid deposition.

The modern atmosphere is an essential medium for life processes. We feel its significance during every space flight and witness the equipment and safeguards needed to protect humans when they venture outside life-sustaining and protective cover of the atmosphere.

An interesting thought exercise is to take the idea of an astronaut doing a spacewalk (EVA). Refer to the photo of astronaut Mark Lee in Figure GN 3.1, or Felix Baumgartner in Figure GN 3.3. If you were in charge of designing and constructing the spacesuit, your design would have to accomplish the protection shown in Figure 3.4.

As before, a list of key learning concepts begins the chapter and is used to organize the Summary and Review section, with definitions, key terms and page numbers, and review questions grouped under each objective. At the beginning of each chapter a section titled "**In This Chapter**" introduces the chapter's content in a succinct statement.

Outline Headings and Key Terms

The first-, second-, and third-order headings that divide Chapter 3 serve as an outline. The key terms and concepts that appear **boldface** in the text are listed here under their appropriate heading in ***bold italics***. All these highlighted terms appear in the text glossary. Note the check-off box (❏) so you can mark class progress. These terms should be in your reading notes or used to prepare note cards.

The outline headings and terms for Chapter 3:

Geosystems Now "Humans help define the atmosphere"

Atmospheric Composition, Temperature, and Function

- ❑ ***air***
- ❑ ***exosphere***

Atmospheric Profile

- ❑ ***air pressure***

Atmospheric Composition Criterion

Heterosphere

- ❑ ***heterosphere***

Homosphere

- ❑ ***homosphere***

Carbon Dioxide

Atmospheric Temperature Criterion

Thermosphere

- ❑ ***thermosphere***
- ❑ ***thermopause***
- ❑ ***kinetic energy***

Mesosphere

- ❑ ***mesosphere***
- ❑ ***noctilucent clouds***

Stratosphere

- ❑ ***stratosphere***

Troposphere

- ❑ ***troposphere***
- ❑ ***tropopause***
- ❑ ***normal lapse rate***
- ❑ ***environmental lapse rate***

Atmospheric Function Criterion

Ionosphere

- ❑ ***ionosphere***

Ozonosphere

- ❑ ***ozonosphere***
- ❑ ***ozone layer***

UV Index Helps Save Your Skin

Pollutants in the Atmosphere

- ❑ ***pollutants***

Natural Sources of Air Pollution

- ❑ ***aerosols***

Anthropogenic Pollution

- ❑ ***carbon monoxide (CO)***

Photochemical Smog Pollution

- ❑ ***photochemical smog***
- ❑ ***volotile organic compounds (VOCs)***
- ❑ ***nitrogen dioxide*** (NO_2)
- ❑ ***peroxyacetyl nitrates (PAN)***
- ❑ ***volatile organic compounds (VOCs)***

Industrial Smog and Sulfur Oxides

- ❑ ***industrial smog***
- ❑ ***sulfur dioxide*** (SO_2)
- ❑ ***sulfate aerosols***

Particulates/Aerosols

- ❑ ***particulate matter (PM)***

Natural Factors that Affect Air Pollution

Winds

Local and Regional Landscapes

Temperature Inversion

- ❑ ***temperature inversion***

Benefits of the Clean Air Act

The Human Denominator 3 The Shared Global Atmosphere

Geosystems Connection

A Quantitative Solution: Lapse Rates

Key Learning Concepts Review

Mastering Geography

Visual Analysis 3 The Atmosphere and Inversion Layers

Focus Studies, Critical Thinking, Geo Reports and Geosystems in Action

Focus Study 3.1 Stratospheric Ozone Losses: A Continuing Health Hazard

Focus Study 3.2 Acid Deposition: Damaging to Ecosystems

Critical Thinking 3.1: Where is your tropopause?

Critical Thinking 3.2: Finding your local ozone

Critical Thinking 3.3: Evaluating costs and benefits

***Geo Report* 3.1** Earth's evolving atmosphere

***Geo Report* 3.2:** Outside the airplane

***Geo Report* 3.3:** Human sources of atmospheric carbon dioxide

***Geo Report* 3.4:** NASA's Global Hawks make scientific flights

***Geo Report* 3.5:** Carbon monoxide—the colourless, odorless pollutant

Geosystems in Action 3 Air Pollution

URLs listed in Chapter 3

Baumgartner jump:
- www.redbullstratos.com
- vimeo.com/10992331

CO_2 monitoring:
- ftp://ftp.cmdl.noaa.gov/ccg/co2/trends/co2_mm_mlo.txt
- www.epa.gov/climatechange/ghgemissions

Noctilucent clouds:
- lasp.colorado.edu/science/atmospheric

Ionosphere:
- science.nasa.gov/science-news/science-at-nasa/2008/30apr_4dionosphere_launch

Stratospheric ozone predicament:
- ozoneaq.gsfc.nasa.gov/ozone_overhead_all_v8.md
- www.ec.gc.ca/uv/default_asp?lang=En&n=C74058DD-1/
- www.epa.gov/sunwise/uvindex.html
- www.ec.gc.ca/ozone/
- ozonewatch.gsfc.nasa.gov/
- ozone.unep.org/new_site/en/index.php
- earthobservatory.nasa.gov/Features/WorldOfChange/ozone.php
- earthobservatory.nasa.gov/IOTD/view.php?id=49874
- www.aeryon.com/products/avs/aeryon-skyranger.html

Air pollution observations and agreements:
- www.cdc.gov/nceh/airpollution
- www.lung.org

Acid deposition:
- www.hubbardbrook.org

Chapter Review Questions

• ***Draw*** a diagram showing three profiles of atmospheric structure based on three criteria for analysis—composition, temperature, and function.

1. What is air? Where did the components in Earth's present atmosphere originate?
Earth's atmosphere is a unique reservoir of gases, the product of billions of years of development. The modern atmosphere is probably Earth's fourth general atmosphere. The principal substance of this atmosphere is air, the medium of life as well as a major industrial and chemical raw material. Air is a simple additive mixture of gases that is naturally odorless, colourless, tasteless, and formless, blended so thoroughly that it behaves as if it were a single gas.

This modern atmosphere is, in reality, a gaseous mixture of ancient origins—the sum of all the exhalations and inhalations of life on Earth throughout time.

2. Characterise the various functions the atmosphere performs that protect the surface environment.
A membrane around a cell regulates the interactions of the delicate inner workings of that cell and the potentially disruptive outer environment. Each membrane is very selective as to what it will and will not allow to pass. The modern atmosphere acts as Earth's protective membrane. The atmosphere absorbs and interacts with harmful wavelengths of electromagnetic radiation, the streams of charged particles in the solar wind, and natural and human-caused space debris—all protecting the delicate aspects of the biosphere in the lower troposphere. As critical as the atmosphere is to us, it represents only a thin-skinned envelope amounting to less than one-millionth of the total mass of Earth.

3. What three distinct criteria are employed in dividing the atmosphere for study?
The atmosphere is conveniently classified using three criteria: composition, temperature, and function. Based on chemical *composition* the atmosphere is divided into two broad regions: the heterosphere and the homosphere. Based on *temperature* the atmosphere is divided into four distinct zones: the thermosphere, mesosphere, stratosphere, and troposphere. Finally, two specific zones are identified on the basis of *function* relative to their role of removing most of the harmful wavelengths of solar radiation**—**these are the ionosphere and the ozonosphere, or ozone layer. See the right-hand column in Figure 3.1.

4. Describe the overall temperature profile of the atmosphere and list the four layers defined by temperature.
The temperature profile in Figure 3.1 shows that temperatures rise sharply in the thermosphere, up to 1200°C and higher at the top of the atmosphere. Individual molecules of nitrogen and oxygen and atoms of oxygen are excited to high levels of vibration from the intense radiation present in this portion of the atmosphere. This *kinetic energy*, the energy of motion, is the vibrational energy stated as temperature, although the density of the molecules is so low

that little heat is produced. Heating in the lower atmosphere closer to Earth differs because the active molecules in the denser atmosphere transmit their kinetic energy as *sensible heat*. The mesosphere is the coldest portion of the atmosphere, averaging –90°C, although that temperature may vary by 25C° to 30C°.

Temperatures increase throughout the stratosphere from –57°C at 20 km (tropopause), warming to freezing at 50 km (stratopause). The tropopause is defined by an average temperature of –57°C, but its exact location varies with the seasons of the year, latitude, and sea level temperatures and pressures.

Tropospheric temperatures decrease with increasing altitude at an average of 6.4C° per km, a rate known as the normal lapse rate. The actual lapse rate at any particular time and place under local weather conditions is called the environmental lapse rate, and may vary greatly from the normal lapse rate.

5. Describe the two divisions of the atmosphere on the basis of composition.
Heterosphere and homosphere—the former organized in layers based on the weight of gases, and the latter an even mixture of gases, "air."

6. What are the two primary functional layers of the atmosphere and what does each do?
Ionosphere (absorbs gamma rays, X-rays, and all wavelengths shorter than ultraviolet); and the ozonosphere (absorbs most wavelengths of ultraviolet, letting only a small portion through to the surface).

• ***List*** and ***describe*** the components of the modern atmosphere, giving their relative percentage contributions by volume.

7. Name the four most prevalent stable gases in the homosphere. Where did each originate? Is the amount of any of these changing at this time?

Symbol	% by Vol.	Parts per million
N_2	78.084	780,840
O_2	20.946	209,460
Ar	0.934	9,340
CO_2	0.0399	399

The atmosphere is a vast reservoir of relatively inert nitrogen, principally originating from volcanic sources. In the soil, nitrogen is bound up by nitrogen-fixing bacteria and is returned to the atmosphere by denitrifying bacteria that remove it from organic materials. Oxygen, a by-product of photosynthesis, is essential for life processes. Along with other elements, oxygen forms compounds that compose about half of Earth's crust. Argon is a residue from the radioactive decay of a form of potassium (^{40}K). A slow process of accumulation accounts for all that is present in the modern atmosphere. Argon is completely inert and as a noble gas is unusable in life processes. Although it has increased over the past 200 years, carbon dioxide is included in this list of stable gases. It is a natural by-product of life processes, and the implications of its current increase are critical to society and the future. The role of carbon dioxide in the gradual warming of Earth is discussed in Chapters 5 and 10.

• ***Describe*** conditions within the stratosphere; specifically, ***review*** the function and status of the ozonosphere, or ozone layer.

8. Why is stratospheric ozone (O_3) so important? Describe the effects created by increases in ultraviolet light reaching the surface.
Ozone absorbs wavelengths of ultraviolet light and subsequently reradiates this energy at longer wavelengths, as infrared energy. Through this process, most harmful ultraviolet radiation is converted, effectively "filtering" it and safeguarding life at Earth's surface. See Focus Study 3.1 for greater discussion of the effects caused by ozone depletion.

9. Summarize the ozone predicament and describe treaties to protect the ozone layer.
See Focus Study 3.1. Environment Canada has a scientific observatory to study the ozone layer over Canada. This high-Arctic facility now is operational at a remote weather station near Eureka on Ellesmere Island, N.W.T., about 1000 km from the North Pole. The Arctic ozone depletion affects concentrations at lower latitudes and thus should draw the United States into further cooperation.

10. Evaluate Crutzen, Rowland, and Molina's use of the scientific method in investigating stratospheric ozone depletion and the public reaction to their findings.
University of California, Irvine professors F. Sherwood Rowland and Mario J. Molina first

suggested the possible depletion of the ozone layer by human activity during the summer of 1974. Rowland and Molina hypothesized that the stable, large CFC molecules remained intact in the atmosphere, eventually migrating upward and working their way into the stratosphere. CFCs do not dissolve in water and do not break down biologically. The increased ultraviolet light encountered by the CFC molecule in the stratosphere dissociates, or splits, the CFC molecules, releasing chlorine (Cl) atoms and forming chlorine oxide (ClO) molecules. At present, after much scientific evidence and verification of actual depletion of stratospheric ozone by chlorine atoms (1987–1990), even industry has had to admit that the problem is real.

The scientific method is discussed in Chapter 1. Recall in the chapter when Dr. Rowland stated his frustration: “What’s the use of having developed a science well enough to make predictions, if in the end all we are willing to do is stand around and wait for them to come true.... Unfortunately, this means that if there is a disaster in the making in the stratosphere, we are probably not going to avoid it.” (Roger B. Barry, “The Annals of Chemistry,” *The New Yorker*, 9 June 1986, p. 83.) The Nobel Committee awarded these men, and Paul Crutzen, the 1995 Nobel Prize for chemistry for their important discovery and actions (see Focus Study 3.1, p. 74).

In 1994 an international scientific consensus confirmed previous assessments of the anthropogenic (human-caused) disruption of the ozone layer—in other words chlorine atoms and chlorine monoxide molecules in the stratosphere are of human origin. The report, *Scientific Assessment of Ozone Depletion*, was prepared by NASA, NOAA, the United Nations Environment Programme, and the World Meteorological Organization.

• ***Distinguish*** between natural and anthropogenic pollutants in the lower atmosphere.

11. Describe two types of natural air pollution. What regions of Earth commonly experience this type of pollution?

Volcanic eruptions and wildfires have occurred throughout human evolution on Earth. They are relatively infrequent in timing, but their effects can cover large areas. However, any attempt to diminish the impact of human-made air pollution through a comparison with natural sources is irrelevant, for we have co-evolved and adapted to the presence of certain natural ingredients in the air. We have not evolved in relation to the concentrations of anthropogenic (human-caused) contaminants found in our metropolitan areas.

Wildfires are common in large forested areas like Canada’s Boreal and Montane forests of British Columbia and the northern parts of Alberta, Saskatchewan, Manitoba, Ontario and Quebec. Volcanic eruptions are associated with subduction zones along the margins of tectonic plates.

12. What are pollutants? What is the relationship between air pollution and urban areas?

Natural and human-caused gases, particles, and other substances in amounts that are harmful to humans or cause environmental damage are atmospheric pollutants.

Anthropogenic air pollution is most prevalent in urbanized regions. According to the World Health Organization, urban outdoor air pollution causes an estimated 1.3 million deaths worldwide. As urban populations grow, human exposure to air pollution increases. India, with an urban population of 31%, has the worst air quality out of 132 countries surveyed. Over half the world’s population now lives in metropolitan regions, some one-third with unhealthful levels of air pollution. This represents a potentially massive public-health issue in this century.

• ***Construct*** a simple diagram illustrating the pollution from photochemical reactions in motor vehicle exhaust, and ***describe*** the sources and effects of industrial smog.

13. What is the difference between industrial smog and photochemical smog?

The air pollution associated with coal-burning industries is known as industrial smog. The term smog was coined by a London physician at the turn of the 20th century to describe the combination of fog and smoke containing sulfur, an impurity found in fossil fuels. The combination of sulfur and moisture droplets forms a sulfuric acid mist that is extremely dangerous in high concentrations.

Photochemical smog is another type of pollution that was not generally experienced in the past but developed with the advent of the automobile. Today, it is the major component of anthropogenic air pollution. Photochemical smog results from the interaction of sunlight and the products of automobile exhaust. Although the term *smog* is a misnomer, it is generally used to describe this phenomenon. Smog is responsible for the hazy appearance of the sky and the reduced intensity of sunlight in many of our cities.

14. Describe the relationship between automobiles and the production of ozone and PANs in city air. What are the principal negative impacts of these gases?

The nitrogen dioxide derived from automobiles, and power plants to a lesser extent, is highly reactive with ultraviolet light, which liberates atomic oxygen (O) and a nitric oxide (NO) molecule (Figure GIA 3.2). The free oxygen atom combines with an oxygen molecule (O_2) to form the oxidant ozone (O_3); the same gas that is beneficial in the stratosphere is an air pollution hazard at Earth's surface. In addition to forming O_3, the nitric oxide (NO) molecule reacts with hydrocarbons (HC) to produce a whole family of chemicals generally called peroxyacetyl nitrates (PANs). PANs produces no known health effects in humans but are particularly damaging to plants, which provided the clue for discovery of these photochemical reactions.

15. How are sulfur impurities in fossil fuels related to the formation of acid in the atmosphere and acid deposition on the land?

Certain anthropogenic gases are converted in the atmosphere into acids that are removed by wet and dry deposition processes. Nitrogen and sulfur oxides (NO_X, and SO_X) released in the combustion of fossil fuel, can produce nitric acid (HNO_3) and sulfuric acid (H_2SO_4) in the atmosphere. Focus Study 3.2, Figure 3.2.2 depicts the improving pattern of sulfate wet deposition in Canada and the United States between two sets of dates. Precipitation as acidic as pH 2.0 has fallen in the eastern United States, Scandinavia, and Europe. By comparison, vinegar and lemon juice register slightly less than 3.0. Aquatic life perishes when lakes drop below pH 4.8..

16. In what ways does a temperature inversion worsen an air pollution episode? Why?

A temperature inversion occurs when the normal decrease of temperature with increasing altitude reverses at any point from ground level up to several thousand feet. Such an inversion most often results from certain weather conditions, for example when the air near the ground is radiatively cooled on clear nights or when cold air drains into valleys. The warm air inversion in Figure 3.7 prevents the vertical mixing of pollutants with other atmospheric gases. Thus, instead of being carried away, the pollutants are trapped below the inversion layer.

17. In summary, what are the results from the first 20 years under Clean Air Act regulations?

The Benefits of the Clean Air Act, 1970 to 1990 (Office of Policy, Planning, and Evaluation, U. S. EPA) calculated the following:

- The *total direct cost* to implement the Clean Air Act for all federal, state, and local rules from 1970 to 1990 was US*$523 billion* (in 1990-value dollars). This cost was borne by businesses, consumers, and government entities.
- The estimate of *direct monetized benefits* from the Clean Air Act from 1970 to 1990 falls in a range from US$5.6 to $49.4 trillion, with a central mean of US$*22.2 trillion*. (The uncertainty of the assessment is indicated by the range of benefit estimates.)
- Therefore, the *net financial benefit* of the Clean Air Act is US*$21.7 trillion*! "The finding is overwhelming. The benefits far exceed the costs of the CAA in the first 20 years," said Richard Morgenstern, associate administrator for policy planning and evaluation at the EPA.

The benefits to society, directly and indirectly, have been widespread across the entire population: improved health and environment, less lead to harm children, lowered cancer rates, less acid deposition, an estimated 206,000 fewer deaths related to air pollution-related deaths in 1990 alone, among many benefits described. These benefits took place during a period in which the U. S. population grew by 22 percent and the economy expanded by 70 percent.

Political forces seem to be moving to weaken or unwind some of these financially and healthful beneficial regulations. This is difficult to understand logically unless a public is not aware of the benefits identified in these published studies. We think it important that this section remain in *Geosystems* to get the word out to people.

Critical Thinking

Critical thinking 3.1
Where is Your Tropopause?
The tropopause is at a higher altitude in summer due to surface heating and warming of the lower atmosphere.

Critical thinking 3.2
Finding Your Local Ozone
Personal answers depending upon students' location and season. An example is ozone measured by OMI over 38.00 degrees latitude -121.00 degrees longitude on 2013/12/01 is 249 Dobson units.

Critical thinking 3.3
Evaluating Costs and Benefits
Personal answers, but one might be: The public is uninformed about the benefits of the CAA because it is not in the financial interest of the fossil-fuel industry for the public to be aware of the true cost of fossil-fuels.

Similar patterns exist for the CWA, hazard zoning, climate change, and the Endangerment Finding by the EPA. These are all examples where the profits of destructive actions go to the company creating the damage, but the costs are borne by all of us—an unacceptable and unfair externality.

GIA Questions and GEOquiz

Analyze: Which pollutants could be reduced by switching to low-sulfur coal and installing scrubbers in smokestacks?
These actions would likely reduce the sulfur oxides which would, in turn, lead to a decreas in the production of sulfuric acid in the environment.

Describe: List the steps in the process by which vehicle exhause leads to the increased ozone levels in smog.
Internal combustion engines produce nitrogen dioxide. Ultraviolet radiation liberates atomic oxygen and a nitric oxide molecule from this. The free oxygen atom combines with an oxygen molecule to form ozone. In the upper atmosphere this ozone protects us from UV radiation. At ground level, ozone is a reactive gas that damages biological tissues and causes a variety of detrimental health effects like lung irritation, asthma, and leads to respiratory illness.

1. Predict: In relation to a coal-fired power plant, where might industrial smog and serious air pollution problems occur? What mitigation strategies exist? Explain.
Coal-fired power plants are the main source of sulfur oxides. They also produce sulfate aerosols, mercury, particulates, and carbon dioxide. Industrial smog and air pollution would result downwind of the plant, especially if there are natural factors such as valleys or inversion layers present.

Mitigation strategies include investing in sustainable, renewable sources of energy like wind and solar power.

2. Compare and Contrast: How are the pollutants carbon monoxide and nitrogen dioxide similar? How are they different?
Carbon monoxide and nitrogen dioxide are both produced by combustion; however, CO is odorless, colourless, and tasteless while NO_2 is a reddish-brown choking gas that leads to acid deposition, inflames the respiratory system, and destroys lung tissue. CO does have health issues in that it replaces oxygen in hemoglobin, which can lead to unconsciousness and death.

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Visual Analysis 3 The Atmosphere and Inversion Layers

1. **During a temperature inversion, where is the layer of warm air relative to the layer of cold air? Can you identify each layer in this photo?**

Cooler air lies below a layer of warmer air. The cold air in the photo is the air containing the haze and the warmer air sits above that layer, capping it

2. **In what ways does a temperature inversion worsen an air pollution episode? What human activities contribute to air pollution during the winter months?**

Because colder air is heavier than warmer air, vertical mixing is prevented during an inversion. This worsens air pollution episodes by trapping pollutants near the surface. During winter months, extended idling of automobiles and trucks, home heating by burning natural gas, and the generation of electricity by coal fired power plants all contribute pollutants to the atmosphere that are trapped during temperature inversions.